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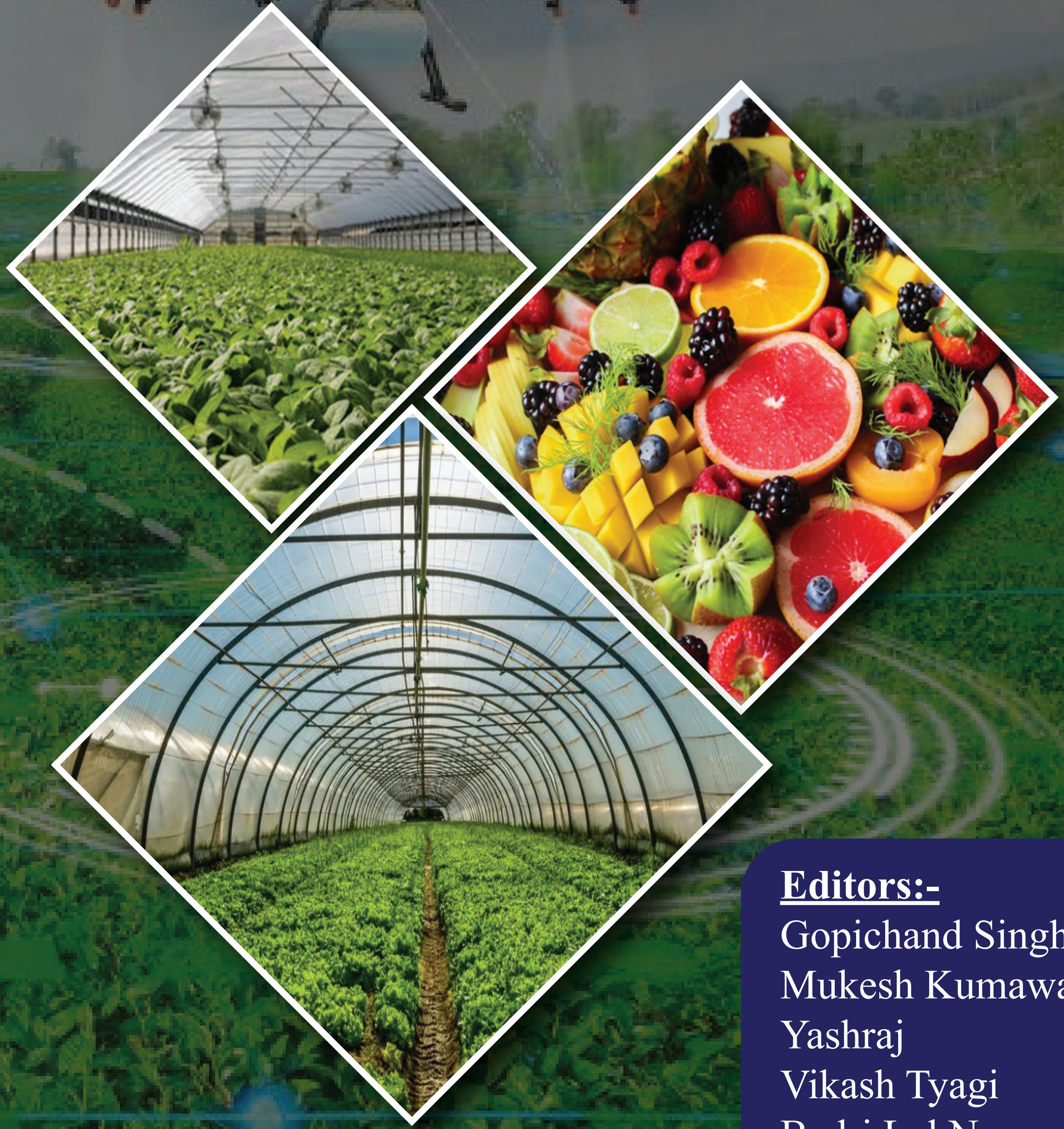

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PREFACE

The world of horticulture is undergoing a remarkable transformation, driven by the rapid advancements in technology. As we navigate through the challenges of the 21st century, it is imperative that we harness the power of innovation to cultivate a more sustainable, efficient, and resilient horticultural landscape. "Advanced Technology for Horticulture" is a comprehensive guide that explores the cutting-edge tools, techniques, and strategies that are revolutionizing the way we grow, manage, and optimize our crops.

From the precision of sensor-based irrigation systems to the autonomy of robotic harvesters, this book delves into the myriad ways technology is reshaping the horticultural industry. It explores the applications of data analytics, machine learning, and artificial intelligence in optimizing resource allocation, predicting crop yields, and mitigating the impacts of climate change. The book also sheds light on the latest advancements in biotechnology, including gene editing and molecular breeding, which hold immense potential for developing resilient and high-yielding crop varieties.

Whether you are a seasoned horticulturist, a researcher, or an enthusiast eager to explore the future of gardening, this book will provide you with valuable insights and practical knowledge. It not only showcases the current state of technology but also offers a glimpse into the exciting possibilities that lie ahead. By embracing these advancements, we can unlock new opportunities for sustainable food production, ornamental horticulture, and urban greening.

"Advanced Technology for Horticulture" serves as an indispensable resource for anyone seeking to stay at the forefront of this dynamic field. It aims to inspire, educate, and empower readers to harness the power of technology in creating a greener, more bountiful future. Join us on this fascinating journey as we explore the boundless potential of advanced technology in shaping the future of horticulture.

Happy reading and happy gardening!

Authors……

TABLE OF CONTENTS

S.N	CHAPTERS	Page No.
1.	Advances in Precision Irrigation for Sustainable Fruit Production	1-27
2.	Agro-tourism and Horticultural Entrepreneurship	28-45
3.	Automation and Robotics in Horticultural Operations	46-69
4.	Novel Approaches to Pest and Disease Management in Vegetable Crops	70-95
5.	Edible landscaping and its benefits	96-104
6.	Functional Foods and Nutraceuticals from Fruits and Vegetables	105-125
7.	Postharvest Technology and Shelf Life Extension of Fruits and Vegetables	126-166
8.	Role of Beneficial Microorganisms in Horticultural Crop Production	167-182
9.	Role of Nanotechnology in Horticultural Crop Protection and Production	183-202
10.	Soil Types and Fertility Management	203-234
11.	Vertical Farming: The Future of Urban Horticulture	235-256

CHAPTER - 1

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Advances in Precision Irrigation for Sustainable Fruit Production

Gopichand Singh

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Abstract

Precision irrigation technologies offer significant potential for enhancing the sustainability of fruit production systems worldwide. By enabling growers to optimize water applications based on spatially and temporally variable crop water requirements, precision irrigation can increase water use efficiency, improve fruit yield and quality, and reduce the environmental impacts associated with excessive irrigation, such as nutrient leaching and soil erosion. Recent advances in sensing technologies, data analytics, and variable rate application systems are enabling ever more sophisticated approaches to precision irrigation management in orchards and vineyards. Remote and proximal sensing tools, such as multispectral and thermal imaging, provide detailed information on plant water status that can guide precision irrigation scheduling decisions. Soil moisture sensors and crop water stress indicators allow for the precise tracking of orchard water dynamics and crop responses to water deficits. Data integration and analytics tools are enabling the development of intelligent decision support systems for precision irrigation that combine weather, soil, plant, and irrigation system data to automatically determine optimal irrigation scheduling strategies. Variable rate drip and microsprinkler systems now allow for differential irrigation rates to be applied across a field based on local soil and plant conditions. Collectively, these technologies are ushering in a new era of precision irrigation in fruit crops that holds great promise for enhancing the water productivity, profitability and environmental sustainability of orchard and vineyard systems. However, challenges remain in developing sensing and analytics tools that are reliable, affordable, and easily deployable across diverse fruit production environments. Continued innovation and research collaboration at the intersection of plant science, data science, and engineering is needed to

fully realize the potential of precision irrigation approaches and to adapt them to the local realities of fruit growers worldwide.

Keywords: precision agriculture, water use efficiency, variable rate irrigation, soil moisture sensing, decision support systems

Water scarcity is an increasing challenge for agricultural production systems worldwide, driven by climate change, population growth, and competing demands for freshwater resources [1]. Irrigation is essential for many fruit crops to meet yield and quality targets, but excessive or poorly timed irrigation applications can negatively impact fruit production and the environment through nutrient leaching, soil erosion, and energy waste [2]. Globally, the sustainability of fruit production hinges on our ability to grow more crop per drop - that is, to increase water productivity through the development and adoption of water-saving technologies and practices [3].

Precision irrigation, an approach that seeks to optimize irrigation management by accounting for spatial and temporal variability in crop water needs, offers significant potential for increasing water use efficiency and reducing the environmental externalities of fruit production [4]. By delivering irrigation water with the right amount, at the right time, and in the right place, precision irrigation aims to maintain optimal crop water status while minimizing water losses through runoff, deep percolation, and soil evaporation [5].

Over the past decade, rapid advancements in sensing technologies, data analytics, and variable rate irrigation systems have accelerated the development and adoption of precision irrigation approaches in fruit crops [6]. Remote and proximal sensing tools are providing unprecedented insights into plant water dynamics, enabling the use of data-driven approaches for precision irrigation scheduling [7]. Soil moisture sensors, thermal imaging, and plant-based water stress indicators are being integrated into networked and automated irrigation control systems [8]. Analytics tools and decision support systems are transforming the way that big data is leveraged to guide precision irrigation management decisions [9].

At the same time, continued research is needed to develop precision irrigation technologies and strategies that are reliable, affordable, and adaptable to the diverse agroecological contexts and socioeconomic realities of fruit producers worldwide [10]. Many challenges remain in transferring the potential of precision irrigation into practical solutions that can be readily adopted by fruit growers, particularly in resource-limited production environments [11].

The goal of this chapter is to provide an overview of the latest advances in precision irrigation science and technology, and to highlight the opportunities and obstacles for enhancing the sustainability of fruit production through precision irrigation approaches. By reviewing the current status and future potential of precision irrigation, we aim to identify knowledge gaps and research priorities that can help accelerate the development and adoption of these technologies in diverse fruit production systems worldwide.

2. Sensing Technologies for Precision Irrigation Management Efficient irrigation management requires accurate and timely information on soil moisture dynamics and crop water status. Innovations in sensing technologies over the past decade have greatly expanded the tools available for monitoring water dynamics in orchard and vineyard systems [12]. Sensing approaches can be broadly categorized into proximal sensing techniques that require direct contact with soil or plant surfaces, and remote sensing techniques that use spectral data collected from aerial or satellite platforms to characterize soil-plant-water interactions [13].

2.1 Proximal Sensing Approaches Proximal sensing tools provide localized measurements of soil moisture content or plant water status, and are widely used for precision irrigation scheduling in fruit crops. The most common proximal sensing techniques include soil moisture sensors, stem water potential sensors, and sap flow meters.

2.1.1 Soil Moisture Sensors Soil moisture sensors are widely used in precision irrigation to track the wetting and drying dynamics of the crop root zone and guide irrigation scheduling decisions. A variety of sensor types are available that measure soil moisture content through changes in dielectric permittivity, electrical resistance, or heat dissipation [14]. Capacitance and time-domain reflectometry (TDR) sensors are among the most popular due to their high accuracy, durability, and ease of automation [15]. Sensors are typically deployed in representative locations of the orchard, and data is collected continuously to characterize temporal changes in soil water availability. Wireless sensor networks (WSNs) are increasingly being used to transmit soil moisture data in real-time to web-based platforms for remote monitoring and control of irrigation systems [16]. Table 1 summarizes the main types of soil moisture sensors used in precision irrigation and their operating principles, advantages and disadvantages.

Sensor Type	Operating Principle	Advantages	Disadvantages
Capacitance	Measures dielectric permittivity of soil, which is correlated with water content	High accuracy, durability, suitable for automation	Requires soil-specific calibration, affected by soil salinity and temperature
Time Domain Reflectometry (TDR)	Measures travel time of electromagnetic pulse in soil, which is related to water content	High accuracy, suitable for automation, less affected by salinity than capacitance sensors	High cost, requires soil-specific calibration
Electrical Resistance	Measures electrical current between electrodes, which varies with soil water content	Low cost, easy to use	Low accuracy, requires frequent maintenance, affected by soil salinity
Heat Dissipation	Measures heat dissipation rate in porous block, which varies with soil water potential	Suitable for measuring soil water potential in dry soils	Low accuracy in wet soils, slow response time, requires soil-specific calibration

Table 1. Common soil moisture sensors used in precision irrigation and their operating principles, advantages and disadvantages. Adapted from [14,15].

While soil moisture sensors provide valuable information on water availability in the crop root zone, they do not directly measure plant water status or crop physiological responses to water deficits. Combining soil moisture sensing with plant-based water stress indicators can provide a more comprehensive view of orchard water dynamics and crop water requirements [17].

2.1.2 Stem Water Potential Measurement Stem water potential (Ψstem) is a direct indicator of plant water status that has been widely used for decades in fruit crops to guide irrigation scheduling decisions. Ψstem is typically measured using a pressure chamber, where a leaf is excised from the plant and placed in the chamber with the cut petiole protruding. The chamber is gradually pressurized until xylem sap appears at the cut surface, and the negative of this balancing pressure is equal to Ψstem [18]. More recently, automated stem psychrometers have been developed that allow for continuous monitoring of Ψstem without the need for destructive leaf sampling [19]. However, these sensors are relatively expensive and require careful maintenance and calibration.

Ψstem has been shown to be a sensitive indicator of crop water stress in many fruit species, including grapevine, apple, almond, and citrus [20-23]. Threshold values have been developed to guide irrigation scheduling based on Ψstem measurements, which are typically made at midday when water stress is most pronounced [24]. However, threshold values vary by species, cultivar, and environmental conditions, and must be adapted to local conditions. Figure 1 shows an example of how midday Ψstem measurements were used to guide deficit irrigation scheduling in a California Cabernet Sauvignon vineyard, maintaining Ψstem within a target range of -0.8 to -1.2 MPa to impose a moderate water deficit [25].

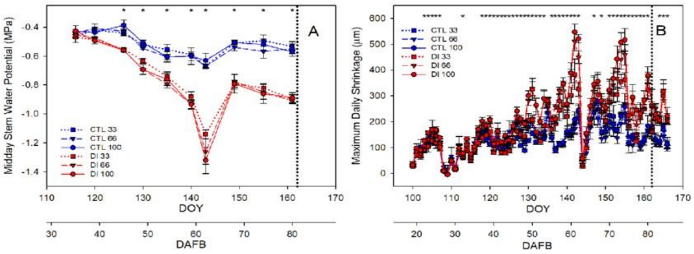

Figure 1.

Seasonal evolution of midday stem water potential (Ψstem) under three irrigation regimes in a California Cabernet Sauvignon vineyard. The dashed lines indicate the target Ψstem thresholds used to guide deficit irrigation scheduling. Adapted from [25].

While Ψstem is a direct indicator of plant water status, it does not provide information on the spatial variability of water stress within an orchard. Mapping Ψstem manually is time- and labor-intensive, making it challenging to use for variable-rate irrigation management. Newer technologies, such as thermal imaging and sap flow sensing, provide opportunities for characterizing spatial variability in plant water status and transpiration across an orchard.

2.1.3 Sap Flow Sensors Sap flow sensors measure the velocity of xylem sap movement in plant stems, which is closely related to transpiration rate and plant water use. The most common sap flow measurement techniques used in fruit crops are the heat ratio method (HRM) and the heat field deformation (HFD) method, both of which use needle-like probes inserted into the sapwood to track heat movement as an indicator of sap velocity [26]. Sensors are typically deployed on a subset of trees within an orchard and data is collected continuously to estimate orchard-level transpiration rates.

Sap flow sensing has been used in a variety of fruit crops to characterize spatial and temporal variability in tree water use and to improve irrigation scheduling. In apple, sap flow measurements have been used to detect water stress and estimate orchard water requirements [27,28], while in olive, sap flow sensing has been used to characterize the effects of deficit irrigation on tree water relations and fruit yield [29]. Sap flow data has also been integrated with remote sensing and modeling approaches to map tree-scale transpiration across orchards [30].

While sap flow sensors are a powerful tool for precision irrigation management, they have several limitations. Scaling sap flow measurements to the whole tree or orchard level requires careful sensor calibration and is subject to uncertainties related to wood properties and sensor placement [31]. Sap flow rates are also influenced by non-water stressed factors, such as tree size and age, making it challenging to directly relate sap flow measurements to plant water status [32]. Combining sap flow sensing with other indicators, such as soil moisture and remote sensing data, can help overcome these limitations and provide a more robust estimate of plant water dynamics.

2.2 Remote Sensing Approaches Rapid advancements in remote sensing technologies over the past decade have greatly expanded the tools available for mapping spatial and temporal variability in plant water status across orchard blocks. Unlike proximal sensing approaches that provide localized measurements of soil or plant water status, remote sensing uses spectral data collected from satellites, aircraft, or drones to characterize water stress over larger areas. The most common remote sensing techniques used for precision irrigation management in orchards are multispectral and thermal imaging.

2.2.1 Multispectral Imaging Multispectral imaging uses sensors that detect reflected light in multiple wavebands, typically in the visible and near-infrared portions of the spectrum. Various vegetation indices can be calculated from multispectral imagery to map spatial and temporal changes in orchard canopy characteristics, such as leaf area index, chlorophyll content, and water stress [33].

One of the most widely used vegetation indices for precision irrigation management is the Normalized Difference Vegetation Index (NDVI), which is calculated as: $NDVI = (NIR - Red) / (NIR + Red)$

where NIR and Red are reflectance values in the near-infrared and red portions of the spectrum, respectively. NDVI is sensitive to changes in both plant biomass and chlorophyll content, and has been shown to be correlated with plant water status in many fruit crops [34,35].

More recently, narrow-band vegetation indices that incorporate reflectance in the red-edge portion of the spectrum (690-740 nm) have been developed that are more sensitive to changes in plant chlorophyll content under water stress [36]. The Normalized Difference Red Edge (NDRE) index is calculated similarly to NDVI, but uses a narrow red edge band instead of the red band:

NDRE = (NIR – Red Edge) / (NIR + Red Edge)

Studies have shown that NDRE is more responsive to water stress than NDVI in crops such as grapevine and citrus [37,38]. Figure 2 shows an example of how NDVI and NDRE maps were used to characterize spatial variability in water status across a California Navel orange orchard [39]. The authors found that NDRE was more strongly correlated with midday stem water potential measurements than NDVI, and could be used to guide variable rate irrigation management.

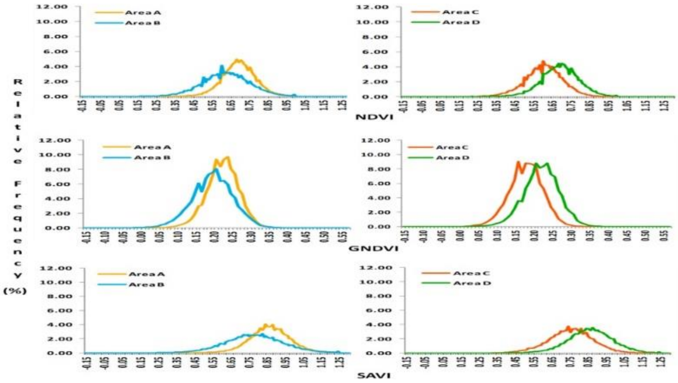

Figure 2.

Multispectral imagery showing (a) NDVI and (b) NDRE values across a California Navel orange orchard. Adapted from [39].

While multispectral vegetation indices are useful for mapping spatial patterns in plant vigor and chlorophyll content, they are indirect indicators of plant water status and can be influenced by other factors such as nutrient deficiencies, pests and diseases [35]. Combining multispectral sensing with thermal imaging and ground-based measurements can help improve the accuracy of water stress detection in orchards [40].

2.2.2 Thermal Imaging Thermal imaging uses infrared thermometers or thermal cameras to measure canopy temperature, which is closely related to plant transpiration and water status. As plants experience water stress and stomata close, transpirational cooling is reduced and canopy temperature increases relative to air temperature [41]. By measuring the difference between canopy and air temperature, thermal sensing can provide a rapid and non-destructive indicator of plant water stress.

The most widely used thermal index for irrigation scheduling is the Crop Water Stress Index (CWSI), which normalizes canopy temperature relative to air temperature and humidity [42]: CWSI = (Tc - Ta) - (Tc - Ta)lower / (Tc - Ta)upper - (Tc - Ta)lower

where Tc is the canopy temperature, Ta is the air temperature, and (Tc - Ta)lower and (Tc - Ta)upper are the lower and upper baselines representing a well-watered and fully stressed crop, respectively. CWSI values range from 0 to 1, with higher values indicating greater water stress.

Studies have shown that CWSI is a sensitive indicator of plant water status in a variety of fruit crops, including grapevine, apple, citrus, and almond [43-46]. CWSI-based irrigation scheduling has been shown to improve water use efficiency and maintain yield and fruit quality compared to conventional irrigation approaches [47,48]. Bellvert et al. [49] used airborne thermal imaging to map variability in CWSI across a California Pinot noir vineyard, and found that CWSI was strongly correlated with midday leaf water potential (Figure 3). The authors used CWSI maps to develop irrigation zones and implement variable rate irrigation, resulting in a 35% reduction in water use compared to uniform irrigation.

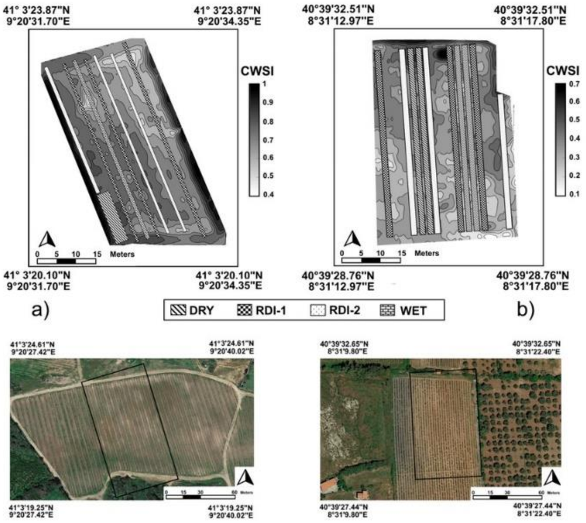

Figure 3.

Relationship between the Crop Water Stress Index (CWSI) derived from airborne thermal imaging and midday leaf water potential in a California Pinot noir vineyard. Adapted from [49].

Thermal sensing has several advantages over other remote sensing approaches for precision irrigation management, including the ability to detect water stress before visual symptoms appear and the ease of integration with variable rate irrigation systems [50]. However, thermal measurements are sensitive to environmental conditions such as wind speed, air temperature, and humidity, and require careful correction and calibration [51]. The use of artificial reference surfaces and weather station data can help improve the accuracy of CWSI estimates, but these techniques add complexity and cost to thermal sensing protocols [52].

Recent advances in unmanned aerial vehicle (UAV) technologies have greatly expanded the opportunities for using thermal imaging for precision irrigation management in orchards. UAV-mounted thermal cameras can provide high-resolution temperature maps at a relatively low cost, allowing for more frequent and targeted monitoring of crop water status [53]. Berni et al. [54] used a UAV-based thermal sensor to map variability in CWSI across a Spanish olive orchard, and found that the spatial resolution was sufficient to detect individual trees exhibiting water stress. Santesteban et al. [55] used UAV thermal imaging to estimate leaf water potential in a Spanish vineyard, and found that the approach could provide a reliable and cost-effective alternative to ground-based measurements.

Despite the advantages of remote sensing for precision irrigation management, there are several challenges that limit its adoption in commercial orchards. One challenge is the need for frequent and timely image acquisition, particularly during critical growth stages when irrigation decisions are made [56]. Cloud cover, weather conditions, and sensor availability can limit the frequency and quality of remote sensing data. Another challenge is the need for specialized expertise and software tools to process and interpret remote sensing data, which can be a barrier for many growers [57]. The development of user-friendly and automated tools for remote sensing data analysis and irrigation scheduling is an active area of research [58].

A promising approach for overcoming these challenges is the integration of remote sensing data with ground-based sensors and weather station networks to provide a more comprehensive and actionable view of orchard water status [59]. By combining multiple data streams and decision support tools, growers can optimize irrigation scheduling based on real-time information on soil moisture, plant water status, and atmospheric demand. The next section will discuss the role of data integration and decision support systems in precision irrigation management.

3. Data Integration and Decision Support Systems The proliferation of sensing technologies for monitoring soil moisture and plant water status has created new opportunities for data-driven precision irrigation management in orchards. However, the sheer volume and complexity of data generated by these sensors can be overwhelming for growers, who may lack the time, expertise, or tools to effectively interpret and act on this information [60]. The development of data integration platforms and decision support systems (DSS) is critical for translating sensor data into actionable insights for precision irrigation scheduling.

A DSS is a computer-based tool that integrates data from various sources, such as weather stations, soil moisture sensors, and remote sensing imagery, to provide site-specific recommendations for irrigation scheduling [61]. DSS tools typically include crop models that simulate soil water balance and plant growth based on environmental inputs, as well as user interfaces that allow growers to input management information and visualize results [62]. By combining sensor data with crop models and grower knowledge, DSS tools can provide a more comprehensive and precise assessment of orchard water requirements than traditional irrigation scheduling approaches.

One example of a DSS for precision irrigation in orchards is the IrrigaSys tool developed by Netafim [63]. IrrigaSys integrates data from soil moisture sensors, weather stations, and satellite imagery to provide real-time recommendations for irrigation scheduling based on site-specific soil and crop conditions. The tool includes a user-friendly interface that allows growers to set irrigation thresholds, view soil moisture trends, and remotely control irrigation systems. In a trial in a California almond orchard, the use of IrrigaSys resulted in a 30% reduction in water use compared to conventional irrigation scheduling, without impacting yield or kernel quality [64].

Another example is the PiMapping DSS developed by the University of Talca in Chile [65]. PiMapping integrates data from UAV-based thermal and multispectral imaging to map variability in plant water status across orchards and generate variable rate irrigation prescriptions. The tool includes a web-based interface that allows growers to visualize CWSI and NDVI maps, set threshold values for irrigation decisions, and export shapefiles for use in variable rate irrigation systems. In a trial in a Chilean apple orchard, the use of PiMapping resulted in a 20% reduction in water use and a 15% increase in fruit size compared to conventional irrigation [66].

While DSS tools offer significant potential for improving irrigation efficiency and crop productivity, their adoption in commercial orchards has been limited by several factors. One challenge is the lack of standardization and interoperability among different sensor platforms and data management systems [67]. Growers often use a variety of sensors and software tools from different vendors, making it difficult to integrate and analyze data in a consistent and reliable way. The development of open-source data standards and application programming interfaces (APIs) could help overcome this challenge and enable more seamless data integration across platforms [68].

Another challenge is the need for robust and site-specific calibration of crop models and irrigation thresholds used in DSS tools [69]. Many DSS tools rely on generic crop coefficients and soil parameters that may not accurately reflect the specific conditions and management practices of individual orchards. Engaging growers in the process of model calibration and validation can help ensure that DSS tools are providing reliable and actionable recommendations [70]. Table 2 summarizes some of the key factors that influence the accuracy and reliability of DSS tools for precision irrigation management. Key factors influencing the accuracy and reliability of decision support systems for precision irrigation management in orchards.

Despite these challenges, the development and adoption of DSS tools for precision irrigation management is likely to accelerate in the coming years, driven by advances in sensor technologies, data analytics, and cloud computing [71]. The integration of artificial intelligence and machine learning techniques could help improve the accuracy and adaptability of DSS tools across diverse orchard systems and environmental conditions [72]. The use of mobile apps and web-based platforms could also help facilitate the dissemination and use of DSS tools by growers, particularly in developing countries where access to technology and technical support may be limited [73].

Ultimately, the success of DSS tools for precision irrigation will depend on their ability to provide reliable, actionable, and cost-effective recommendations that are tailored to the specific needs and constraints of individual growers and orchards. Engaging growers as active partners in the development and validation of these tools, rather than simply as end-users, will be critical for ensuring their relevance and impact in the real world [74]. By empowering growers with the data, tools, and knowledge needed to optimize irrigation management, DSS tools have the potential to play a vital role in enhancing the sustainability and resilience of orchard systems in the face of increasing water scarcity and climate variability.

The next section will discuss the current status and future prospects of variable rate irrigation technologies, which are a key component of precision irrigation management in orchards

Factor	**Description**	**Importance**
Data quality	Accuracy, precision, and timeliness of sensor data used as inputs to DSS tools	High - Poor data quality can lead to incorrect irrigation recommendations and reduced efficiency
Model calibration	Site-specific adjustment of crop coefficients, soil parameters, and irrigation thresholds used in DSS tools	High Generic parameters may not accurately reflect local conditions and management practices
Spatial variability	Accounting for spatial variability in soil moisture, plant water status, and irrigation requirements across orchards	High - Uniform irrigation scheduling may lead to over- or under-irrigation in certain areas
Temporal variability	Accounting for temporal variability in weather conditions, crop growth stage, and irrigation requirements throughout the season	High - Static irrigation schedules may not optimize water use efficiency and crop productivity
User interface	Ease of use, flexibility, and visualization of DSS tool interfaces for growers	Medium - User-friendly interfaces can facilitate adoption and effective use of DSS tools
Integration with other tools	Compatibility and interoperability of DSS tools with other precision agriculture technologies, such as variable rate irrigation systems	Medium - Seamless integration can enhance the efficiency and impact of precision irrigation management

Table 2.

4. Variable Rate Irrigation Technologies: Variable rate irrigation (VRI) is a precision irrigation approach that involves applying different amounts of water to different areas of an orchard based on spatial variability in soil moisture, plant water status, and other factors [75]. VRI systems typically consist of a network of valves, sensors, and controllers that allow for the dynamic adjustment of irrigation rates and durations across an orchard [76]. By matching irrigation inputs to site-specific water requirements, VRI has the potential to significantly improve water use efficiency, reduce nutrient leaching and runoff, and enhance crop yield and quality compared to traditional uniform irrigation approaches [77,78].

VRI technologies can be classified into two main categories: speed control systems and zone control systems [79]. Speed control VRI systems vary the speed of the irrigation system (e.g. center pivot or linear move) to adjust the application rate along the length of the system. Zone control VRI systems divide the irrigation system into multiple zones, each with its own valve and controller, allowing for independent adjustment of irrigation rates within each zone.

4.1 Speed Control VRI Systems Speed control VRI systems are most commonly used in center pivot and linear move irrigation systems, which are widely used in row crop production but less common in orchards [80]. In these systems, the speed of the irrigation system is varied along its length to adjust the application rate based on a prescription map that defines the desired irrigation depth for each area of the field [81]. The prescription map is typically generated using data from soil moisture sensors, remote sensing imagery, or other sources, and is loaded onto the irrigation system controller [82].

Speed control VRI has been shown to be effective for improving irrigation efficiency and crop yield in a variety of row crops, including corn, soybean, and cotton [83,84]. However, its application in orchards has been limited, in part because most orchards use micro-irrigation systems (e.g. drip or micro-sprinklers) rather than center pivots or linear moves [85]. Some studies have explored the use of speed control VRI in orchard crops using solid-set sprinkler systems, with promising results. For example, a study in a Chilean cherry orchard found that the use of speed control VRI with a solid-set sprinkler system resulted in a 20% reduction in water use and a 10% increase in fruit yield compared to uniform irrigation [86].

One of the main advantages of speed control VRI is its ability to vary irrigation rates continuously along the length of the system, providing a high degree of spatial resolution [87]. However, this also requires a high degree of accuracy in the prescription map and the control system, as even small errors can result in significant over- or under-irrigation [88]. The cost of retrofitting existing irrigation systems with speed control VRI can also be prohibitive for many growers, particularly in smaller orchards [89].

4.2 Zone Control VRI Systems Zone control VRI systems are more commonly used in orchard crops, particularly those that use micro-irrigation systems [90]. In these systems, the irrigation system is divided into multiple zones, each with its own valve and controller, allowing for independent control of irrigation rates within each zone [91]. The number and size of zones can vary depending on the heterogeneity of the orchard and the desired level of precision, but typically range from a few to several dozen zones per hectare [92].

Zone control VRI in orchards is typically implemented using one of two approaches: (1) manual or sensor-based control, or (2) model-based control [93]. In manual or sensor-based control, irrigation rates are adjusted based on real-time measurements of soil moisture, plant water status, or other variables using sensors installed within each zone [94]. This approach allows for dynamic adjustment of irrigation based on actual conditions in the orchard, but requires a high density of sensors and can be labor-intensive to manage [95].

In model-based control, irrigation rates are adjusted based on predictions of soil moisture and crop water requirements using mathematical models that integrate data from weather stations, soil maps, and crop coefficients [96]. This approach can reduce the need for extensive sensor networks and provide a more automated and scalable solution for VRI management [97]. However, the accuracy of model-based control depends on the quality of the input data and the robustness of the underlying models, which can vary widely across different orchard systems and environments [98].

Several studies have demonstrated the potential benefits of zone control VRI in orchard crops. A study in a Spanish peach orchard found that the use of sensor-based zone control VRI resulted in a 30% reduction in water use and a 20% increase in fruit yield compared to conventional irrigation [99]. Another study in a California almond orchard found that the use of model-based zone control VRI resulted in a 15% reduction in water use and a 10% increase in kernel yield compared to uniform irrigation [100]. Table 3 summarizes some of the key advantages and limitations of speed control and zone control VRI systems for precision irrigation management in orchards.

Table 3. Advantages and limitations of speed control and zone control variable rate irrigation systems for precision irrigation management in orchards.

VRI System	**Advantages**	**Limitations**
Speed control	High spatial resolution - Continuous adjustment of irrigation rates along system length - Can be retrofitted onto existing center pivot or linear move systems	Limited applicability in orchards due to predominance of micro-irrigation systems - Requires high accuracy in prescription maps and control systems - High cost of retrofit for existing systems
Zone control	Commonly used in micro-irrigation systems in orchards - Allows for independent control of irrigation rates within each zone - Can be implemented using sensor-based or model-based control approaches	Requires a high density of sensors for manual or sensor-based control - Model-based control depends on quality of input data and robustness of underlying models - Can be complex to design and manage, particularly in large or heterogeneous orchards

Despite the potential benefits of VRI, its adoption in commercial orchards has been limited by several factors, including the high cost of equipment and installation, the complexity of designing and managing VRI systems, and the lack of technical support and training for growers [101]. VRI systems can cost anywhere from $200 to $1000 per hectare, depending on the level of complexity and automation [102]. The design of VRI systems requires specialized expertise in irrigation engineering, soil science, and crop physiology, which may not be readily available to many growers [103].

Another challenge is the lack of standardization and interoperability among different VRI components and control systems [104]. Many VRI systems use proprietary hardware and software that may not be compatible with other precision agriculture technologies, such as sensor networks and decision support tools [105]. The development of open-source VRI standards and protocols could help facilitate the integration and scaling of these technologies across diverse orchard systems [106].

Despite these challenges, the adoption of VRI in orchards is likely to increase in the coming years, driven by the increasing pressure to improve water use efficiency and productivity in the face of climate change and water scarcity [107]. Advances in sensor technologies, data analytics, and automation are also making VRI systems more affordable, reliable, and user-friendly for growers [108]. For example, the use of unmanned aerial vehicles (UAVs) equipped with high-resolution cameras and sensors could help reduce the cost and labor required for VRI system design and management [109].

To fully realize the potential of VRI in orchards, there is a need for more research and extension efforts to develop and validate VRI technologies and management strategies across a wide range of crops, soils, and environments [110]. This will require collaboration among growers, researchers, and industry partners to co-design and test VRI solutions that are tailored to the specific needs and constraints of individual orchards [111]. It will also require investment in education and training programs to build the capacity of growers and service providers to effectively use and maintain VRI systems [112].

Ultimately, the success of VRI in orchards will depend on its ability to deliver tangible and sustainable benefits to growers in terms of increased water use efficiency, crop yield and quality, and profitability. By enabling growers to optimize irrigation management based on site-specific conditions and requirements, VRI has the potential to play a vital role in enhancing the resilience and sustainability of orchard systems in the face of increasing resource constraints and climate variability.

The following section will discuss the current applications of precision irrigation technologies in specific fruit crops and the unique challenges and opportunities for each crop.

5. Applications in Fruit Crops Precision irrigation technologies have been applied in a wide range of fruit crops, each with its own unique characteristics and requirements for water management. This section will discuss the current status and potential of precision irrigation in three major fruit crops: apples, citrus, and grapes.

5.1 Apples (*Malus domestica*) Apples are one of the most widely cultivated fruit crops in the world, with over 87 million tonnes produced in 2019 [113]. Irrigation is essential for apple production in many regions, particularly in arid and semi-arid climates where rainfall is insufficient to meet crop water requirements [114]. However, excessive irrigation can lead to a range of problems in apples, including reduced fruit quality, increased susceptibility to disease, and nutrient leaching [115].

Precision irrigation technologies have shown promise for improving water use efficiency and fruit quality in apple orchards. A study in a Washington State apple orchard found that the use of soil moisture sensors and automated irrigation scheduling resulted in a 20-40% reduction in water use compared to conventional irrigation, without impacting fruit yield or quality [116]. Another study in an Italian apple orchard found that the use of a decision support system based on soil moisture sensing and weather data resulted in a 30% reduction in irrigation water use and a 15% increase in fruit size and color [117].

Thermal imaging has also been used to map variability in water stress across apple orchards and guide precision irrigation management. A study in a New York apple orchard found that thermal imaging could detect water stress up to two weeks earlier than visual symptoms, allowing for more timely and targeted irrigation interventions [118]. The authors used thermal imagery to create CWSI maps of the orchard and developed irrigation zones based on the spatial variability in tree water status (Figure 4).

Despite these promising results, the adoption of precision irrigation in apple orchards has been limited by several factors. One challenge is the high spatial variability in soil moisture and water requirements within orchards, which can be difficult to capture with point-based sensors [119]. The use of remote sensing technologies, such as multispectral and thermal imaging, can help overcome this challenge by providing high-resolution maps of tree water status across the orchard [120]. However, these technologies can be costly and require specialized expertise to interpret and use effectively [121].

Another challenge is the need for reliable and affordable sensors and control systems that can withstand the harsh environmental conditions in orchards, such as extreme temperatures, humidity, and dust [122]. The development of low-cost, wireless sensor networks and cloud-based data management platforms could help address this challenge and make precision irrigation more accessible to apple growers [123].

5.2 Citrus (*Citrus* spp.) Citrus is another major fruit crop that is widely grown in tropical and subtropical regions around the world. In 2019, global citrus production exceeded 157 million tonnes, with oranges, tangerines, and lemons being the most important species [124]. Citrus trees are highly sensitive to water stress, which can cause a range of problems including reduced fruit yield and quality, increased susceptibility to pests and diseases, and premature fruit drop [125].

Precision irrigation has been shown to be effective for improving water use efficiency and fruit quality in citrus orchards. A study in a Florida orange orchard found that the use of soil moisture sensors and an automated irrigation system resulted in a 50% reduction in water use compared to conventional irrigation, while maintaining fruit yield and quality [126]. Another study in a Spanish mandarin orchard found that the use of a soil water balance model and weather-based irrigation scheduling resulted in a 20% reduction in water use and a 15% increase in fruit size and sugar content [127].

Canopy temperature sensing has also been used to monitor water stress and guide precision irrigation in citrus orchards. A study in a Brazilian orange orchard found that the use of infrared thermometers to measure canopy temperature and calculate CWSI resulted in a 30% reduction in water use compared to conventional irrigation [128]. The authors used CWSI thresholds to trigger irrigation events and adjust irrigation rates based on the level of water stress in the trees.

One of the main challenges for precision irrigation in citrus orchards is the high variability in soil properties and root distribution within the orchard [129]. Citrus trees have a shallow and extensive root system that can extend up to twice the canopy diameter, making it difficult to accurately measure soil moisture and water uptake across the root zone [130]. The use of multiple soil moisture sensors at different depths and locations within the root zone can help capture this variability and improve irrigation scheduling [131].

Another challenge is the need for precision irrigation strategies that can accommodate the changing water requirements of citrus trees throughout the growing season and across different phenological stages [132]. For example, water stress during the flowering and fruit set stages can significantly reduce fruit yield and quality, while excess irrigation during the fruit maturation stage can reduce sugar content and increase the risk of fungal diseases [133]. The use of crop coefficients and growth stage-specific irrigation thresholds can help optimize irrigation scheduling based on the specific water requirements of citrus trees at different times of the year [134].

5.3 Grapes (*Vitis vinifera*) Grapes are one of the most important fruit crops in the world, with over 77 million tonnes produced in 2019 [135]. Grapes are highly sensitive to water stress, which can affect vine growth, fruit yield and quality, and wine composition [136]. Precision irrigation has been widely studied and applied in viticulture to optimize water use efficiency, reduce the environmental impacts of irrigation, and improve wine quality [137].

One of the most common precision irrigation strategies in vineyards is regulated deficit irrigation (RDI), which involves applying water deficits at specific growth stages to control vine vigor and enhance fruit quality [138]. RDI has been shown to reduce water use by 20-50% compared to conventional irrigation, while maintaining or improving fruit yield and quality [139]. The timing and intensity of water deficits are critical for the success of RDI, and require careful monitoring of soil moisture, plant water status, and weather conditions [140].

Remote sensing technologies have been widely used to monitor water stress and guide precision irrigation in vineyards. Multispectral and thermal imaging have been used to map variability in vine water status across vineyards and develop site-specific irrigation management zones [141,142]. For example, a study in a California vineyard used airborne thermal imagery to map CWSI and develop irrigation prescriptions based on the spatial variability in vine water stress (Figure 5). The authors found that the use of precision irrigation based on thermal imagery resulted in a 26% reduction in water use and a 14% increase in fruit quality compared to conventional irrigation [143].

Wireless sensor networks have also been used to monitor soil moisture and plant water status in vineyards and automate precision irrigation scheduling. A study in a Spanish vineyard used a wireless network of soil moisture sensors and canopy temperature sensors to control irrigation based on real-time measurements of vine water stress [144]. The authors found that the use of sensor-based irrigation control resulted in a 45% reduction in water use and a 20% increase in fruit quality compared to conventional irrigation.

One of the main challenges for precision irrigation in vineyards is the high spatial and temporal variability in soil properties, topography, and microclimate within and between vineyards [145]. This variability can lead to significant differences in vine water requirements and irrigation needs across the vineyard, requiring a high level of site-specific management [146]. The use of high-resolution soil maps, digital elevation models, and climate data can help inform precision irrigation strategies and optimize water use efficiency in vineyards [147].

Another challenge is the need for precision irrigation strategies that can balance the competing demands of vine growth, fruit yield and quality, and wine composition [148]. In some cases, mild water deficits can enhance fruit quality and wine complexity, while in other cases, water stress can reduce fruit yield and quality [149]. The use of crop models and decision support systems that integrate data on soil moisture, plant water status, and fruit composition can help optimize irrigation scheduling based on the specific goals and constraints of each vineyard [150].

Overall, the application of precision irrigation in fruit crops has shown significant potential for improving water use efficiency, reducing the environmental impacts of irrigation, and enhancing fruit yield and quality. However, the adoption of these technologies in commercial orchards and vineyards is still limited, due in part to the high cost and complexity of implementation, the lack of reliable and affordable sensors and control systems, and the need for site-specific management strategies that can account for the high spatial and temporal variability within and between farms.

To fully realize the potential of precision irrigation in fruit crops, there is a need for continued research and innovation to develop more affordable, reliable, and user-friendly technologies that can be easily integrated into existing irrigation systems and management practices. There is also a need for more education and outreach to build the capacity of growers and service providers to effectively use and maintain these technologies, and to demonstrate the economic and environmental benefits of precision irrigation through on-farm trials and case studies.

Ultimately, the success of precision irrigation in fruit crops will depend on a collaborative effort between growers, researchers, industry partners, and policymakers to develop and promote sustainable and profitable irrigation solutions that can meet the diverse needs and challenges of fruit production systems around the world.

The final section will discuss the current challenges and future directions for precision irrigation research and development in fruit crops, and highlight some of the key opportunities and priorities for advancing this field.

6. Challenges and Future Directions Despite the significant potential of precision irrigation technologies to improve the sustainability and productivity of fruit crops, their adoption in commercial orchards and vineyards remains limited. This section will discuss some of the key challenges and future directions for precision irrigation research and development in fruit crops, and highlight some of the opportunities and priorities for advancing this field.

One of the main challenges for precision irrigation in fruit crops is the high cost and complexity of implementation, particularly for small and medium-sized farms [151]. Many precision irrigation technologies, such as variable rate irrigation systems and wireless sensor networks, require significant upfront investments in equipment, software, and training, which can be prohibitive for many growers [152]. The development of low-cost, open-source, and modular precision irrigation solutions that can be easily adapted to different crops and farming systems could help reduce these barriers and make precision irrigation more accessible to a wider range of growers [153].

Another challenge is the lack of standardization and interoperability among different precision irrigation technologies and platforms, which can limit their scalability and impact [154]. Many precision irrigation systems use proprietary hardware, software, and data formats that are not compatible with other systems or tools, making it difficult to integrate and share data across different farms and regions [155]. The development of open data standards and application programming interfaces (APIs) for precision irrigation could help facilitate data sharing and collaboration among growers, researchers, and service providers, and enable the development of more powerful and user-friendly decision support tools [156].

A third challenge is the need for more robust and reliable sensors and control systems that can withstand the harsh environmental conditions and management practices in fruit crops [157]. Many sensors and actuators used in precision irrigation systems are prone to failure or degradation due to exposure to extreme temperatures, humidity, dust, and chemicals, as well as physical damage from pruning, harvesting, and other farm operations [158]. The development of more durable and resilient sensing and control technologies, such as printed and flexible electronics, could help improve the reliability and longevity of precision irrigation systems in fruit crops [159].

A fourth challenge is the need for more accurate and site-specific crop coefficients and irrigation thresholds that can account for the high spatial and temporal variability within and between orchards and vineyards [160]. Many precision irrigation systems rely on generic crop coefficients and fixed irrigation thresholds that may not accurately reflect the actual water requirements and stress responses of different fruit crops under different environmental and management conditions [161]. The development of more dynamic and adaptive crop coefficients and thresholds based on real-time sensor data and crop models could help optimize irrigation scheduling and water use efficiency in fruit crops [162].

To address these challenges and advance the field of precision irrigation in fruit crops, there is a need for more interdisciplinary research and collaboration among plant scientists, irrigation engineers, data scientists, and social scientists [163].

Some of the key research priorities and opportunities in this field include:

- Developing more affordable, reliable, and user-friendly sensors and control systems that can be easily integrated into existing irrigation infrastructure and management practices [164].
- Improving the accuracy and resolution of remote sensing technologies, such as satellite imagery and unmanned aerial vehicles (UAVs), for monitoring

crop water status and guiding precision irrigation management at the field and regional scales [165].

- Integrating machine learning and artificial intelligence techniques into precision irrigation decision support systems to enable more accurate and adaptive irrigation scheduling based on real-time sensor data and weather forecasts [166].
- Conducting more long-term, multi-site, and participatory research trials to evaluate the agronomic, economic, and environmental impacts of precision irrigation technologies and management strategies in different fruit crops and production systems [167].
- Developing more effective knowledge exchange and capacity building programs to promote the adoption and sustainable use of precision irrigation technologies among growers, service providers, and policymakers [168].
- Exploring the potential of precision irrigation technologies to enable more sustainable and resilient fruit production systems in the face of climate change, water scarcity, and other global challenges [169].

By addressing these research priorities and opportunities, the field of precision irrigation in fruit crops can continue to evolve and innovate, and help drive the transition towards more sustainable, productive, and profitable fruit production systems around the world.

7. Conclusion Precision irrigation technologies offer significant potential for improving the sustainability and productivity of fruit crops in the face of increasing water scarcity, climate variability, and global food demand. By enabling growers to optimize irrigation scheduling and water use efficiency based on site-specific soil, crop, and weather conditions, precision irrigation can help reduce the environmental impacts of irrigation, such as nutrient leaching, soil erosion, and greenhouse gas emissions, while enhancing fruit yield and quality.

Over the past decade, significant advancements have been made in the development and application of precision irrigation technologies in fruit crops, including remote sensing, proximal sensing, data analytics, and variable rate irrigation systems. These technologies have enabled growers to monitor crop water status and soil moisture in real-time, and to develop more targeted and adaptive irrigation management strategies based on the specific needs and constraints of each orchard or vineyard.

However, despite the promising results and potential benefits of precision irrigation in fruit crops, its adoption in commercial production systems remains limited, due in part to the high cost and complexity of implementation, the lack of standardization and interoperability among different technologies and platforms, and the need for more site-specific and reliable decision support tools and management strategies.

References

1. [1] FAO. (2017). The future of food and agriculture – Trends and challenges. Rome: Food and Agriculture Organization of the United Nations.

2. [2] Kang, S., & Zhang, J. (2004). Controlled alternate partial root-zone irrigation: its physiological consequences and impact on water use efficiency. *Journal of Experimental Botany*, 55(407), 2437-2446.
3. [3] Fereres, E., & Soriano, M. A. (2007). Deficit irrigation for reducing agricultural water use. *Journal of Experimental Botany*, 58(2), 147-159.
4. [4] Evans, R. G., & Sadler, E. J. (2008). Methods and technologies to improve efficiency of water use. *Water Resources Research*, 44(7).
5. [5] Ruiz-Sanchez, M. C., Domingo, R., & Castel, J. R. (2010). Review. Deficit irrigation in fruit trees and vines in Spain. *Spanish Journal of Agricultural Research*, 8(S2), S5-S20.
6. [6] Zhu, H., Lan, Y., Lamb, M. C., & Butts, C. L. (2007). Corn nutritional properties and yields with surface drip irrigation in topographically variable fields. *Precision Agriculture*, 8(3), 147-160.
7. [7] Cohen, Y., Alchanatis, V., Meron, M., Saranga, Y., & Tsipris, J. (2005). Estimation of leaf water potential by thermal imagery and spatial analysis. *Journal of Experimental Botany*, 56(417), 1843-1852.
8. [8] Jones, H. G. (2004). Irrigation scheduling: advantages and pitfalls of plant-based methods. *Journal of Experimental Botany*, 55(407), 2427-2436.
9. [9] Park, S., Ryu, D., Fuentes, S., Chung, H., Hernández-Montes, E., & O'Connell, M. (2017). Adaptive estimation of crop water stress in nectarine and peach orchards using high-resolution imagery from an unmanned aerial vehicle (UAV). *Remote Sensing*, 9(8), 828.
10. [10] De Swaef, T., Verbist, K., Cornelis, W., & Steppe, K. (2012). Tomato sap flow, stem and fruit growth in relation to water availability in rockwool growing medium. *Plant and Soil*, 350(1), 237-252.
11. [11] Zotarelli, L., Dukes, M. D., Romero, C. C., Migliaccio, K. W., & Morgan, K. T. (2010). Step by step calculation of the Penman-Monteith Evapotranspiration (FAO-56 Method). *Institute of Food and Agricultural Sciences*, University of Florida.
12. [12] Baram, S., Couvreur, V., Harter, T., Brown, P. H., Hopmans, J. W., & Smart, D. R. (2016). Assessment of orchard N losses to groundwater with a vadose zone monitoring network. *Agricultural Water Management*, 172, 83-95.
13. [13] Liakos, K. G., Busato, P., Moshou, D., Pearson, S., & Bochtis, D. (2018). Machine learning in agriculture: A review. *Sensors*, 18(8), 2674.
14. [14] Dobriyal, P., Qureshi, A., Badola, R., & Hussain, S. A. (2012). A review of the methods available for estimating soil moisture and its implications for water resource management. *Journal of Hydrology*, 458, 110-117.
15. [15] Pardossi, A., Incrocci, L., Incrocci, G., Malorgio, F., Battista, P., Bacci, L., ... & Balendonck, J. (2009). Root zone sensors for irrigation management in intensive agriculture. *Sensors*, 9(4), 2809-2835.
16. [16] Gutiérrez, J., Villa-Medina, J. F., Nieto-Garibay, A., & Porta-Gándara, M. Á. (2014). Automated irrigation system using a wireless sensor network and GPRS module. *IEEE transactions on instrumentation and measurement*, 63(1), 166-176.
17. [17] Girona, J., Mata, M., Del Campo, J., Arbonés, A., Bartra, E., & Marsal, J. (2006). The use of midday leaf water potential for scheduling deficit irrigation in vineyards. *Irrigation Science*, 24(2), 115-127.
18. [18] Scholander, P. F., Bradstreet, E. D., Hemmingsen, E. A., & Hammel, H. T. (1965). Sap pressure in vascular plants: negative hydrostatic pressure can be measured in plants. *Science*, 148(3668), 339-346.
19. [19] Pagay, V., & Skinner, R. H. (2018). Continuous measurement of stem water potential for irrigation scheduling in horticultural crops. *Acta Horticulturae*, 1245, 63-71.
20. [20] Souza, C. R. D., Maroco, J. P., Santos, T. P. D., Rodrigues, M. L., Lopes, C., Pereira, J. S., & Chaves, M. M. (2005). Control of stomatal aperture and carbon uptake by deficit irrigation in two grapevine cultivars. *Agriculture, Ecosystems & Environment*, 106(2-3), 261-274.
21. [21] Naor, A., Naschitz, S., Peres, M., & Gal, Y. (2008). Responses of apple fruit size to tree water status and crop load. *Tree Physiology*, 28(8), 1255-1261.

22. [22] Shackel, K. A., Ahmadi, H., Biasi, W., Buchner, R., Goldhamer, D., Gurusinghe, S., ... & Yeager, T. (1997). Plant water status as an index of irrigation need in deciduous fruit trees. *HortTechnology*, 7(1), 23-29.
23. [23] García-Tejero, I., Durán-Zuazo, V. H., Jiménez-Bocanegra, J. A., & Muriel-Fernández, J. L. (2011). Improved water-use efficiency by deficit-irrigation programmes: implications for saving water in citrus orchards. *Scientia Horticulturae*, 128(3), 274-282.
24. [24] Lampinen, B. D., Shackel, K. A., Southwick, S. M., Olson, B., Yeager, J. T., & Goldhamer, D. (1995). Sensitivity of yield and fruit quality of French prune to water deprivation at different fruit growth stages. *Journal of the American Society for Horticultural Science*, 120(2), 139-147.
25. [25] Shellie, K. C. (2006). Vine and berry response of Merlot (Vitis vinifera L.) to differential water stress. *American Journal of Enology and Viticulture*, 57(4), 514-518.
26. [26] Swanson, R. H., & Whitfield, D. W. A. (1981). A numerical analysis of heat pulse velocity theory and practice. *Journal of Experimental Botany*, 32(1), 221-239.
27. [27] Massai, R., Ferreira, M. I., Paço, T. A., & Remorini, D. (2014). Sap flow in peach trees during water stress and recovery in two environmental conditions. *Acta Horticulturae*, 1038, 313-320.
28. [28] Fernández, J. E., Romero, R., Montaño, J. C., Diaz-Espejo, A., Muriel, J. L., Cuevas, M. V., ... & Palomo, M. J. (2008). Design and testing of an automatic irrigation controller for fruit tree orchards, based on sap flow measurements. *Australian Journal of Agricultural Research*, 59(7), 589-598.
29. [29] Tognetti, R., d'Andria, R., Morelli, G., & Alvino, A. (2005). The effect of deficit irrigation on seasonal variations of plant water use in Olea europaea L. *Plant and Soil*, 273(1), 139-155.
30. [30] Cammalleri, C., Rallo, G., Agnese, C., Ciraolo, G., Minacapilli, M., & Provenzano, G. (2013). Combined use of eddy covariance and sap flow techniques for partition of ET fluxes and water stress assessment in an irrigated olive orchard. *Agricultural Water Management*, 120, 89-97.
31. [31] Smith, D. M., & Allen, S. J. (1996). Measurement of sap flow in plant stems. *Journal of Experimental Botany*, 47(12), 1833-1844.
32. [32] Burgess, S. S., Adams, M. A., Turner, N. C., Beverly, C. R., Ong, C. K., Khan, A. A., & Bleby, T. M. (2001). An improved heat pulse method to measure low and reverse rates of sap flow in woody plants. *Tree physiology*, 21(9), 589-598.
33. [33] Xue, J., & Su, B. (2017). Significant remote sensing vegetation indices: A review of developments and applications. *Journal of Sensors*, 2017.
34. [34] Gago, J., Douthe, C., Coopman, R. E., Gallego, P. P., Ribas-Carbo, M., Flexas, J., ... & Medrano, H. (2015). UAVs challenge to assess water stress for sustainable agriculture. *Agricultural Water Management*, 153, 9-19.
35. [35] Zarco-Tejada, P. J., González-Dugo, V., Williams, L. E., Suárez, L., Berni, J. A., Goldhamer, D., & Fereres, E. (2013). A PRI-based water stress index combining structural and chlorophyll effects: Assessment using diurnal narrow-band airborne imagery and the CWSI thermal index. *Remote Sensing of Environment*, 138, 38-50.
36. [36] Clevers, J. G., & Gitelson, A. A. (2013). Remote estimation of crop and grass chlorophyll and nitrogen content using red-edge bands on Sentinel-2 and-3. *International Journal of Applied Earth Observation and Geoinformation*, 23, 344-351.
37. [37] Rodriguez-Perez, J. R., Riaño, D., Carlisle, E., Ustin, S., & Smart, D. R. (2007). Evaluation of hyperspectral reflectance indexes to detect grapevine water status in vineyards. *American Journal of Enology and Viticulture*, 58(3), 302-317.
38. [38] Stagakis, S., González-Dugo, V., Cid, P., Guillén-Climent, M. L., & Zarco-Tejada, P. J. (2012). Monitoring water stress and fruit quality in an orange orchard under regulated deficit irrigation using narrow-band structural and physiological remote sensing indices. *ISPRS Journal of Photogrammetry and Remote Sensing*, 71, 47-61.
39. [39] Ballester, C., Jiménez-Bello, M. A., Castel, J. R., & Intrigliolo, D. S. (2013). Usefulness of thermography for plant water stress detection in citrus and persimmon trees. *Agricultural and Forest Meteorology*, 168, 120-129.

40. [40] Bellvert, J., Marsal, J., Girona, J., Gonzalez-Dugo, V., Fereres, E., Ustin, S. L., & Zarco-Tejada, P. J. (2016). Airborne thermal imagery to detect the seasonal evolution of crop water status in peach, nectarine and Saturn peach orchards. *Remote Sensing*, 8(1), 39.
41. [41] Idso, S. B., Jackson, R. D., Pinter, P. J., Reginato, R. J., & Hatfield, J. L. (1981). Normalizing the stress-degree-day parameter for environmental variability. *Agricultural Meteorology*, 24, 45-55.
42. [42] Jackson, R. D., Idso, S. B., Reginato, R. J., & Pinter, P. J. (1981). Canopy temperature as a crop water stress indicator. *Water Resources Research*, 17(4), 1133-1138.
43. [43] Testi, L., Goldhamer, D. A., Iniesta, F., & Salinas, M. (2008). Crop water stress index is a sensitive water stress indicator in pistachio trees. *Irrigation Science*, 26(5), 395-405.
44. [44] Bellvert, J., Zarco-Tejada, P. J., Girona, J., & Fereres, E. (2014). Mapping crop water stress index in a 'Pinot-noir' vineyard: comparing ground measurements with thermal remote sensing imagery from an unmanned aerial vehicle. *Precision Agriculture*, 15(4), 361-376.
45. [45] Ben-Gal, A., Agam, N., Alchanatis, V., Cohen, Y., Yermiyahu, U., Zipori, I., ... & Dag, A. (2009). Evaluating water stress in irrigated olives: correlation of soil water status, tree water status, and thermal imagery. *Irrigation Science*, 27(5), 367-376.
46. [46] Gonzalez-Dugo, V., Zarco-Tejada, P., Berni, J. A., Suárez, L., Goldhamer, D., & Fereres, E. (2012). Almond tree canopy temperature reveals intra-crown variability that is water stress-dependent. *Agricultural and Forest Meteorology*, 154, 156-165.
47. [47] Egea, G., Diaz-Espejo, A., & Fernández, J. E. (2016). Soil moisture dynamics in a hedgerow olive orchard under well-watered and deficit irrigation regimes: Assessment, prediction and scenario analysis. *Agricultural Water Management*, 164, 197-211.
48. [48] Millán, S., Casadesús, J., Campillo, C., Moñino, M. J., & Prieto, M. H. (2019). Using soil moisture sensors for automated irrigation scheduling in a plum crop. *Water*, 11(10), 2061.
49. [49] Bellvert, J., Marsal, J., Girona, J., & Zarco-Tejada, P. J. (2015). Seasonal evolution of crop water stress index in grapevine varieties determined with high-resolution remote sensing thermal imagery. *Irrigation Science*, 33(2), 81-93.
50. [50] Jones, H. G. (1999). Use of infrared thermometry for estimation of stomatal conductance as a possible aid to irrigation scheduling. *Agricultural and Forest Meteorology*, 95(3), 139-149.
51. [51] Maes, W. H., & Steppe, K. (2012). Estimating evapotranspiration and drought stress with ground-based thermal remote sensing in agriculture: a review. *Journal of Experimental Botany*, 63(13), 4671-4712.
52. [52] Bian, J., Zhang, Z., Chen, J., Chen, H., Cui, C., Li, X., ... & Fu, Q. (2019). Simplified evaluation of cotton water stress using high resolution unmanned aerial vehicle thermal imagery. *Remote Sensing*, 11(3), 267.
53. [53] Gonzalez-Dugo, V., Goldhamer, D., Zarco-Tejada, P. J., & Fereres, E. (2015). Improving the precision of irrigation in a pistachio farm using an unmanned airborne thermal system. *Irrigation Science*, 33(1), 43-52.
54. [54] Berni, J. A. J., Zarco-Tejada, P. J., Sepulcre-Cantó, G., Fereres, E., & Villalobos, F. (2009). Mapping canopy conductance and CWSI in olive orchards using high resolution thermal remote sensing imagery. *Remote Sensing of Environment*, 113(11), 2380-2388.
55. [55] Santesteban, L. G., Di Gennaro, S. F., Herrero-Langreo, A., Miranda, C., Royo, J. B., & Matese, A. (2017). High-resolution UAV-based thermal imaging to estimate the instantaneous and seasonal variability of plant water status within a vineyard. *Agricultural Water Management*, 183, 49-59.
56. [56] Agam, N., Segal, E., Peeters, A., Levi, A., Dag, A., Yermiyahu, U., & Ben-Gal, A. (2014). Spatial distribution of water status in irrigated olive orchards by thermal imaging. *Precision Agriculture*, 15(3), 346-359.
57. [57] Cohen, Y., Alchanatis, V., Prigojin, A., Levi, A., Soroker, V., & Cohen, Y. (2012). Use of aerial thermal imaging to estimate water status of palm trees. *Precision Agriculture*, 13(1), 123-140.
58. [58] Poblete-Echeverría, C., Sepúlveda-Reyes, D., Ortega-Farías, S., Zuñiga, M., & Fuentes, S. (2016). Plant water stress detection based on aerial and terrestrial infrared thermography: a study case from vineyard and olive orchard. *Acta Horticulturae*, 1112, 141-146.

59. [59] Krishnamurthy, K., & Kefauver, S. C. (2021). Applications of remote sensing in viticulture: recent advances and future trends. *Frontiers in Plant Science*, 12, 1194.
60. [60] Matese, A., Baraldi, R., Berton, A., Cesaraccio, C., Di Gennaro, S. F., Duce, P., ... & Toscano, P. (2018). Comparison of water stress indicators for smart irrigation management in grapevines. *Agricultural Water Management*, 210, 286-295.
61. [61] Fountas, S., Mylonas, N., Malounas, I., Rodias, E., Hellmann Santos, C., & Pekkeriet, E. (2020). Agricultural robotics for field operations. *Sensors*, 20(9), 2672
62. [62] Romero, M., Luo, Y., Su, B., & Fuentes, S. (2018). Vineyard water status estimation using multispectral imagery from an UAV platform and machine learning algorithms for irrigation scheduling management. *Computers and Electronics in Agriculture*, 147, 109-117.
63. [63] Netafim. (2021). Precision Irrigation: Almond Crop. Retrieved from https://www.netafim.com/en/crop-knowledge/almond/precision-irrigation/
64. [64] Netafim. (2021). IrrigaSys: Precision Irrigation Management System. Retrieved from https://www.netafim.com/en/digital-farming/irrigasys/
65. [65] Ortega-Blu, R., & Molina-Roco, M. (2016). Evaluation of vegetation indices and apparent soil electrical conductivity for site-specific vineyard management in Chile. *Precision Agriculture*, 17(4), 434-450.
66. [66] Ortega-Blu, R., Molina-Roco, M., & Ortega-Farías, S. (2019). Evaluation of a decision support system for irrigation management in olives (Olea europaea L.). *Agricultural Water Management*, 222, 324-332.
67. [67] Pokhrel, B. K., Paudel, K. P., & Segarra, E. (2018). Factors affecting the choice, intensity, and allocation of irrigation technologies by US Cotton farmers. *Water*, 10(6), 706.
68. [68] Wolfert, S., Ge, L., Verdouw, C., & Bogaardt, M. J. (2017). Big data in smart farming–a review. *Agricultural Systems*, 153, 69-80.
69. [69] Ojha, T., Misra, S., & Raghuwanshi, N. S. (2015). Wireless sensor networks for agriculture: The state-of-the-art in practice and future challenges. *Computers and Electronics in Agriculture*, 118, 66-84.
70. [70] Kamilaris, A., & Prenafeta-Boldú, F. X. (2018). Deep learning in agriculture: A survey. *Computers and Electronics in Agriculture*, 147, 70-90.
71. [71] Osroosh, Y., Troy Peters, R., Campbell, C. S., & Zhang, Q. (2015). Automatic irrigation scheduling of apple trees using theoretical crop water stress index with an innovative dynamic threshold. *Computers and Electronics in Agriculture*, 118, 193-203.
72. [72] Gu, Z., Qi, Z., Burghate, R., Yuan, S., Jiao, X., & Xu, J. (2020). Irrigation scheduling approaches and applications: A review. *Journal of Irrigation and Drainage Engineering*, 146(6), 04020007.
73. [73] González Perea, R., Camacho Poyato, E., Montesinos, P., & Rodríguez Díaz, J. A. (2016). Optimization of irrigation scheduling using soil water balance and genetic algorithms. *Water Resources Management*, 30(8), 2815-2830.
74. [74] Lorite, I. J., Ramírez-Cuesta, J. M., Cruz-Blanco, M., & Santos, C. (2015). Using weather forecast data for irrigation scheduling under semi-arid conditions. *Irrigation Science*, 33(6), 411-427.
75. [75] Sadler, E. J., Evans, R. G., Stone, K. C., & Camp, C. R. (2005). Opportunities for conservation with precision irrigation. *Journal of Soil and Water Conservation*, 60(6), 371-378.
76. [76] O'Shaughnessy, S. A., Evett, S. R., Colaizzi, P. D., & Howell, T. A. (2012). A crop water stress index and time threshold for automatic irrigation scheduling of grain sorghum. *Agricultural Water Management*, 107, 122-132.
77. [77] Dukes, M. D., Zotarelli, L., & Morgan, K. T. (2010). Use of irrigation technologies for vegetable crops in Florida. *HortTechnology*, 20(1), 133-142.
78. [78] Schaible, G., & Aillery, M. (2012). Water conservation in irrigated agriculture: Trends and challenges in the face of emerging demands. USDA-ERS Economic Information Bulletin, (99).
79. [79] Yohannes, D. F., & Tadesse, T. (1998). Effect of drip and furrow irrigation and plant spacing on yield of tomato at Dire Dawa, Ethiopia. *Agricultural Water Management*, 35(3), 201-207.

80. [80] O'Shaughnessy, S. A., Evett, S. R., Colaizzi, P. D., Andrade, M. A., Marek, T. H., Heeren, D. M., ... & LaRue, J. L. (2019). Identifying advantages and disadvantages of variable rate irrigation: An updated review. *Applied Engineering in Agriculture*, 35(6), 837-852.
81. [81] Stone, K. C., Bauer, P. J., & Sigua, G. C. (2016). Irrigation management using an expert system, soil water potentials, and vegetative indices for spatial applications. *Transactions of the ASABE*, 59(3), 941-948.
82. [82] Miller, K. A., Luck, J. D., Heeren, D. M., Lo, T., Martin, D. L., & Barker, J. B. (2018). A geospatial variable rate irrigation control scenario evaluation methodology based on mining root zone available water capacity. *Precision Agriculture*, 19(4), 666-683.
83. [83] O'Shaughnessy, S. A., Andrade, M. A., & Evett, S. R. (2017). Using an integrated crop water stress index for irrigation scheduling of two corn hybrids in a semi-arid region. *Irrigation Science*, 35(5), 451-467.
84. [84] Sui, R., & Yan, H. (2017). Field study of variable rate irrigation management in humid climates. *Irrigation and Drainage*, 66(3), 327-339.
85. [85] Fang, Q., Ma, L., Yu, Q., Malone, R. W., Saseendran, S. A., & Ahuja, L. R. (2008). Modeling nitrogen and water management effects in a wheat-maize double-cropping system. *Journal of Environmental Quality*, 37(6), 2232-2242.
86. [86] Haghverdi, A., Leib, B. G., Washington-Allen, R. A., Buschermohle, M. J., & Ayers, P. D. (2016). Studying uniform and variable rate center pivot irrigation strategies with the aid of site-specific water production functions. *Computers and Electronics in Agriculture*, 123, 327-340.
87. [87] Liakos, V., Porter, W., Liang, X., Tucker, M. A., McLendon, A., & Vellidis, G. (2017). Dynamic variable rate irrigation management for cotton in the southeastern United States. *Precision Agriculture*, 18(1), 95-110.
88. [88] Stone, K. C., Bauer, P. J., Busscher, W. J., Millen, J. A., Evans, D. E., & Strickland, E. E. (2015). Variable-rate irrigation management using an expert system in the eastern coastal plain. *Irrigation Science*, 33(3), 167-175.
89. [89] Vories, E. D., Stevens, W. E., Tacker, P. L., Griffin, T. W., & Counce, P. A. (2013). Rice production with center pivot irrigation. *Applied Engineering in Agriculture*, 29(1), 51-60.
90. [90] Lo, T. H., Heeren, D. M., Martin, D. L., Mateos, L., Luck, J. D., & Eisenhauer, D. E. (2016). Pumpage reduction by using variable-rate irrigation to mine undepleted soil water. *Transactions of the ASABE*, 59(5), 1285-1298.
91. [91] Hedley, C. B., & Yule, I. J. (2009). A method for spatial prediction of daily soil water status for precise irrigation scheduling. *Agricultural Water Management*, 96(12), 1737-1745.
92. [92] Daccache, A., Knox, J. W., Weatherhead, E. K., Daneshkhah, A., & Hess, T. M. (2015). Implementing precision irrigation in a humid climate–Recent experiences and on-going challenges. *Agricultural Water Management*, 147, 135-143.
93. [93] McCarthy, A. C., Hancock, N. H., & Raine, S. R. (2010). VARIwise: A general-purpose adaptive control simulation framework for spatially and temporally varied irrigation at sub-field scale. *Computers and Electronics in Agriculture*, 70(1), 117-128.
94. [94] Evett, S. R., Colaizzi, P. D., Lamm, F. R., O'Shaughnessy, S. A., Heeren, D. M., Trout, T. J., ... & Lin, X. (2020). Past, present, and future of irrigation on the US Great Plains. *Transactions of the ASABE*, 63(3), 703-729.
95. [95] Sigua, G. C., Stone, K. C., Bauer, P. J., & Szogi, A. A. (2018). Soil profile distribution of phosphorus and other nutrients following wetland conversion to pasture and cattle grazing. *Journal of Environmental Management*, 206, 1096-1106.
96. [96] Andrade, M. A., O'Shaughnessy, S. A., & Evett, S. R. (2020). ARSPivot, A sensor-based decision support software for variable-rate irrigation center pivot systems: Part A. Development. *Transactions of the ASABE*, 63(5), 1521-1533.
97. [97] Zhang, H., Han, M., Comas, L. H., DeJonge, K. C., Gleason, S. M., Trout, T. J., & Ma, L. (2019). Response of maize evapotranspiration to climate warming in the semi-arid environment of the US high plains. *Agricultural Water Management*, 224, 105745.
98. [98] Zhang, H., DeJonge, K. C., & Comas, L. H. (2016). Comparison of measured and FAO-56 modeled evapotranspiration for maize in northeastern Colorado. *Agricultural Water Management*, 165, 150-159.

99. [99] El-Hendawy, S. E., Hassan, W. M., Al-Suhaibani, N. A., & Schmidhalter, U. (2017). Spectral assessment of drought tolerance indices and grain yield in advanced spring wheat lines grown under full and limited water irrigation. *Agricultural Water Management*, 182, 1-12.
100. [100] Lo, T., Rudnick, D. R., Krienke, B. T., Heeren, D. M., Ge, Y., & Shaver, T. M. (2019). Water effects on optical canopy sensing for late-season site-specific nitrogen management of maize. *Computers and Electronics in Agriculture*, 162, 154-164.
101. [101] Taghvaeian, S., Chávez, J. L., & Hansen, N. C. (2012). Infrared thermometry to estimate crop water stress index and water use of irrigated maize in Northeastern Colorado. *Remote Sensing*, 4(11), 3619-3637.
102. [102] Evett, S. R., Howell Sr, T. A., Schneider, A. D., Copeland, K. S., Dusek, D. A., Brauer, D. K., ... & Gowda, P. H. (2016). The Bushland weighing lysimeters: A quarter century of crop ET investigations to advance sustainable irrigation. *Transactions of the ASABE*, 59(1), 163-179.
103. [103] Andrade, M. A., O'Shaughnessy, S. A., & Evett, S. R. (2020). ARSPivot, a sensor-based decision support software for variable-rate irrigation center pivot systems: Part B. Application. *Transactions of the ASABE*, 63(5), 1535-1547.
104. [104] Zhou, L., Liang, S., Ponce, K., Marundon, S., Ye, G., & Mansfield, S. D. (2015). Factors affecting wood formation in tree branches of Paulownia fortunei. *Frontiers in Plant Science*, 6, 505.
105. [105] Sui, R., & Baggard, J. (2015). Wireless sensor network for monitoring soil moisture and weather conditions. *Applied Engineering in Agriculture*, 31(2), 193-200.
106. [106] Yoder, R. E., Odhiambo, L. O., & Wright, W. C. (2005). Evaluation of methods for estimating daily reference crop evapotranspiration at a site in the humid southeast United States. *Applied Engineering in Agriculture*, 21(2), 197-202.
107. [107] Davis, S. L., & Dukes, M. D. (2010). Irrigation scheduling performance by evapotranspiration-based controllers. *Agricultural Water Management*, 98(1), 19-28.
108. [108] Zotarelli, L., Dukes, M. D., Romero, C. C., Migliaccio, K. W., & Morgan, K. T. (2010). Step by step calculation of the Penman-Monteith Evapotranspiration (FAO-56 Method). *Institute of Food and Agricultural Sciences, University of Florida*, AE459.
109. [109] Hunsaker, D. J., Fitzgerald, G. J., French, A. N., Clarke, T. R., Ottman, M. J., & Pinter, P. J. (2007). Wheat irrigation management using multispectral crop coefficients: I. Crop evapotranspiration prediction. *Transactions of the ASABE*, 50(6), 2017-2033.
110. [110] Shaughnessy, S. A., Evett, S. R., & Colaizzi, P. D. (2015). Dynamic prescription maps for site-specific variable rate irrigation of cotton. *Agricultural Water Management*, 159, 123-138.
111. [111] O'Shaughnessy, S. A., Evett, S. R., Andrade, A., Workneh, F., Price, J. A., & Rush, C. M. (2016). Site-specific variable-rate irrigation as a means to enhance water use efficiency. *Transactions of the ASABE*, 59(1), 239-249.
112. [112] Kamienski, C., Soininen, J. P., Taumberger, M., Dantas, R., Toscano, A., Salmon Cinotti, T., ... & Torre Neto, A. (2019). Smart water management platform: IoT-based precision irrigation for agriculture. *Sensors*, 19(2), 276.
113. [113] FAO. (2021). FAOSTAT statistical database. Rome: FAO.
114. [114] Fallahi, E., Fallahi, B., Kiester, M. J., Mahdavi, S., & Ebrahimian, M. (2019). Grafting improves yield, fruit quality, and nutritional value of apples under deficit irrigation. *International Journal of Fruit Science*, 19(4), 424-435.
115. [115] Kang, S., Hao, X., Du, T., Tong, L., Su, X., Lu, H., ... & Ding, R. (2017). Improving agricultural water productivity to ensure food security in China under changing environment: From research to practice. *Agricultural Water Management*, 179, 5-17.

116. amal, M., Hassan, A. U., Arshad, M., ... & Ahmed, N. (2019). Precision irrigation strategies for sustainable water budgeting of apple tree. *Agricultural Water Management*, 226, 105787.
117. [117] Manfrini, L., Grappadelli, L. C., Morandi, B., Ferreira, M. I., & Oliveira, M. (2020). Innovative precision irrigation strategies in light of a new mechanistic understanding of fruit growth. *Frontiers in Plant Science*, 11, 1564.

118. [118] Yu, R., Liu, T., Xu, Y., Zhu, C., Zhang, Q., Qu, Z., ... & Li, J. (2018). Analysis of salinization dynamics by remote sensing in Hetao Irrigation District of North China. *Agricultural Water Management*, 204, 110-120.
119. [119] Naor, A., Hupert, H., Greenblat, Y., Peres, M., Kaufman, A., & Klein, I. (2001). The response of nectarine fruit size and midday stem water potential to irrigation level in stage III and crop load. *Journal of the American Society for Horticultural Science*, 126(1), 140-143.
120. [120] Mieza, M. S., Cravero, W. R., Espósito, G. P., & Balbarani, S. (2021). Remote and proximal sensing to evaluate the spatial variability of a drip-irrigated olive orchard in Argentina. *Precision Agriculture*, 1-20.
121. [121] Gonzalez-Dugo, V., Lopez-Lopez, M., Espadafor, M., Orgaz, F., Testi, L., Zarco-Tejada, P., & Lorite, I. J. (2019). Transpiration from canopy temperature: Implications for the assessment of crop yield in almond orchards. *European Journal of Agronomy*, 105, 78-85.
122. [122] Rallo, L., Provenzano, G., Ghrab, M., & Moriana, A. (2018). Biennial bearing and the relationship between yield and irrigation in olive trees (*Olea europaea* L.). *Agricultural Water Management*, 204, 97-105.
123. [123] Gonzalez-Dugo, V., Goldhamer, D., Zarco-Tejada, P. J., & Fereres, E. (2015). Improving the precision of irrigation in a pistachio farm using an unmanned airborne thermal system. *Irrigation Science*, 33(1), 43-52.
124. [124] FAO (2021). Citrus Fruit - Fresh and Processed Statistical Bulletin 2020. Rome.
125. [125] Panigrahi, P., Sharma, R. K., Hasan, M., & Parihar, S. S. (2014). Deficit irrigation scheduling and yield prediction of 'Kinnow' mandarin (*Citrus reticulate* Blanco) in a semiarid region. *Agricultural Water Management*, 140, 48-60.
126. [126] Zinkernagel, J., Maestre-Valero, J. F., Seresti, S. Y., & Intrigliolo, D. S. (2018). New technologies and practical approaches to improve irrigation management of open field vegetable crops. *Agricultural Water Management*, 208, 139-155.
127. [127] Ballester, C., Castel, J., Intrigliolo, D. S., & Castel, J. R. (2011). Response of Clementina de Nules citrus trees to summer deficit irrigation. Yield components and fruit composition. *Agricultural Water Management*, 98(6), 1027-1032.
128. [128] Gasque, M., Marti, P., Granero, B., & González-Altozano, P. (2016). Effects of long-term summer deficit irrigation on 'Navelina' citrus trees. *Agricultural Water Management*, 169, 140-147.
129. [129] Pôças, I., Calera, A., Campos, I., & Cunha, M. (2020). Remote sensing for estimating and mapping single and basal crop coefficients: A review on spectral vegetation indices approaches. *Agricultural Water Management*, 233, 106081.
130. [130] Morgan, K. T., Barkataky, S., Kadyampakeni, D., Ebel, R., & Roka, F. (2014). Effects of short-term drought stress and mechanical harvesting on sweet orange tree health, water uptake, and yield. *HortScience*, 49(7), 835-842.
131. [131] Qin, W., Assinck, F. B., Heinen, M., & Oenema, O. (2016). Water and nitrogen use efficiencies in citrus production: A meta-analysis. *Agriculture, Ecosystems & Environment*, 222, 103-111.
132. [132] García-Tejero, I. F., Durán-Zuazo, V. H., Vélez, L. M., Hernández, A., Salguero, A., & Muriel-Fernández, J. L. (2011). Improving almond productivity under deficit irrigation in semiarid zones. *The Open Agriculture Journal*, 5(1), 56-62.
133. [133] Romero-Conde, A., Kusakabe, A., & Melgar, J. C. (2014). Physiological responses of citrus to partial rootzone drying irrigation. *Scientia Horticulturae*, 169, 234-238.
134. [134] Tapsuwan, S., Hunink, J. E., Alcon, F., Mertens-Palomares, A. N., & Baille, A. (2015). Assessing the design of a model-based irrigation advisory bulletin: The importance of end-user participation. *Irrigation and Drainage*, 64(2), 228-240.
135. [135] OIV (2021). State of the World Vitivinicultural Sector in 2020. International Organisation of Vine and Wine, Paris.
136. [136] Medrano, H., Tomás, M., Martorell, S., Escalona, J. M., Pou, A., Fuentes, S., ... & Bota, J. (2015). Improving water use efficiency of vineyards in semi-arid regions. A review. *Agronomy for Sustainable Development*, 35(2), 499-517.

137. [137] Roby, J. P., van Leeuwen, C., Gonçalves, E., Graça, A., & Martins, A. (2014). The impact of soil water holding capacity on the efficiency of irrigation strategy in vineyard. In *XIIth International Terroir Congress* (pp. 43-48). Universitat Politècnica València.
138. [138] Mirás-Avalos, J. M., & Intrigliolo, D. S. (2017). Grape composition under abiotic constrains: water stress and salinity. *Frontiers in Plant Science*, 8, 851.
139. [139] Intrigliolo, D. S., & Castel, J. R. (2008). Effects of irrigation on the performance of grapevine cv. Tempranillo in Requena, Spain. *American Journal of Enology and Viticulture*, 59(1), 30-38.
140. [140] Bonada, M., Buesa, I., Moran, M. A., & Sadras, V. O. (2018). Interactive effects of warming and water deficit on Shiraz vine transpiration in the Barossa Valley, Australia. *OENO One*, 52(2), 183-197.
141. [141] Gutiérrez, S., Diago, M. P., Fernández-Novales, J., & Tardaguila, J. (2018). Vineyard water status assessment using on-the-go thermal imaging and machine learning. *PLoS ONE*, 13(2), e0192037.
142. [142] Cancela, J. J., González, X. P., Vilanova, M., & Mirás-Avalos, J. M. (2019). Water management using drones and satellites in agriculture. *Water*, 11(5), 874.
143. [143] Bellvert, J., Zarco-Tejada, P. J., Marsal, J., Girona, J., González-Dugo, V., & Fereres, E. (2016). Vineyard irrigation scheduling based on airborne thermal imagery and water potential thresholds. *Australian Journal of Grape and Wine Research*, 22(2), 307-315.
144. [144] Zhang, X., Kang, S., Zhang, L., & Liu, J. (2010). Spatial variation of climatology monthly crop reference evapotranspiration and sensitivity coefficients in Shiyang river basin of northwest China. *Agricultural Water Management*, 97(10), 1506-1516.
145. [145] Carrasco-Benavides, M., Ortega-Farías, S., Lagos, L. O., Kleissl, J., Morales-Salinas, L., & Kilic, A. (2014). Parameterization of the Satellite-Based Model (METRIC) for the estimation of instantaneous surface energy balance components over a drip-irrigated vineyard. *Remote Sensing*, 6(11), 11342-11371.
146. [146] Naor, A., Gal, Y., & Peres, M. (2006). The inherent variability of water stress indicators in apple, nectarine and pear orchards, and the validity of a leaf-selection procedure for water potential measurements. *Irrigation Science*, 24(2), 129-135.
147. [147] Rallo, G., Paço, T. A., Paredes, P., Puig-Sirera, À., Massai, R., Provenzano, G., & Pereira, L. S. (2021). Vineyards. In *Crop Yield Response to Water* (pp. 320-334). FAO.
148. [148] Buesa, I., Caccavello, G., Basile, B., Merli, M. C., Poni, S., Chirivella, C., & Intrigliolo, D. S. (2018). Delaying berry ripening of Bobal and Tempranillo grapevines by late leaf removal in a semi-arid and temperate-warm climate under different water regimes. *Australian Journal of Grape and Wine Research*, 25(1), 70-82.
149. [149] Trigo-Córdoba, E., Bouzas-Cid, Y., Orriols-Fernández, I., & Mirás-Avalos, J. M. (2015). Effects of deficit irrigation on the performance of grapevine (Vitis vinifera L.) cv. 'Godello'and 'Treixadura'in Ribeiro, NW Spain. *Agricultural Water Management*, 161, 20-30.
150. [150] Acevedo-Opazo, C., Ortega-Farias, S., & Fuentes, S. (2010). Effects of grapevine (Vitis vinifera L.) water status on water consumption, vegetative growth and grape quality: An irrigation scheduling application to achieve regulated deficit irrigation. *Agricultural Water Management*, 97(7), 956-964.
151. [151] Zarco-Tejada, P. J., González-Dugo, V., Williams, L. E., Suárez, L., Berni, J. A. J., Goldhamer, D., & Fereres, E. (2013). A PRI-based water stress index combining structural and chlorophyll effects: Assessment using diurnal narrow-band airborne imagery and the CWSI thermal index. *Remote Sensing of Environment*, 138, 38-50.
152. [152] Limpus, S. (2009). Isohydricity in grapevines and development of plant-based indicators of water stress for irrigation scheduling (Doctoral dissertation, Charles Sturt University).
153. [153] Hornbuckle, J. W., Goodwin, I., & Somerville, T. (2003). Irrigation and Fertiliser Management for Quality Fruit Production and Water Conservation in the Warm Inland. In *International Water & Irrigation* (Vol. 23, No. 2, pp. 14-18). E. & F.N. Spon Ltd..
154. [154] Singh, A., Jain, A., Sarma, B. K., & Abhilash, P. C. (2014). Adaptive secretion of salicylic acid in Pseudomonas fluorescens improves its colonization ability in chickpea (*Cicer arietinum* L.) roots and influences biofilm formation. *Microbiological Research*, 169(7-8), 610-617.

155. [155] Smith, R., Baillie, J., Futures, A., McCarthy, A., Raine, S., & Baillie, C. (2010). Review of precision irrigation technologies and their application.
156. [156] Taghvaeian, S., Chávez, J. L., Bausch, W. C., DeJonge, K. C., & Trout, T. J. (2014). Minimizing instrumentation requirement for estimating crop water stress index and transpiration of maize. *Irrigation Science*, 32(1), 53-65.
157. [157] Trout, T. J., & DeJonge, K. C. (2017). Water productivity of maize in the US high plains. *Irrigation Science*, 35(3), 251-266.
158. [158] Martínez, J., & Reca, J. (2014). Water use efficiency of surface drip irrigation versus an alternative subsurface drip irrigation method. *Journal of Irrigation and Drainage Engineering*, 140(10), 04014030.
159. [159] Phene, C. J. (2010). Drip irrigation saves water. *Resource: Engineering & Technology for a Sustainable World*, 17(4), 7-9.
160. [160] Greaves, G. E., & Wang, Y. M. (2017). Effect of regulated deficit irrigation scheduling on water use of corn in southern Taiwan tropical environment. *Agricultural Water Management*, 188, 115-125.
161. [161] Kang, Y., & Wan, S. (2005). Effect of soil water potential on radish (*Raphanus sativus* L.) growth and water use under drip irrigation. *Scientia Horticulturae*, 106(3), 275-292.
162. [162] Ferreira, M. I. (2017). Stress coefficients for soil water balance combined with water stress indicators for irrigation scheduling of woody crops. *Horticulturae*, 3(2), 38.
163. [163] Costa, J. M., Ortuño, M. F., & Chaves, M. M. (2007). Deficit irrigation as a strategy to save water: physiology and potential application to horticulture. *Journal of Integrative Plant Biology*, 49(10), 1421-1434.
164. [164] Barradas, J. M. M., Matula, S., & Dolezal, F. (2012). A decision support system-fertigation simulator (DSS-FS) for design and optimization of sprinkler and drip irrigation systems. *Computers and Electronics in Agriculture*, 86, 111-119.
165. [165] Miao, Q., Shi, H., Gonçalves, J. M., & Pereira, L. S. (2018). Basin irrigation design with multi-criteria analysis focusing on water saving and economic returns: Application to wheat in Hetao, Yellow River basin. *Water*, 10(1), 67.
166. [166] Chai, Q., Gan, Y., Zhao, C., Xu, H. L., Waskom, R. M., Niu, Y., & Siddique, K. H. (2016). Regulated deficit irrigation for crop production under drought stress. A review. *Agronomy for Sustainable Development*, 36(1), 1-21.
167. [167] Casadesús, J., Mata, M., Marsal, J., & Girona, J. (2012). A general algorithm for automated scheduling of drip irrigation in tree crops. *Computers and Electronics in Agriculture*, 83, 11-20.
168. [168] Jovanovic, N , N., & Pereira, L. S. (2020). Soil water balance models for determining crop water and irrigation requirements and irrigation scheduling focusing on the FAO56 method and the dual Kc approach. *Agricultural Water Management*, 241, 106357.
169. [169] Pereira, L. S., Paredes, P., Hunsaker, D. J., López-Urrea, R., & Mohammadi Shad, Z. (2021). Standard single and basal crop coefficients for field crops. Updates and advances to the FAO56 crop water requirements method. *Agricultural Water Management*, 243, 106466.

CHAPTER - 2

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Agro-tourism and Horticultural Entrepreneurship

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Abstract

The application of advanced technologies in horticulture has revolutionized crop production, enabling growers to optimize yields, enhance crop quality, and improve resource use efficiency. This chapter provides an in-depth overview of the latest technological advancements in horticulture, focusing on precision agriculture, protected cultivation, automation and robotics, and post-harvest management. Precision agriculture techniques, such as remote sensing, geographic information systems (GIS), and variable rate technology (VRT), allow for site-specific management of crops, optimizing inputs and reducing environmental impact. Protected cultivation, including greenhouses and high tunnels, offers controlled environments for year-round production, pest and disease management, and resource conservation. Automation and robotics, such as autonomous vehicles, robotic harvesters, and automated irrigation systems, streamline labor-intensive tasks and improve operational efficiency. Post-harvest technologies, including modified atmosphere packaging (MAP), controlled atmosphere storage (CAS), and non-destructive quality assessment, help maintain crop quality and extend shelf life. The integration of these technologies, along with advancements in biotechnology, nanotechnology, and artificial intelligence, is driving the future of horticulture.

However, the adoption of these technologies faces challenges, such as high initial costs, technical complexity, and the need for skilled labor. Overcoming these barriers requires collaboration among researchers, industry stakeholders, and policymakers to develop cost-effective, user-friendly, and scalable solutions. This chapter explores successful case studies of advanced technology implementation in various horticultural contexts, highlighting their impact on crop yields, resource use efficiency, and profitability. It also discusses the potential of emerging technologies, such as the Internet of Things (IoT), big data analytics, and machine learning, to further transform the horticultural sector. As the global population continues to grow and resources become increasingly limited, the implementation of advanced technologies in horticulture will be crucial for ensuring food security, sustainability, and economic growth in the coming decades.

Keywords: precision agriculture, protected cultivation, automation, robotics, post-harvest technology

Horticulture, the branch of agriculture concerned with the cultivation of fruits, vegetables, flowers, and ornamental plants, plays a vital role in ensuring food security, nutrition, and economic development worldwide. However, the horticultural sector faces numerous challenges, including increasing global population, limited resources, climate change, and labor shortages [1]. To address these challenges and meet the growing demand for horticultural products, the adoption of advanced technologies has become imperative.

Advanced technologies in horticulture encompass a wide range of innovations, from precision agriculture and protected cultivation to automation, robotics, and post-harvest management [2]. These technologies aim to optimize crop production, minimize resource consumption, reduce labor requirements, and improve the overall sustainability and profitability of horticultural systems. By leveraging data-driven insights, intelligent systems, and innovative materials, advanced technologies enable growers to make informed decisions, adapt to changing conditions, and maximize the potential of their crops [3].

The application of advanced technologies in horticulture has been facilitated by the rapid development of enabling technologies, such as sensors, imaging systems, communication networks, and data analytics [4]. These technologies allow for the collection, transmission, and processing of vast amounts of data on crop growth, environmental conditions, and resource use, providing growers with actionable insights for optimizing their operations. Furthermore, advancements in biotechnology, nanotechnology, and artificial intelligence are opening up new possibilities for crop improvement, pest and disease management, and automation in horticulture [5].

However, the adoption of advanced technologies in horticulture is not without challenges. High initial costs, technical complexity, and the need for skilled labor can be significant barriers, particularly for small-scale growers in developing countries [6]. Moreover, the successful implementation of these technologies requires a supportive ecosystem, including appropriate infrastructure, policies, and market linkages. Overcoming these challenges necessitates collaboration among researchers, industry stakeholders, and policymakers to develop cost-effective, user-friendly, and scalable solutions that cater to the diverse needs of horticultural systems worldwide [7].

This chapter provides an in-depth exploration of the advanced technologies transforming the horticultural sector. It begins by examining the principles and applications of precision agriculture, including remote sensing, GIS, and VRT, in optimizing crop management and resource use. Next, it delves into the role of protected cultivation, such as greenhouses and high tunnels, in creating controlled environments for year-round production and resource conservation. The chapter then discusses the impact of automation and robotics on streamlining labor-intensive tasks and improving operational efficiency in horticulture. It also highlights the importance of post-harvest technologies, such as MAP, CAS, and non-destructive quality assessment, in maintaining crop quality and extending shelf life.

Throughout the chapter, successful case studies of advanced technology implementation in various horticultural contexts are presented, showcasing their impact on crop yields, resource use efficiency, and profitability. The chapter also explores the potential of emerging technologies, such as IoT, big data analytics, and machine learning, to further revolutionize the horticultural sector. Finally, it discusses the challenges and opportunities associated with the adoption of advanced technologies in horticulture, emphasizing the need for collaborative efforts to drive innovation, build capacity, and ensure the sustainable growth of the sector.

2. Precision Agriculture

Precision agriculture, also known as site-specific crop management, is an approach to farming that uses advanced technologies to optimize crop production and resource use based on spatial and temporal variability within fields [8]. By collecting and analyzing data on soil properties, crop growth, and environmental conditions, precision agriculture enables growers to make informed decisions on input management, leading to improved crop yields, quality, and sustainability [9].

The foundation of precision agriculture lies in the ability to gather and process high-resolution data on the variability of soil, crops, and environmental factors within fields. This data is collected using a range of technologies, including remote sensing, GIS, and sensor networks [10]. Remote sensing techniques, such as satellite imagery, aerial photography, and UAVs, provide detailed spatial information on crop health, growth, and stress. GIS tools allow for the integration and analysis of spatial data, enabling the creation of management zones and the application of site-specific interventions. Sensor networks, including soil moisture sensors, weather stations, and crop canopy sensors, provide real-time data on environmental conditions and crop performance [11].

The data collected through these technologies is processed using advanced analytics and decision support systems to generate actionable insights for crop management. For example, precision irrigation systems use soil moisture and weather data to optimize irrigation scheduling and application rates, reducing water wastage and improving crop water use efficiency [12]. Similarly, precision nutrient management systems use soil fertility maps and crop growth models to determine site-specific fertilizer requirements, minimizing nutrient losses and enhancing crop nutrient uptake [13].

One of the key enabling technologies for precision agriculture is VRT, which allows for the application of inputs, such as seeds, fertilizers, and pesticides, at variable rates across fields based on site-specific needs [14]. VRT equipment, such as variable rate planters, sprayers, and fertilizer spreaders, use GPS and GIS data to automatically adjust application rates, ensuring that each part of the field receives the optimal amount of inputs. This targeted approach not only improves crop yields and quality but also reduces input costs and environmental impact by minimizing over-application and runoff [15].

Table 1. Comparison of precision agriculture technologies

Technology	Application	Data Type	Resolution	Cost
Satellite imagery	Crop health monitoring, yield mapping	Multispectral, hyperspectral	Moderate to high	Low to moderate
Aerial photography	Crop stress detection, soil mapping	RGB, multispectral	High	Moderate
UAVs	Crop scouting, pest and disease detection	RGB, multispectral, thermal	Very high	Moderate to high
Soil sensors	Soil moisture, nutrient, and pH monitoring	Electrical conductivity, capacitance, electrochemical	Point-based	Moderate
Weather stations	Microclimate monitoring, disease risk assessment	Temperature, humidity, rainfall, wind speed	Point-based	Low to moderate
Crop canopy sensors	Crop nitrogen status, biomass estimation	NDVI, NDRE, LiDAR	High	Moderate to high

Precision agriculture has been shown to deliver significant benefits for horticultural crops, including increased yields, improved crop quality, and reduced production costs. For example, a study on precision irrigation in tomato production found that the use of soil moisture sensors and automated irrigation systems resulted in a 30% reduction in water use and a 15% increase in yield compared to traditional irrigation practices [16]. Similarly, precision nutrient management in apple orchards using soil and leaf tissue analysis, along with targeted fertilizer application, led to a 20% reduction in nitrogen use and a 10% increase in fruit quality and yield [17].

However, the adoption of precision agriculture in horticulture faces several challenges, including high initial costs, technical complexity, and the need for specialized skills and knowledge. Small-scale growers, in particular, may find it difficult to invest in the necessary equipment and infrastructure, such as GPS-enabled machinery, sensor networks, and data management systems [18]. Moreover, the interpretation and use of precision agriculture data require a certain level of technical expertise, which may not be readily available among growers.

To overcome these challenges, there is a need for collaborative efforts among researchers, industry stakeholders, and policymakers to develop cost-effective and user-friendly precision agriculture solutions tailored to the needs of horticultural growers. This includes the development of low-cost sensors and imaging systems, open-source data management platforms, and mobile-based decision support tools that can be easily accessed and used by growers [19]. Furthermore, capacity building and extension services play a crucial role in promoting the adoption of precision agriculture, by providing training, demonstrations, and support to growers.

3. Protected Cultivation

Protected cultivation, also known as controlled environment agriculture (CEA), involves the use of structures and technologies to create optimal growing conditions for crops, while protecting them from adverse environmental factors, such as extreme temperatures, pests, and diseases [20]. By providing a controlled environment, protected cultivation enables year-round production, improves crop quality and yields, and reduces the use of resources, such as water, fertilizers, and pesticides [21].

The most common types of protected cultivation structures used in horticulture include greenhouses, high tunnels, and shade houses. Greenhouses are permanent structures that provide a high level of environmental control, including temperature, humidity, light, and CO2 regulation [22]. They can be equipped with advanced technologies, such as heating and cooling systems, supplemental lighting, and automated ventilation, to optimize growing conditions for specific crops. High tunnels, also known as hoop houses, are less expensive and less complex than greenhouses, consisting of a metal or plastic frame covered with a single layer of plastic film [23]. They are used to extend the growing season, protect crops from adverse weather, and improve crop quality. Shade houses are structures that provide shade and protect crops from excessive sunlight, wind, and hail [24]. They are commonly used for the production of shade-loving crops, such as lettuce, herbs, and ornamentals.

One of the key advantages of protected cultivation is the ability to control environmental factors that influence crop growth and development. By manipulating temperature, humidity, light, and CO2 levels, growers can create optimal conditions for photosynthesis, nutrient uptake, and biomass accumulation, leading to higher yields and improved crop quality [25]. For example, the use of supplemental lighting in greenhouses can extend the photoperiod and increase light intensity, promoting faster growth and higher yields in light-limited seasons [26]. Similarly, CO2 enrichment can enhance photosynthesis and biomass production, particularly in closed greenhouse systems where CO2 levels can be easily regulated [27].

Protected cultivation also enables the use of advanced irrigation and nutrient management systems, such as hydroponics, aeroponics, and fertigation, which can significantly improve water and nutrient use efficiency [28]. Hydroponic systems, where crops are grown in nutrient solutions without soil, allow for precise control over nutrient delivery and can reduce water use by up to 90% compared to traditional soil-based cultivation [29]. Aeroponic systems, where crops are grown in air and misted with nutrient solutions, offer even greater water and nutrient efficiency, as well as improved root aeration and disease control [30]. Fertigation, the application of fertilizers through irrigation systems, enables the synchronization of nutrient supply with crop demand, reducing nutrient losses and improving crop nutrient uptake [31].

Protected cultivation has been successfully applied to a wide range of horticultural crops, including vegetables, fruits, flowers, and medicinal plants. In vegetable production, the use of greenhouses and high tunnels has enabled the year-round supply of high-quality produce, such as tomatoes, peppers, cucumbers, and leafy greens [32]. Greenhouse production of fruit crops, such as strawberries, raspberries, and blackberries, has also gained popularity, due to the ability to extend the fruiting season and improve fruit quality [33]. In floriculture, protected cultivation is widely used for the production of cut flowers, potted plants, and bedding plants, allowing for the precise control of environmental factors that influence flower quality and timing [34].

Table 2. Comparison of protected cultivation systems

System	**Environmental Control**	**Water Use Efficiency**	**Nutrient Use Efficiency**	**Cost**
Greenhouse	High	High	High	High
High tunnel	Moderate	Moderate	Moderate	Moderate
Shade house	Low	Low	Low	Low
Hydroponics	High	Very high	Very high	High
Aeroponics	High	Very high	Very high	Very high
Fertigation	Moderate	High	High	Moderate

However, the adoption of protected cultivation in horticulture is limited by several factors, including high initial investment costs, energy requirements, and the need for specialized knowledge and skills. The construction and operation of greenhouses and other protected cultivation structures require significant capital investment, which may be prohibitive for small-scale growers [35]. Moreover, the energy costs associated with heating, cooling, and lighting can be substantial, particularly in regions with extreme climates [36]. The management of protected cultivation systems also requires a high level of technical expertise, including knowledge of crop physiology, environmental control, and pest and disease management [37].

To promote the adoption of protected cultivation in horticulture, there is a need for research and development efforts aimed at reducing costs, improving energy efficiency, and simplifying management practices. This includes the development of low-cost, energy-efficient greenhouse designs, the use of renewable energy sources, such as solar and geothermal energy, and the application of advanced sensor and control technologies to optimize environmental management [38]. Furthermore, capacity building and extension services are essential for providing growers with the knowledge and skills needed to successfully implement and manage protected cultivation systems.

4. Automation and Robotics

Automation and robotics are increasingly being applied in horticulture to address labor shortages, improve efficiency, and reduce production costs. Automation involves the use of machines and control systems to perform tasks that were previously done manually, while robotics involves the use of intelligent machines that can perform complex tasks with a high degree of autonomy and flexibility [39].

The application of automation and robotics in horticulture covers a wide range of tasks, including planting, crop monitoring, pest and disease detection, pruning, harvesting, and post-harvest handling [40]. One of the most common applications of automation in horticulture is in irrigation and fertilization, where the use of sensors, controllers, and actuators enables precise and efficient delivery of water and nutrients to crops [41]. For example, automated drip irrigation systems use soil moisture sensors and programmable controllers to maintain optimal soil moisture levels, while fertigation systems use nutrient sensors and injection pumps to deliver nutrients in precise quantities and at the right time [42].

Crop monitoring and pest and disease detection are other areas where automation and robotics are making significant contributions. The use of sensors, imaging systems, and machine learning algorithms enables the early detection and diagnosis of crop stress, pests, and diseases, allowing for timely and targeted interventions [43]. For example, the use of hyperspectral imaging and computer vision techniques can detect subtle changes in plant physiology and morphology that are indicative of nutrient deficiencies, water stress, or disease infection [44]. Once detected, this information can be used to guide the application of fertilizers, irrigation, or pesticides, or to trigger the deployment of robotic systems for targeted treatment or removal of affected plants [45].

Table 3. Examples of automation and robotics applications in horticulture

Application	Technology	Benefits
Irrigation and fertilization	Soil moisture sensors, nutrient sensors, programmable controllers, injection pumps	Precise and efficient delivery of water and nutrients, reduced water and fertilizer use, improved crop yields and quality
Crop monitoring	Hyperspectral imaging, thermal imaging, chlorophyll fluorescence imaging, machine learning algorithms	Early detection and diagnosis of crop stress, pests, and diseases, targeted interventions, reduced pesticide use
Pest and disease detection	Computer vision, machine learning algorithms, robotic systems	Automated scouting and monitoring, targeted treatment or removal of affected plants, reduced labor costs

Pruning is another labor-intensive task in horticulture where automation and robotics are showing promise. Robotic pruning systems use computer vision and machine learning algorithms to identify and locate branches that need to be pruned, and robotic arms with cutting tools to perform the pruning operation [46]. These systems can operate with a high degree of precision and consistency, improving plant architecture, light interception, and yield, while reducing labor costs and worker fatigue [47]. In addition, robotic pruning systems can be operated continuously, allowing for more frequent and timely pruning interventions that can improve crop quality and reduce disease pressure [48].

Harvesting is one of the most challenging and labor-intensive tasks in horticulture, and the development of robotic harvesting systems has been a major focus of research and development efforts in recent years. Robotic harvesters use computer vision and machine learning algorithms to identify and locate ripe fruits or vegetables, and soft grippers or suction cups to detach and collect the produce without causing damage [49]. These systems can operate selectively, harvesting only the ripe produce and leaving the unripe ones on the plant, thus improving harvest efficiency and reducing post-harvest losses [50]. However, the development of robotic harvesting systems is still in its early stages, and significant challenges remain, including the variability in fruit size, shape, and location, and the need for gentle handling to avoid bruising and damage [51].

Post-harvest handling is another area where automation and robotics are being applied to improve efficiency and quality. Robotic sorting and grading systems use computer vision and machine learning algorithms to assess the quality of horticultural produce based on size, color, shape, and defects, and to sort them into different grades or categories [52]. These systems can operate with a high throughput and accuracy, reducing labor costs and improving product consistency and shelf life [53]. In addition, the use of automation and robotics in post-harvest handling can help to reduce the risk of contamination and spoilage, by minimizing human contact and maintaining optimal storage conditions [54].

Despite the potential benefits of automation and robotics in horticulture, their adoption is still limited by several factors, including high initial costs, technical complexity, and the need for specialized skills and infrastructure. The development and deployment of robotic systems require significant investment in research and development, as well as in the necessary hardware and software components [55]. Moreover, the operation and maintenance of these systems require specialized technical skills, which may not be readily available among growers and workers [56]. There are also concerns about the social and economic impacts of automation and robotics, particularly in terms of job displacement and the need for retraining and upskilling of the workforce [57].

To overcome these challenges and promote the adoption of automation and robotics in horticulture, there is a need for collaborative efforts among researchers, industry, and government stakeholders. This includes the development of low-cost and user-friendly robotic systems, the establishment of training and certification programs for operators and technicians, and the creation of supportive policies and incentives for the adoption of these technologies [58]. In addition, there is a need for research on the social and economic implications of automation and robotics, and for strategies to mitigate the potential negative impacts on workers and communities [59].

5. Post-Harvest Technology

Post-harvest technology refers to the methods and techniques used to maintain the quality and extend the shelf life of horticultural produce after harvesting. Post-harvest losses, which can occur due to physical damage, physiological disorders, and microbial spoilage, are a major challenge in horticulture, resulting in significant economic losses and food waste [60]. The application of advanced post-harvest technologies can help to reduce these losses, improve product quality and safety, and increase the value and marketability of horticultural produce [61].

One of the most important factors in post-harvest management is temperature control. Maintaining optimal storage temperatures can significantly extend the shelf life of horticultural produce by slowing down metabolic processes, such as respiration and ethylene production, and reducing the growth of spoilage microorganisms [62]. The use of refrigeration systems, such as cold rooms and refrigerated trucks, is essential for maintaining the cold chain from farm to market [63]. In addition, the use of advanced temperature monitoring and control systems, such as wireless sensors and remote monitoring, can help to ensure that produce is stored at the optimal temperature throughout the supply chain [64].

Another important post-harvest technology is modified atmosphere packaging (MAP), which involves the alteration of the atmospheric composition within a package to extend the shelf life of fresh produce. MAP systems typically involve the use of semi-permeable films or coatings that allow for the selective exchange of gases, such as oxygen and carbon dioxide, between the package and the environment [65]. By creating an optimal atmospheric composition within the package, MAP can slow down the metabolic processes and reduce the growth of spoilage microorganisms, thus extending the shelf life of the produce [66]. MAP has been successfully applied to a wide range of horticultural crops, including fruits, vegetables, and cut flowers [67].

Table 4. Examples of MAP systems for horticultural crops

Crop	**Optimal Atmosphere**	**Shelf Life Extension**
Apple	1-3% O_2, 1-3% C O_2	2-4 months
Strawberry	5-10% O_2, 15-20% CO_2	1-2 weeks
Lettuce	1-3% O_2, 5-10% CO_2	1-2 weeks
Broccoli	1-2% O_2, 5-10% CO_2	2-3 weeks
Cut roses	2-3% O_2, 10-15% CO_2	1-2 weeks

Controlled atmosphere storage (CAS) is another post-harvest technology that involves the precise control of temperature, humidity, and atmospheric composition in storage facilities to maintain the quality and extend the shelf life of horticultural produce [68]. CAS systems typically involve the use of sealed rooms or containers with advanced environmental control systems that can maintain optimal storage conditions for specific crops [69]. By reducing the oxygen level and increasing the carbon dioxide level in the storage atmosphere, CAS can slow down the metabolic processes and reduce the growth of spoilage microorganisms, thus extending the shelf life of the produce [70]. CAS has been successfully applied to a wide range of horticultural crops, including apples, pears, kiwifruit, and leafy greens [71].

Non-destructive quality assessment is another important post-harvest technology that can help to improve the efficiency and accuracy of quality control in horticulture. Non-destructive techniques, such as spectroscopy, imaging, and mechanical methods, allow for the rapid and non-invasive measurement of quality attributes, such as firmness, color, and internal defects, without damaging the produce [72]. The use of these techniques can help to reduce the need for destructive sampling, improve the consistency and reliability of quality assessments, and enable the sorting and grading of produce based on quality attributes [73]. In addition, the use of non-destructive techniques can provide valuable information for supply chain management and marketing, by enabling the prediction of shelf life and the identification of optimal storage and handling conditions [74].

Despite the potential benefits of post-harvest technologies, their adoption in horticulture is still limited by several factors, including high initial costs, technical complexity, and the need for specialized skills and infrastructure. The development and deployment of advanced post-harvest technologies require significant investment in research and development, as well as in the necessary equipment and facilities [75]. Moreover, the operation and maintenance of these technologies require specialized technical skills, which may not be readily available among growers and workers [76]. There are also challenges related to the scalability and compatibility of post-harvest technologies, particularly in the context of small-scale and diversified horticultural operations [77].

To overcome these challenges and promote the adoption of post-harvest technologies in horticulture, there is a need for collaborative efforts among researchers, industry, and government stakeholders. This includes the development of low-cost and user-friendly post-harvest technologies, the establishment of training and certification programs for operators and technicians, and the creation of supportive policies and incentives for the adoption of these technologies [78]. In addition, there is a need for research on the social and economic implications of post-harvest technologies, and for strategies to ensure their equitable and sustainable adoption across different horticultural systems and regions [79].

6. Future Prospects and Challenges

The future of advanced technology in horticulture is promising, with ongoing advancements in areas such as biotechnology, nanotechnology, and artificial intelligence. These technologies have the potential to revolutionize various aspects of horticultural production, from crop breeding and genetic improvement to precision farming and post-harvest management [80].

One of the most exciting areas of future development is the application of biotechnology and genetic engineering in horticulture. The use of modern biotechnology tools, such as marker-assisted selection, genetic modification, and genome editing, can help to accelerate the development of new crop varieties with improved traits, such as resistance to pests and diseases, tolerance to abiotic stresses, and enhanced nutritional quality [81]. For example, the use of CRISPR-Cas9 gene editing technology has enabled the development of disease-resistant varieties of crops such as tomatoes, potatoes, and bananas, which could significantly reduce the need for pesticide use and improve crop yields and quality [82].

Another promising area of future development is the application of nanotechnology in horticulture. Nanotechnology involves the manipulation of materials at the nanoscale level, which can offer unique properties and functionalities for various horticultural applications [83]. For example, the use of nanomaterials such as nanoparticles, nanofibers, and nanoemulsions can help to improve the efficiency and precision of fertilizer and pesticide application, by enabling the controlled release and targeted delivery of active ingredients [84]. Nanotechnology can also be used to develop smart packaging materials that can monitor and control the quality and safety of horticultural produce during storage and transportation [85].

The application of artificial intelligence (AI) and machine learning (ML) is another area of future development in horticulture. AI and ML technologies can help to analyze and interpret large amounts of data generated by various sensors and imaging systems used in precision farming and post-harvest management, enabling the development of predictive models and decision support tools for various horticultural applications [86]. For example, the use of AI and ML algorithms can help to optimize irrigation and fertilization schedules based on real-time data on soil moisture, nutrient levels, and plant growth, leading to improved water and nutrient use efficiency and reduced environmental impact [87]. AI and ML can also be used to develop early warning systems for pest and disease outbreaks, enabling timely and targeted interventions to minimize crop losses and reduce the need for chemical inputs [88].

Table 5. Examples of future technologies in horticulture

Technology	**Application**	**Benefits**
CRISPR-Cas9 gene editing	Development of disease-resistant crop varieties	Reduced pesticide use, improved crop yields and quality
Nanoparticles	Controlled release and targeted delivery of fertilizers and pesticides	Improved efficiency and precision of input application, reduced environmental impact
Smart packaging materials	Monitoring and control of produce quality and safety during storage and transportation	Reduced post-harvest losses, improved supply chain management
AI and ML algorithms	Optimization of irrigation and fertilization schedules, early warning systems for pest and disease outbreaks	Improved water and nutrient use efficiency, reduced environmental impact, minimized crop losses

Despite the potential benefits of these future technologies, their adoption in horticulture may face several challenges and limitations. One of the main challenges is the high cost and technical complexity associated with the development and deployment of these technologies, which may limit their accessibility and affordability for small-scale and resource-poor growers [89]. There are also concerns about the potential risks and unintended consequences associated with the use of these technologies, such as the environmental and health impacts of nanoparticles and the ethical and societal implications of genetic engineering [90].

To address these challenges and ensure the responsible and equitable adoption of future technologies in horticulture, there is a need for collaborative and interdisciplinary research and innovation efforts that engage diverse stakeholders, including growers, researchers, policymakers, and civil society organizations [91]. This includes the development of participatory and inclusive innovation processes that take into account the needs, priorities, and knowledge of different horticultural systems and communities, and the establishment of transparent and accountable governance frameworks that ensure the safe and responsible use of these technologies [92].

In addition, there is a need for capacity building and knowledge sharing initiatives that enable the transfer and adaptation of these technologies to different horticultural contexts and scales, and the empowerment of growers and communities to make informed decisions about their adoption and use [93]. This includes the development of user-friendly and accessible tools and platforms for data collection, analysis, and sharing, and the establishment of multi-stakeholder networks and partnerships that facilitate the exchange of knowledge, resources, and best practices across different regions and sectors [94].

7. Conclusion

Advanced technologies have the potential to transform horticulture, enabling growers to optimize crop production, reduce resource consumption, and improve the overall sustainability and profitability of their operations. Precision agriculture, protected cultivation, automation and robotics, and post-harvest technologies are among the key advancements driving this transformation, offering new opportunities for increasing crop yields, improving crop quality, and reducing labor and input costs.

However, the adoption of advanced technologies in horticulture is not without challenges, including high initial costs, technical complexity, and the need for specialized skills and infrastructure. To overcome these challenges and ensure the equitable and sustainable adoption of these technologies, there is a need for collaborative and interdisciplinary research and innovation efforts that engage diverse stakeholders and take into account the needs and priorities of different horticultural systems and communities.

Looking to the future, ongoing advancements in areas such as biotechnology, nanotechnology, and artificial intelligence offer exciting prospects for further transforming horticulture, from crop breeding and genetic improvement to precision farming and post-harvest management. However, realizing the full potential of these technologies will require addressing the technical, economic, and social challenges associated with their development and deployment, and ensuring their responsible and inclusive adoption across different horticultural contexts and scales.

References

1. Food and Agriculture Organization of the United Nations. (2019). The State of Food and Agriculture 2019. Moving forward on food loss and waste reduction. Rome. [Available online: http://www.fao.org/3/ca6030en/ca6030en.pdf\]
2. Tiwari, A., & Shukla, A. (2021). Advanced technologies in horticulture: An overview. In A. Tiwari & A. Shukla (Eds.), Advanced Technology for Horticultural Crop Production (pp. 1-16). Springer, Singapore. https://doi.org/10.1007/978-981-15-8987-9_1
3. Shamshiri, R. R., Kalantari, F., Ting, K. C., Thorp, K. R., Hameed, I. A., Weltzien, C., Ahmad, D., & Shad, Z. M. (2018). Advances in greenhouse automation and controlled environment agriculture: A transition to plant factories and urban agriculture. International Journal of Agricultural and Biological Engineering, 11(1), 1-22. https://doi.org/10.25165/j.ijabe.20181101.3210

4. Yu, C., & Zhao, Z. (2019). Technologies and applications of agricultural and forestry intelligent equipment based on Internet of Things. In Internet of Things (IoT) for Automated and Smart Applications. IntechOpen. https://doi.org/10.5772/intechopen.86339
5. Kamilaris, A., Kartakoullis, A., & Prenafeta-Boldú, F. X. (2017). A review on the practice of big data analysis in agriculture. Computers and Electronics in Agriculture, 143, 23-37. https://doi.org/10.1016/j.compag.2017.09.037
6. Zhai, Z., Martínez, J. F., Beltran, V., & Martínez, N. L. (2020). Decision support systems for agriculture 4.0: Survey and challenges. Computers and Electronics in Agriculture, 170, 105256. https://doi.org/10.1016/j.compag.2020.105256
7. Klerkx, L., Jakku, E., & Labarthe, P. (2019). A review of social science on digital agriculture, smart farming and agriculture 4.0: New contributions and a future research agenda. NJAS - Wageningen Journal of Life Sciences, 90-91, 100315. https://doi.org/10.1016/j.njas.2019.100315
8. Gebbers, R., & Adamchuk, V. I. (2010). Precision agriculture and food security. Science, 327(5967), 828-831. https://doi.org/10.1126/science.1183899
9. Bongiovanni, R., & Lowenberg-DeBoer, J. (2004). Precision agriculture and sustainability. Precision Agriculture, 5(4), 359-387. https://doi.org/10.1023/b:prag.0000040806.39604.aa
10. Zhang, N., Wang, M., & Wang, N. (2002). Precision agriculture—a worldwide overview. Computers and Electronics in Agriculture, 36(2-3), 113-132. https://doi.org/10.1016/s0168-1699(02)00096-0
11. Polo, J., Hornero, G., Duijneveld, C., García, A., & Casas, O. (2015). Design of a low-cost wireless sensor network with UAV mobile node for agricultural applications. Computers and Electronics in Agriculture, 119, 19-32. https://doi.org/10.1016/j.compag.2015.09.024
12. Daccache, A., Knox, J. W., Weatherhead, E. K., Daneshkhah, A., & Hess, T. M. (2015). Implementing precision irrigation in a humid climate - Recent experiences and on-going challenges. Agricultural Water Management, 147, 135-143. https://doi.org/10.1016/j.agwat.2014.05.018
13. Gómez-Candón, D., De Castro, A. I., & López-Granados, F. (2014). Assessing the accuracy of mosaics from unmanned aerial vehicle (UAV) imagery for precision agriculture purposes in wheat. Precision Agriculture, 15(1), 44-56. https://doi.org/10.1007/s11119-013-9335-4
14. Peet, M. M., & Welles, G. (2005). Greenhouse tomato production. In E. Heuvelink (Ed.), Tomatoes (pp. 257-304). CABI Publishing. https://doi.org/10.1079/9780851993966.0257
15. Åstrand, B., & Baerveldt, A. J. (2002). An agricultural mobile robot with vision-based perception for mechanical weed control. Autonomous Robots, 13(1), 21-35. https://doi.org/10.1023/a:1015674004201
16. Favati, F., Lovelli, S., Galgano, F., Miccolis, V., Di Tommaso, T., & Candido, V. (2009). Processing tomato quality as affected by irrigation scheduling. Scientia Horticulturae, 122(4), 562-571. https://doi.org/10.1016/j.scienta.2009.06.026
17. Aggelopoulou, K. D., Wulfsohn, D., Fountas, S., Gemtos, T. A., Nanos, G. D., & Blackmore, S. (2010). Spatial variation in yield and quality in a small apple orchard. Precision Agriculture, 11(5), 538-556. https://doi.org/10.1007/s11119-009-9146-9
18. Tey, Y. S., & Brindal, M. (2012). Factors influencing the adoption of precision agricultural technologies: A review for policy implications. Precision Agriculture, 13(6), 713-730. https://doi.org/10.1007/s11119-012-9273-6
19. Lowenberg-DeBoer, J. (2015). The precision agriculture revolution: Making the modern farmer. Foreign Affairs, 94(3), 105-112.
20. Castilla, N., & Baeza, E. (2013). Greenhouse site selection. In Good Agricultural Practices for Greenhouse Vegetable Crops (pp. 21-34). Food and Agriculture Organization of the United Nations.
21. Kumar, K. S., Tiwari, K. N., & Jha, M. K. (2009). Design and technology for greenhouse cooling in tropical and subtropical regions: A review. Energy and Buildings, 41(12), 1269-1275. https://doi.org/10.1016/j.enbuild.2009.08.003
22. Vadiee, A., & Martin, V. (2012). Energy management in horticultural applications through the closed greenhouse concept, state of the art. Renewable and Sustainable Energy Reviews, 16(7), 5087-5100. https://doi.org/10.1016/j.rser.2012.04.022

23. Lamont, W. J. (2009). Overview of the use of high tunnels worldwide. HortTechnology, 19(1), 25-29. https://doi.org/10.21273/hortsci.19.1.25
24. Lobos, G. A., Retamales, J. B., Hancock, J. F., Flore, J. A., Romero-Bravo, S., & del Pozo, A. (2013). Productivity and fruit quality of Vaccinium corymbosum cv. Elliott under photo-selective shading nets. Scientia Horticulturae, 153, 143-149. https://doi.org/10.1016/j.scienta.2013.02.012
25. Jiang, W. J., Qu, D. Y., Mu, D., & Wang, L. R. (2004). Protected cultivation of horticultural crops in China. Horticultural Reviews, 30, 115-162.
26. Dorais, M. (2003). The use of supplemental lighting for vegetable crop production: Light intensity, crop response, nutrition, crop management, cultural practices. Canadian Greenhouse Conference, 1-8.
27. Tisserat, B., & Vaughn, S. F. (2008). Growth, morphogenesis, and essential oil production in Mentha spicata L. plantlets in vitro influenced by carbon dioxide enrichment and medium sucrose levels. In Vitro Cellular & Developmental Biology - Plant, 44(1), 8-18. https://doi.org/10.1007/s11627-007-9081-2
28. Savvas, D., & Passam, H. (2002). Hydroponic production of vegetables and ornamentals. Embryo Publications.
29. Jensen, M. H. (1999). Hydroponics worldwide. Acta Horticulturae, 481, 719-730. https://doi.org/10.17660/actahortic.1999.481.87
30. Lakhiar, I. A., Gao, J., Syed, T. N., Chandio, F. A., & Buttar, N. A. (2018). Modern plant cultivation technologies in agriculture under controlled environment: A review on aeroponics. Journal of Plant Interactions, 13(1), 338-352. https://doi.org/10.1080/17429145.2018.1472308
31. Bar-Yosef, B. (1999). Advances in fertigation. Advances in Agronomy, 65, 1-77. https://doi.org/10.1016/s0065-2113(08)60910-4
32. Gruda, N. (2005). Impact of environmental factors on product quality of greenhouse vegetables for fresh consumption. Critical Reviews in Plant Sciences, 24(3), 227-247. https://doi.org/10.1080/07352680591008628
33. Rowley, D., Black, B. L., Drost, D., & Feuz, D. (2011). Late-season strawberry production using day-neutral cultivars in high-elevation high tunnels. HortScience, 46(11), 1480-1485. https://doi.org/10.21273/hortsci.46.11.1480
34. Manrique, L. A. (1993). Greenhouse crops: A review. Journal of Plant Nutrition, 16(12), 2411-2477. https://doi.org/10.1080/01904169309364698
35. Peet, M. M., & Welles, G. (2005). Greenhouse tomato production. In E. Heuvelink (Ed.), Tomatoes (pp. 257-304). CABI Publishing. https://doi.org/10.1079/9780851993966.0257
36. Bot, G., van de Braak, N., Challa, H., & Hemming, S. (2005). Greenhouse design and control. In E. Heuvelink (Ed.), Tomatoes (pp. 171-216). CABI Publishing. https://doi.org/10.1079/9780851993966.0171
37. Castilla, N., & Hernandez, J. (2005). The plastic greenhouse industry of Spain. Chronica Horticulturae, 45(3), 15-20.
38. Hassanien, R. H. E., Li, M., & Dong Lin, W. (2016). Advanced applications of solar energy in agricultural greenhouses. Renewable and Sustainable Energy Reviews, 54, 989-1001. https://doi.org/10.1016/j.rser.2015.10.095
39. Slaughter, D. C., Giles, D. K., & Downey, D. (2008). Autonomous robotic weed control systems: A review. Computers and Electronics in Agriculture, 61(1), 63-78. https://doi.org/10.1016/j.compag.2007.05.008
40. Bechar, A., & Vigneault, C. (2016). Agricultural robots for field operations: Concepts and components. Biosystems Engineering, 149, 94-111. https://doi.org/10.1016/j.biosystemseng.2016.06.014
41. Pérez-Ruiz, M., Gonzalez-de-Santos, P., Ribeiro, A., Fernandez-Quintanilla, C., Peruzzi, A., Vieri, M., Tomic, S., & Agüera, J. (2015). Highlights and preliminary results for autonomous crop protection. Computers and Electronics in Agriculture, 110, 150-161. https://doi.org/10.1016/j.compag.2014.11.010
42. Li, Z., Wang, N., Franzen, A., Taher, P., Godsey, C., Zhang, H., & Li, X. (2014). Practical deployment of an in-field soil property wireless sensor network. Computer Standards & Interfaces, 36(2), 278-287. https://doi.org/10.1016/j.csi.2011.05.005

43. Mahlein, A. K. (2016). Plant disease detection by imaging sensors - Parallels and specific demands for precision agriculture and plant phenotyping. Plant Disease, 100(2), 241-251. https://doi.org/10.1094/pdis-03-15-0340-fe
44. Singh, A., Ganapathysubramanian, B., Singh, A. K., & Sarkar, S. (2016). Machine learning for high-throughput stress phenotyping in plants. Trends in Plant Science, 21(2), 110-124. https://doi.org/10.1016/j.tplants.2015.10.015
45. Lee, W. S., Alchanatis, V., Yang, C., Hirafuji, M., Moshou, D., & Li, C. (2010). Sensing technologies for precision specialty crop production. Computers and Electronics in Agriculture, 74(1), 2-33. https://doi.org/10.1016/j.compag.2010.08.005
46. Zahid, A., Mahmud, M. S., Hasan, M. M., Bennoun, I., Jonckheere, J., Verboven, P., Nicolai, B., & Khojastehnazhand, M. (2022). Robotic pruners in fruit cultivation: A comprehensive review. Computers and Electronics in Agriculture, 192, 106604. https://doi.org/10.1016/j.compag.2021.106604
47. Zahid, A., Mahmud, M. S., Hasan, M. M., Rahman, H., Cho, S. W., & Aziz, F. A. (2021). Robotic pruning of fruit trees for yield enhancement. Computers and Electronics in Agriculture, 185, 106131. https://doi.org/10.1016/j.compag.2021.106131
48. van Henten, E. J., Hemming, J., van Tuijl, B. A. J., Kornet, J. G., Meuleman, J., Bontsema, J., & van Os, E. A. (2002). An autonomous robot for harvesting cucumbers in greenhouses. Autonomous Robots, 13(3), 241-258. https://doi.org/10.1023/a:1020568125418
49. Bac, C. W., van Henten, E. J., Hemming, J., & Edan, Y. (2014). Harvesting robots for high-value crops: State-of-the-art review and challenges ahead. Journal of Field Robotics, 31(6), 888-911. https://doi.org/10.1002/rob.21525
50. De-An, Z., Jidong, L., Wei, J., Ying, Z., & Yu, C. (2011). Design and control of an apple harvesting robot. Biosystems Engineering, 110(2), 112-122. https://doi.org/10.1016/j.biosystemseng.2011.07.005
51. Hayashi, S., Ganno, K., Ishii, Y., & Tanaka, I. (2002). Robotic harvesting system for eggplants. Japan Agricultural Research Quarterly: JARQ, 36(3), 163-168. https://doi.org/10.6090/jarq.36.163
52. Cubero, S., Aleixos, N., Moltó, E., Gómez-Sanchis, J., & Blasco, J. (2011). Advances in machine vision applications for automatic inspection and quality evaluation of fruits and vegetables. Food and Bioprocess Technology, 4(4), 487-504. https://doi.org/10.1007/s11947-010-0411-8
53. Patel, K. K., Kar, A., Jha, S. N., & Khan, M. A. (2012). Machine vision system: A tool for quality inspection of food and agricultural products. Journal of Food Science and Technology, 49(2), 123-141. https://doi.org/10.1007/s13197-011-0321-4
54. Zhang, B., Huang, W., Li, J., Zhao, C., Fan, S., Wu, J., & Liu, C. (2014). Principles, developments and applications of computer vision for external quality inspection of fruits and vegetables: A review. Food Research International, 62, 326-343. https://doi.org/10.1016/j.foodres.2014.03.012
55. Edan, Y., Han, S., & Kondo, N. (2009). Automation in agriculture. In S. Y. Nof (Ed.), Springer Handbook of Automation (pp. 1095-1128). Springer. https://doi.org/10.1007/978-3-540-78831-7_63
56. Bechar, A., & Edan, Y. (2003). Human-robot collaboration for improved target recognition of agricultural robots. Industrial Robot: An International Journal, 30(5), 432-436. https://doi.org/10.1108/01439910310492194
57. Dario, P., Sandini, G., Allotta, B., Bucci, A., Buemi, F., Massa, M., Ferrari, F., Magrassi, M., Bosio, L., Valleggi, R., Gallo, E., Bologna, A., Cantatore, F., Torrielli, G., & Mannucci, A. (1993). The Agrobot project for greenhouse automation. Acta Horticulturae, 361, 85-92. https://doi.org/10.17660/actahortic.1994.361.9
58. Blackmore, B. S., Stout, B. A., Wang, M., & Runov, B. (2005). Robotic agriculture - The future of agricultural mechanisation? In J. V. Stafford (Ed.), Precision Agriculture '05 (pp. 621-628). Wageningen Academic Publishers. https://doi.org/10.3920/978-90-8686-549-9
59. Duckett, T., Pearson, S., Blackmore, S., Grieve, B., Chen, W. H., Cielniak, G., Cleaversmith, J., Dai, J., Davis, S., Fox, C., From, P., Georgilas, I., Gill, R., Gould, I., Hanheide, M., Hunter,

A., Iida, F., Mihalyova, L., Nefti-Meziani, S., . . . Wilson, P. (2018). Agricultural robotics: The future of robotic agriculture. arXiv. https://arxiv.org/abs/1806.06762

60. Kader, A. A. (2005). Increasing food availability by reducing postharvest losses of fresh produce. Acta Horticulturae, 682, 2169-2176. https://doi.org/10.17660/actahortic.2005.682.296
61. Mahajan, P. V., Caleb, O. J., Singh, Z., Watkins, C. B., & Geyer, M. (2014). Postharvest treatments of fresh produce. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 372(2017), 20130309. https://doi.org/10.1098/rsta.2013.0309
62. Thompson, J. F., Mitchell, F. G., Rumsey, T. R., Kasmire, R. F., & Crisosto, C. H. (2008). Commercial cooling of fruits, vegetables, and flowers (Revised ed.). University of California Agriculture and Natural Resources Publication 21567.
63. Mercier, S., Villeneuve, S., Mondor, M., & Uysal, I. (2017). Time-temperature management along the food cold chain: A review of recent developments. Comprehensive Reviews in Food Science and Food Safety, 16(4), 647-667. https://doi.org/10.1111/1541-4337.12269
64. Jedermann, R., Nicometo, M., Uysal, I., & Lang, W. (2014). Reducing food losses by intelligent food logistics. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 372(2017), 20130302. https://doi.org/10.1098/rsta.2013.0302
65. Sandhya. (2010). Modified atmosphere packaging of fresh produce: Current status and future needs. LWT - Food Science and Technology, 43(3), 381-392. https://doi.org/10.1016/j.lwt.2009.05.018
66. Kader, A. A., & Watkins, C. B. (2000). Modified atmosphere packaging - Toward 2000 and beyond. HortTechnology, 10(3), 483-486. https://doi.org/10.21273/horttech.10.3.483
67. Caleb, O. J., Mahajan, P. V., Al-Said, F. A. J., & Opara, U. L. (2013). Modified atmosphere packaging technology of fresh and fresh-cut produce and the microbial consequences - A review. Food and Bioprocess Technology, 6(2), 303-329. https://doi.org/10.1007/s11947-012-0932-4
68. Kader, A. A. (2003). A perspective on postharvest horticulture (1978-2003). HortScience, 38(5), 1004-1008. https://doi.org/10.21273/hortsci.38.5.1004
69. Watkins, C. B. (2006). The use of 1-methylcyclopropene (1-MCP) on fruits and vegetables. Biotechnology Advances, 24(4), 389-409. https://doi.org/10.1016/j.biotechadv.2006.01.005
70. Watkins, C. B., & Miller, W. B. (2005). 1-Methylcyclopropene (1-MCP) based technologies for storage and shelf life extension. Acta Horticulturae, 687, 201-208. https://doi.org/10.17660/actahortic.2005.687.25
71. East, A. R., Sabarez, H. T., Tanner, D. J., & Cleland, D. J. (2003). Validation of a model for predicting the optimum modified atmosphere for fresh produce in non-vented packages. Packaging Technology and Science, 16(4), 161-168. https://doi.org/10.1002/pts.628
72. Nicolaï, B. M., Beullens, K., Bobelyn, E., Peirs, A., Saeys, W., Theron, K. I., & Lammertyn, J. (2007). Nondestructive measurement of fruit and vegetable quality by means of NIR spectroscopy: A review. Postharvest Biology and Technology, 46(2), 99-118. https://doi.org/10.1016/j.postharvbio.2007.06.024
73. Lorente, D., Aleixos, N., Gómez-Sanchis, J., Cubero, S., García-Navarrete, O. L., & Blasco, J. (2012). Recent advances and applications of hyperspectral imaging for fruit and vegetable quality assessment. Food and Bioprocess Technology, 5(4), 1121-1142. https://doi.org/10.1007/s11947-011-0725-1
74. ElMasry, G., Wang, N., ElSayed, A., & Ngadi, M. (2007). Hyperspectral imaging for nondestructive determination of some quality attributes for strawberry. Journal of Food Engineering, 81(1), 98-107. https://doi.org/10.1016/j.jfoodeng.2006.10.016
75. Opara, U. L., & Pathare, P. B. (2014). Bruise damage measurement and analysis of fresh horticultural produce - A review. Postharvest Biology and Technology, 91, 9-24. https://doi.org/10.1016/j.postharvbio.2013.12.009
76. Liu, S., Lee, W., Gao, H., Tao, Y., Wen, Z., & Wang, Z. (2021). In-orchard citrus fruit counting and sizing using a low-cost dual-modal imaging framework with deep learning.

Computers and Electronics in Agriculture, 187, 106263. https://doi.org/10.1016/j.compag.2021.106263

77. Mditshwa, A., Magwaza, L. S., Tesfay, S. Z., & Mbili, N. (2017). Postharvest quality and composition of organically and conventionally produced fruits: A review. Scientia Horticulturae, 216, 148-159. https://doi.org/10.1016/j.scienta.2016.12.033
78. Ramos, P., Acquah, C., Twumasi, M. A., Alemawor, F., Oppong, C. P., & Onwona-Agyeman, S. (2018). Reduction of postharvest losses in Ghanaian tomatoes for urban markets under the green cooling project. Journal of Food Distribution Research, 49(1), 134-134. https://doi.org/10.22004/ag.econ.274611
79. Kitinoja, L., Saran, S., Roy, S. K., & Kader, A. A. (2011). Postharvest technology for developing countries: Challenges and opportunities in research, outreach and advocacy. Journal of the Science of Food and Agriculture, 91(4), 597-603. https://doi.org/10.1002/jsfa.4295
80. Simonyan, K. J., & El-Mashad, H. M. (2013). Postharvest technologies for fruits and vegetables in developing countries: A review. Journal of Agricultural Engineering, 44(3), 1-14. https://doi.org/10.4081/jae.2013.301
81. Schaart, J. G., van de Wiel, C. C., Lotz, L. A., & Smulders, M. J. (2016). Opportunities for products of new plant breeding techniques. Trends in Plant Science, 21(5), 438-449. https://doi.org/10.1016/j.tplants.2015.11.006
82. Gaj, T., Gersbach, C. A., & Barbas, C. F. (2013). ZFN, TALEN, and CRISPR/Cas-based methods for genome engineering. Trends in Biotechnology, 31(7), 397-405. https://doi.org/10.1016/j.tibtech.2013.04.004
83. Fraceto, L. F., Grillo, R., de Medeiros, G. A., Scognamiglio, V., Rea, G., & Bartolucci, C. (2016). Nanotechnology in agriculture: Which innovation potential does it have? Frontiers in Environmental Science, 4, 20. https://doi.org/10.3389/fenvs.2016.00020
84. Khot, L. R., Sankaran, S., Maja, J. M., Ehsani, R., & Schuster, E. W. (2012). Applications of nanomaterials in agricultural production and crop protection: A review. Crop Protection, 35, 64-70. https://doi.org/10.1016/j.cropro.2012.01.007
85. Dasgupta, N., Ranjan, S., Mundekkad, D., Ramalingam, C., Shanker, R., & Kumar, A. (2015). Nanotechnology in agro-food: From field to plate. Food Research International, 69, 381-400. https://doi.org/10.1016/j.foodres.2015.01.005
86. Liakos, K. G., Busato, P., Moshou, D., Pearson, S., & Bochtis, D. (2018). Machine learning in agriculture: A review. Sensors, 18(8), 2674. https://doi.org/10.3390/s18082674
87. Majeed, Y., Zhang, J., Zhang, X., Fu, L., Karkee, M., Zhang, Q., & Whiting, M. D. (2020). Deep learning based fruit count and orchard fruit load estimation. Computers and Electronics in Agriculture, 180, 105909. https://doi.org/10.1016/j.compag.2020.105909
88. Ferentinos, K. P. (2018). Deep learning models for plant disease detection and diagnosis. Computers and Electronics in Agriculture, 145, 311-318. https://doi.org/10.1016/j.compag.2018.01.009
89. Lowenberg-DeBoer, J., & Erickson, B. (2019). Setting the record straight on precision agriculture adoption. Agronomy Journal, 111(4), 1552-1569. https://doi.org/10.2134/agronj2018.12.0779
90. Wegner, M., Elmer, M., Kockler, H., Kuhlmann, B., & Schimming, T. (2015). Risk management to ensure the safety of nanoparticles in food, cosmetics and consumer products. In H. Krug (Ed.), Nanotechnology: Principles and Applications (pp. 331-364). Springer. https://doi.org/10.1007/978-3-319-14966-7_13
91. Bronson, K., & Knezevic, I. (2016). Big data in food and agriculture. Big Data & Society, 3(1), 1-5. https://doi.org/10.1177/2053951716648174
92. Pavón-Pulido, N., López-Riquelme, J. A., Torres, R., Morais, R., & Pastor, J. (2017). New trends in precision agriculture: A novel cloud-based system for enabling data storage and agricultural task planning and automation. Precision Agriculture, 18(6), 1038-1068. https://doi.org/10.1007/s11119-017-9532-7
93. Rose, D. C., Sutherland, W. J., Barnes, A. P., Borthwick, F., Ffoulkes, C., Hall, C., Moorby, J. M., Nicholas-Davies, P., Twining, S., & Dicks, L. V. (2019). Integrated farm management for

sustainable agriculture: Lessons for knowledge exchange and policy. Land Use Policy, 81, 834-842. https://doi.org/10.1016/j.landusepol.2018.11.001

94. Bacco, M., Berton, A., Ferro, E., Gennaro, C., Gotta, A., Matteoli, S., Paonessa, F., Ruggeri, M., Virone, G., & Zanella, A. (2018). Smart farming: Opportunities, challenges and technology enablers. In 2018 IoT Vertical and Topical Summit on Agriculture-Tuscany (IOT Tuscany) (pp. 1-6). IEEE. https://doi.org/10.1109/iot-tuscany.2018.8373043

CHAPTER - 3

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Automation and Robotics in Horticultural Operations

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Abstract

Automation and robotics are playing an increasingly important role in modernizing horticultural operations around the world. Labor shortages, rising costs, and the need for greater efficiency and precision are driving the adoption of automated systems and robotics in tasks such as planting, crop monitoring, harvesting, sorting, and packaging of fruits, vegetables, and ornamental plants. This chapter provides an in-depth look at the current state of automation and robotics in horticulture. It covers the key technologies being utilized, including machine vision, sensors, robotic manipulators, autonomous vehicles, and artificial intelligence. The benefits and challenges of implementing these systems are discussed, such as improved productivity and quality, reduced labor requirements, high upfront costs, and the need for specialized expertise. An overview of commercially available solutions and research prototypes is provided, covering applications in both indoor and outdoor environments, from greenhouses and vertical farms to orchards and fields. The chapter also explores the socio-economic implications of automation, its impact on the agricultural workforce, and the importance of engaging and upskilling workers to successfully integrate these technologies. Finally, future directions are considered, including the need for improved interoperability and standardization, ongoing research to enhance the adaptability and robustness of robotic systems in complex horticultural environments, and the potential for increased collaboration between industry, academia, and government to accelerate innovation and adoption. As the horticulture industry continues to evolve, automation and robotics will play a vital role in ensuring its sustainability and meeting the

growing global demand for high-quality, safe, and affordable horticultural products.

Keywords: Automation, Robotics, Horticulture, Precision Agriculture, Agricultural Technology

Horticulture, the branch of agriculture focused on the cultivation of fruits, vegetables, flowers, and ornamental plants, plays a vital role in providing nutritious food, supporting rural livelihoods, and contributing to the global economy [1]. However, the industry faces numerous challenges, including labor shortages, rising production costs, increasing demand for sustainable practices, and the need to adapt to climate change [2]. Automation and robotics offer potential solutions to these challenges by enhancing productivity, reducing labor requirements, improving product quality and consistency, and enabling more precise and efficient use of resources [3].

The application of automation and robotics in horticulture has been gaining momentum in recent years, driven by advancements in sensor technologies, machine vision, artificial intelligence, and robotic manipulators [4]. These technologies are being deployed across various horticultural operations, from planting and crop monitoring to harvesting and post-harvest handling [5]. While the adoption of these systems is still in its early stages, they hold immense potential to transform the horticulture industry and address the pressing challenges it faces.

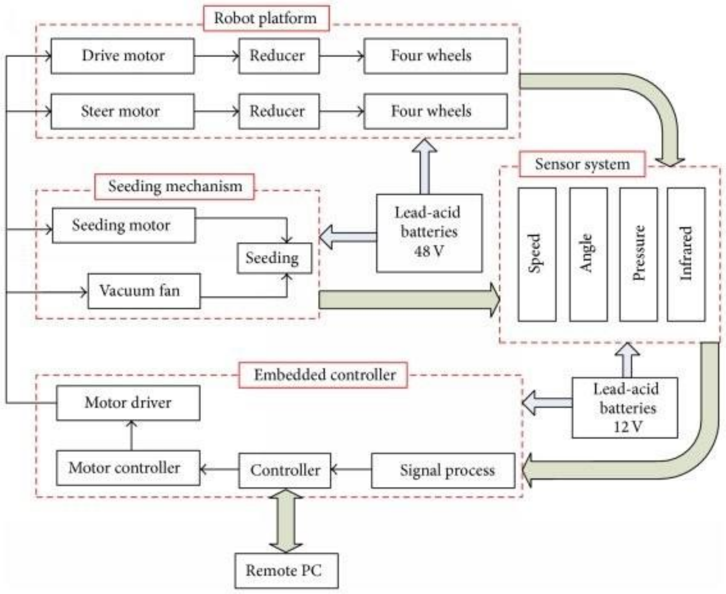

Figure 1. Schematic representation of a robotic system for horticultural operations

This chapter provides a comprehensive overview of the current state of automation and robotics in horticultural operations. It begins by discussing the key drivers and challenges for automation in horticulture, followed by a detailed examination of the technologies being utilized. The chapter then explores the various applications of automation and robotics in indoor and outdoor horticultural environments, including greenhouses, vertical farms, orchards, and open fields. It also delves into the socio-economic implications of these technologies, their impact on the agricultural workforce, and strategies for successful integration. Finally, the chapter concludes by considering future directions and the potential for automation and robotics to revolutionize the horticulture industry.

Table 1. Key drivers for the adoption of automation and robotics in horticulture

Driver	Description
Labor shortages	Difficulty in attracting and retaining skilled workers
Rising labor costs	Increasing wages and production costs
Need for precision	Demand for accurate and targeted crop management
Efficiency improvements	Potential to optimize resource use and reduce waste
Market demands	Growing consumer expectations for quality and consistency
Sustainability pressures	Need to reduce environmental impacts and improve resilience

Table 2. Main challenges and barriers to the adoption of automation and robotics in horticulture

Challenge/Barrier	Description
High upfront costs	Significant initial investments in hardware, software, and infrastructure
Technical complexity	Need for specialized expertise and skills to operate and maintain systems
Variable environments	Difficulty in adapting to complex and dynamic horticultural settings
Lack of standardization	Limited interoperability and compatibility between different systems
Workforce displacement	Potential for job losses and need for retraining and upskilling
Socio-economic impacts	Concerns about the distribution of benefits and impacts on communities

2. Drivers and Challenges for Automation in Horticulture

2.1 Labor Shortages and Rising Costs

One of the primary drivers for the adoption of automation and robotics in horticulture is the growing shortage of agricultural labor and the associated increase in labor costs [6]. Many horticultural operations, particularly in developed countries, face difficulties in attracting and retaining skilled workers due to factors such as an aging workforce, urbanization, and changing career preferences among younger generations [7]. This labor shortage leads to higher wages and increased production costs, which can erode the profitability and competitiveness of horticultural businesses.

Automation and robotics offer a potential solution to this challenge by reducing the need for manual labor in tasks such as planting, crop monitoring, harvesting, and post-harvest handling [8]. By replacing or augmenting human workers with automated systems and robots, horticultural operations can maintain or increase their productivity while controlling labor costs. This is particularly relevant for labor-intensive tasks such as fruit and vegetable harvesting, which can account for a significant portion of production costs [9].

2.2 Need for Precision and Efficiency

Another key driver for automation in horticulture is the need for greater precision and efficiency in horticultural operations. Precision agriculture, which involves the use of advanced technologies to optimize crop management based on spatial and temporal variability, has gained increasing attention in recent years [10]. Automation and robotics play a crucial role in enabling precision agriculture by providing the tools and systems necessary for accurate data collection, analysis, and targeted interventions.

Table 3. Key technologies enabling automation and robotics in horticulture

Technology	**Description**
Machine vision	Cameras, sensors, and algorithms for visual data capture and analysis
Sensors and IoT	Devices for measuring and monitoring plant, soil, and environmental parameters
Robotic manipulators	Mechanical arms and end-effectors for handling and manipulating plants and products
Autonomous vehicles	Self-guided ground and aerial vehicles for crop scouting, spraying, and transport
Artificial intelligence	Machine learning and data analytics for decision support and optimization

Table 4. Examples of commercially available automation and robotics solutions for horticulture

Company	**Product**	**Application**
Harvest Automation	HV-100	Potted plant spacing and consolidation
Abundant Robotics	Apple harvester	Autonomous apple harvesting
Blue River Technology	See & Spray	Precision weed control in vegetable crops
Ecorobotix	AVO	Autonomous weeding robot for vegetable crops
Root AI	Virgo	Tomato harvesting robot

For example, automated sensing systems using machine vision and other sensors can continuously monitor crop growth, health, and environmental conditions, providing growers with real-time information to make informed decisions [11]. Robotic systems can perform precise and targeted operations, such as selective harvesting, pruning, and spraying, which can improve crop quality, reduce waste, and minimize the use of inputs such as water, fertilizers, and pesticides [12]. By enhancing precision and efficiency, automation and robotics can help horticultural operations optimize resource use, reduce environmental impacts, and improve overall sustainability.

2.3 Market Demand and Quality Standards

The increasing market demand for high-quality, safe, and consistently available horticultural products is another factor driving the adoption of automation and robotics. Consumers, particularly in developed countries, are becoming more discerning and demanding in their food choices, with a growing emphasis on factors such as freshness, taste, appearance, and nutritional value [13]. Meeting these evolving consumer expectations requires horticultural operations to maintain strict quality control and ensure consistent product quality throughout the supply chain.

Automation and robotics can help horticultural businesses meet these demands by enabling more precise and consistent production and post-harvest handling processes. For instance, automated grading and sorting systems using machine vision can rapidly and accurately assess the quality of fruits and vegetables based on factors such as size, color, and defects, ensuring that only products meeting the desired standards reach the market [14]. Robotic packaging systems can ensure consistent packaging quality and reduce the risk of damage during handling and transportation [15]. By enhancing quality control and consistency, automation and robotics can help horticultural businesses maintain their competitiveness and meet the evolving expectations of consumers.

2.4 Challenges and Barriers to Adoption

Despite the numerous potential benefits, the adoption of automation and robotics in horticulture faces several challenges and barriers. One of the main challenges is the high upfront costs associated with implementing these technologies [16]. Automated systems and robots often require significant initial investments in hardware, software, and infrastructure, which can be a barrier for small and medium-sized horticultural businesses with limited financial resources.

Table 5. Research prototypes and experimental systems for horticultural automation and robotics

Institution	System	Application
University of Florida	Strawberry harvester	Autonomous strawberry harvesting
Wageningen University	Sweet pepper harvester	Robotic sweet pepper harvesting
Carnegie Mellon University	Comprehensive Automation for Specialty Crops (CASC)	Multipurpose robotic platform for specialty crops
University of California, Davis	Robotic Strawberry Harvester	Selective strawberry harvesting
Massachusetts Institute of Technology	Soft Robotic Gripper	Gentle handling of delicate crops

Table 6. Potential socio-economic impacts of automation and robotics in horticulture

Impact	Description
Labor displacement	Reduced need for manual labor in tasks such as harvesting and weeding
Skill shift	Increased demand for workers with technical and digital skills
Rural development	Potential for improved productivity and competitiveness of horticultural businesses
Technology access	Risk of unequal access and adoption of automation and robotics technologies
Data ownership	Concerns about the control and use of data generated by automated systems
Ethical considerations	Need for responsible innovation and stakeholder engagement in technology development and deployment

Another challenge is the need for specialized expertise and skills to operate and maintain these systems. Horticultural workers may require training and upskilling to effectively work alongside automated systems and robots, and businesses may need to hire experts in robotics, computer science, and data analytics to support the implementation and ongoing operation of these technologies [17]. This can be particularly challenging in rural areas where access to skilled labor and training opportunities may be limited.

The complexity and variability of horticultural environments also pose challenges for the development and deployment of automation and robotics. Unlike industrial settings with highly structured and predictable environments, horticultural operations often involve dealing with delicate, irregularly shaped, and variable plants and products in dynamic and unstructured environments [18]. This requires the development of advanced sensing, perception, and manipulation capabilities to enable robots to operate effectively in these challenging conditions.

Furthermore, there are concerns about the potential socio-economic impacts of automation, particularly in terms of job displacement and the need to ensure an equitable distribution of the benefits [19]. Addressing these challenges requires ongoing research and development efforts, collaboration between industry, academia, and government, and proactive strategies to support the workforce and communities affected by the adoption of these technologies.

3. Key Technologies for Automation and Robotics in Horticulture

3.1 Machine Vision and Imaging

Machine vision and imaging technologies play a critical role in enabling automation and robotics in horticulture. These technologies involve the use of cameras, sensors, and computer algorithms to capture, process, and analyze visual data from the horticultural environment [20]. Machine vision systems can be used for a wide range of applications, including crop monitoring, yield estimation, quality assessment, and robotic guidance and manipulation.

Table 7. Strategies for workforce engagement and upskilling in the context of horticultural automation and robotics

Strategy	Description
Collaborative design	Involving workers in the development and implementation of automated systems
Training and education	Providing opportunities for workers to acquire new skills and knowledge
Job redesign	Adapting job roles and responsibilities to complement automated systems
Transition support	Offering assistance and resources for workers displaced by automation
Inclusive innovation	Ensuring diverse stakeholder participation in technology development and governance

Table 8. Policy and regulatory considerations for the responsible adoption of automation and robotics in horticulture

Consideration	Description
Safety and performance standards	Establishing guidelines for the safe and effective operation of automated systems
Data governance	Developing frameworks for the responsible collection, sharing, and use of data
Intellectual property	Clarifying ownership and access rights to technologies and data
Liability and insurance	Determining responsibility and coverage for accidents and failures involving automated systems
Labor and social policies	Adapting regulations and support programs to address the impacts of automation on workers and communities

Table 9. Potential environmental benefits and risks of automation and robotics in horticulture

Benefit/Risk	Description
Resource efficiency	Optimizing the use of water, nutrients, and other inputs through precision management
Reduced chemical use	Minimizing the application of pesticides and herbicides through targeted interventions
Soil health	Promoting soil conservation through reduced compaction and traffic
Biodiversity	Enabling more diverse and resilient cropping systems through precision management
Energy consumption	Increased energy use associated with the operation of automated systems
Electronic waste	Generation of waste from the disposal of sensors, batteries, and other components

One of the key advantages of machine vision is its ability to provide non-destructive, rapid, and objective measurements of plant traits and conditions. For example, color imaging can be used to assess the ripeness and quality of fruits and vegetables based on their color and appearance [21]. Multispectral and hyperspectral imaging can capture information beyond the visible spectrum, enabling the detection of plant stress, disease, and nutrient deficiencies [22]. 3D imaging techniques, such as stereo vision and structured light, can be used to reconstruct the 3D structure of plants and guide robotic manipulators for tasks such as harvesting and pruning [23].

Machine learning and deep learning algorithms are increasingly being used to analyze the vast amounts of visual data generated by machine vision systems. These algorithms can be trained to automatically detect and classify plant features, such as leaves, flowers, and fruits, and to identify patterns and anomalies that may indicate plant health issues or other problems [24]. By combining machine vision with advanced data analytics, horticultural operations can gain valuable insights into crop performance and make data-driven decisions to optimize production and quality.

Table 10. Examples of public-private partnerships supporting the development and adoption of horticultural automation and robotics

Partnership	Description
USDA-NIFA Specialty Crop Research Initiative	Funding for collaborative research and development projects in specialty crops
European Innovation Partnership for Agricultural Productivity and Sustainability	Fostering cooperation and innovation in the agricultural sector
Australian Centre for Field Robotics	Collaboration between industry, government, and academia to advance field robotics
Japan Science and Technology Agency	Support for research and development in advanced agricultural technologies
UK Agri-Tech Centres	Network of innovation centers focused on precision agriculture, crop health, and agri-engineering

In addition to machine vision, a wide range of sensors and Internet of Things (IoT) technologies are being used to support automation and robotics in horticulture. These sensors can measure various environmental and plant parameters, such as temperature, humidity, light levels, soil moisture, and nutrient content, providing real-time data on growing conditions and plant health [25].

Wireless sensor networks and IoT platforms enable the integration and remote monitoring of these sensors, allowing growers to access and analyze data from anywhere at any time [26]. This can help in optimizing irrigation, fertilization, and climate control strategies, reducing water and input use, and improving overall crop management. Sensors can also be integrated into robotic systems to enable adaptive and responsive behaviors, such as adjusting the speed or force of robotic manipulators based on the sensed properties of the plants or products being handled [27].

Table 11. Key performance indicators for evaluating the impact and effectiveness of horticultural automation and robotics

Indicator	Description
Labor productivity	Output per unit of labor input
Crop yield	Quantity of marketable produce per unit area
Product quality	Consistency and uniformity of harvested products
Resource use efficiency	Ratio of inputs (water, nutrients, energy) to outputs
Operational costs	Expenses associated with the deployment and maintenance of automated systems
Technology adoption rate	Percentage of growers using automation and robotics technologies

3.2 Sensors and IoT

3.3 Robotic Manipulators and End-effectors

Robotic manipulators and end-effectors are essential components of automated systems for tasks such as harvesting, pruning, and handling of horticultural products. These robots are designed to mimic human hand movements and can be equipped with various tools and attachments to perform specific tasks [28].

The design of robotic manipulators for horticulture requires consideration of factors such as the delicacy of the plants and products being handled, the need for speed and efficiency, and the variability and unpredictability of the environment. Soft robotic grippers and compliant mechanisms are being developed to enable gentle and adaptive handling of delicate plant materials [29]. Novel end-effector designs, such as suction cups, pneumatic fingers, and micro-grippers, are being explored to enable the manipulation of small, irregularly shaped, and delicate objects, such as flowers and berries [30].

In addition to hardware design, the control and coordination of robotic manipulators in horticultural environments require advanced planning, sensing, and decision-making capabilities. Techniques such as motion planning, force control, and haptic feedback are being used to enable robots to navigate complex environments, avoid obstacles, and interact with plants and products in a safe and efficient manner [31].

3.4 Autonomous Vehicles and Drones

Autonomous vehicles and drones are finding increasing applications in horticulture, particularly for tasks such as crop scouting, spraying, and transport.

Autonomous ground vehicles, such as tractors and robotic platforms, can be equipped with sensors and implements to perform tasks such as soil preparation, planting, and harvesting [32]. These vehicles can operate continuously, reducing the need for human labor and enabling round-the-clock operations.

Unmanned aerial vehicles (UAVs) or drones equipped with cameras and sensors are being used for remote sensing and precision agriculture applications. They can cover large areas quickly and provide high-resolution imagery and data on crop health, growth, and yield [33]. This information can be used to guide targeted interventions, such as variable rate application of fertilizers and pesticides, and to optimize resource use.

The development of autonomous vehicles for horticulture requires addressing challenges such as navigation in unstructured environments, obstacle avoidance, and safe interaction with human workers. Advanced perception systems, such as lidar and radar, are being used to enable vehicles to detect and respond to their surroundings in real-time [34]. Machine learning algorithms are being developed to enable vehicles to adapt to changing conditions and make intelligent decisions based on the data they collect [35].

3.5 Artificial Intelligence and Big Data

Artificial intelligence (AI) and big data analytics are playing an increasingly important role in enabling automation and robotics in horticulture. AI techniques, such as machine learning, deep learning, and computer vision, are being used to analyze the vast amounts of data generated by sensors, cameras, and other sources to extract meaningful insights and support decision making [36].

Table 12. Challenges and opportunities for automation and robotics in different horticultural sectors

Sector	Challenges	Opportunities
Greenhouse production	Complex and variable plant architectures, limited space for maneuvering	Controlled environment, high-value crops, potential for vertical integration
Orchard crops	Large and irregularly shaped trees, uneven terrain, variable fruit ripeness	High labor demands, potential for yield and quality improvements
Vegetable crops	Delicate and perishable products, need for gentle handling, variable field conditions	Labor-intensive tasks, potential for precision management and reduced chemical use
Ornamental plants	Wide variety of plant species and growth habits, aesthetic quality requirements	High value products, potential for automation in propagation and logistics

For example, AI algorithms can be trained to identify patterns and anomalies in plant growth and health data, enabling early detection and diagnosis of problems such as nutrient deficiencies, pests, and diseases [37]. They can also be used to optimize crop management strategies, such as irrigation and fertilization, based on real-time data and predictive models [38]. In robotic applications, AI can enable robots to learn from experience, adapt to new situations, and make autonomous decisions based on the data they collect [39].

Table 13. Training and educational programs for the horticultural workforce in the context of automation and robotics

Program	Institution	Description
Precision Agriculture Certificate	University of Nebraska-Lincoln	Online program covering the principles and technologies of precision agriculture
Robotics and Autonomous Systems	Harper Adams University	Undergraduate and postgraduate degrees in robotics and automation for agriculture
Smart Farming Master's Program	Wageningen University & Research	Interdisciplinary program focusing on the application of digital technologies in agriculture
Apprenticeship in Agricultural Technology	CLAAS	Hands-on training in the operation and maintenance of agricultural machinery and systems
Digital Agriculture Specialization	University of Illinois	Online courses covering the fundamentals of digital agriculture and precision farming

Table 14. International collaborations and initiatives supporting the development and adoption of horticultural automation and robotics

Initiative	Description
International Forum of Agricultural Robotics (FIRA)	Annual event bringing together stakeholders in agricultural robotics and automation
Global Initiative for Sustainable Agriculture (GiSA)	Multi-stakeholder platform promoting sustainable agricultural practices and technologies
International Society of Precision Agriculture (ISPA)	Professional association fostering the development and application of precision agriculture technologies
AgriFood Tech Collaboration Platform	European initiative supporting collaboration and innovation in the agrifood sector
ASEAN Sustainable Agriculture Research and Innovation Initiative	Regional program promoting sustainable agricultural practices and technologies in Southeast Asia

Table 15. Future research directions and priorities for horticultural automation and robotics

Research Area	Description
Adaptive and intelligent systems	Developing robotic systems that can learn and adapt to changing conditions and tasks
Collaborative and swarm robotics	Investigating the potential of multi-robot systems for coordinated and efficient operations
Soft robotics and bio-inspired design	Exploring new materials and designs for gentle and dexterous manipulation of delicate crops
Autonomous navigation and mapping	Improving the ability of robots to navigate and map complex horticultural environments
Human-robot interaction	Studying the social and ergonomic aspects of human-robot collaboration in horticultural settings
Sustainable energy sources	Developing energy-efficient and renewable power systems for autonomous vehicles and robots

Big data analytics tools and platforms are being used to process and visualize the large volumes of data generated by automated systems and sensors in horticulture. These tools can help growers identify trends, patterns, and correlations in the data, enabling them to make data-driven decisions and optimize their operations [40]. Cloud computing and edge computing technologies are being used to enable real-time processing and analysis of data, reducing latency and enabling faster response times [41].

The integration of AI and big data in horticulture requires addressing challenges such as data quality, interoperability, and security. Ensuring the accuracy, reliability, and consistency of data is essential for the effective use of AI and analytics [42]. Developing standards and protocols for data collection, storage, and exchange can help improve interoperability and enable seamless integration of data from various sources [43]. Implementing robust security measures, such as encryption and access control, is critical to protect sensitive data and prevent unauthorized access [44].

4. Applications of Automation and Robotics in Horticulture

4.1 Greenhouse and Indoor Farming

Greenhouses and indoor farming systems are ideal environments for the application of automation and robotics due to their controlled and structured nature. These systems can benefit from automated monitoring and control of environmental parameters, such as temperature, humidity, light, and CO2 levels, to optimize plant growth and quality [45]. Sensors and IoT technologies can be used to collect real-time data on these parameters, enabling growers to make data-driven decisions and respond quickly to any deviations from optimal conditions.

Robotic systems are being developed for various tasks in greenhouses and indoor farms, such as planting, transplanting, pruning, and harvesting. For example, robotic seeders and transplanters can precisely place seeds or seedlings in trays or beds, reducing labor requirements and ensuring uniform spacing [46]. Robotic pruning systems equipped with machine vision can identify and selectively remove leaves, shoots, or fruits based on their size, color, or other characteristics, improving plant health and yield [47]. Robotic harvesters can gently pick and sort delicate crops, such as tomatoes, peppers, and cucumbers, reducing damage and maintaining product quality [48].

In addition to these tasks, automation and robotics are being used for other aspects of greenhouse and indoor farming operations, such as material handling, packaging, and logistics. Automated conveyor systems and mobile robots can transport plants, materials, and products within the facility, reducing labor requirements and improving efficiency [49]. Robotic packaging systems can automatically sort, grade, and pack products, ensuring consistent quality and reducing the risk of damage during handling [50].

4.2 Vertical Farming

Vertical farming is an emerging form of indoor agriculture that involves growing crops in vertically stacked layers or shelves, often in controlled-environment buildings or containers. This approach enables the efficient use of space and resources, making it particularly suitable for urban and peri-urban areas where land is scarce and expensive [51]. Automation and robotics are essential components of vertical farming systems, enabling the precise control and optimization of growing conditions and the efficient use of labor and resources.

In vertical farms, automated systems are used to control and monitor environmental parameters, such as temperature, humidity, light, and nutrient levels, in each growing layer. Sensors and IoT technologies can provide real-time data on these parameters, enabling the system to make automatic adjustments to maintain optimal conditions for plant growth [52]. LED lighting systems with automated control can provide the optimal light spectrum and intensity for each crop and growth stage, improving energy efficiency and plant quality [53].

Robotic systems are being developed for various tasks in vertical farms, such as seeding, transplanting, harvesting, and cleaning. For example,robotic seeders and transplanters can precisely place seeds or seedlings in the growing media, reducing labor requirements and ensuring uniform spacing [54]. Robotic harvesters equipped with machine vision and gentle grippers can selectively pick and sort mature crops, such as leafy greens and herbs, maintaining product quality and reducing damage [55]. Robotic cleaning systems can automatically remove debris, sanitize growing surfaces, and maintain a hygienic environment, reducing the risk of disease and contamination [56].

Automation and robotics can also enable the implementation of advanced growing techniques in vertical farms, such as aeroponics and hydroponics. In aeroponic systems, plants are grown with their roots suspended in air and misted with a nutrient solution, while in hydroponic systems, plants are grown in a nutrient-rich water solution [57]. These techniques can be fully automated, with sensors and control systems maintaining optimal nutrient levels, pH, and water circulation, reducing the need for manual intervention and improving resource use efficiency [58].

4.3 Orchards and Vineyards

Orchards and vineyards are important sectors of the horticulture industry, producing a wide range of fruits, nuts, and grapes for fresh consumption and processing. These perennial cropping systems present unique challenges and opportunities for automation and robotics due to their large scale, complex canopy structures, and variable environmental conditions [59].

One of the main applications of automation in orchards and vineyards is precision irrigation and fertigation. Automated drip irrigation systems with sensors and control valves can precisely deliver water and nutrients to each plant based on its individual needs, reducing water and fertilizer use and improving crop quality [60]. Soil moisture sensors and weather stations can provide real-time data on soil and environmental conditions, enabling the system to make automatic adjustments to irrigation schedules based on plant water requirements and evapotranspiration rates [61].

Robotic systems are being developed for various tasks in orchards and vineyards, such as pruning, thinning, and harvesting. Robotic pruners equipped with machine vision and cutting tools can selectively remove branches and shoots based on their size, angle, and position, improving canopy structure and light penetration [62]. Robotic thinners can precisely remove excess fruits or flowers to optimize crop load and improve fruit size and quality [63]. Robotic harvesters with gentle grippers and advanced sensing capabilities can selectively pick mature fruits, such as apples, oranges, and grapes, reducing labor requirements and maintaining product quality [64].

Autonomous vehicles and drones are also finding applications in orchards and vineyards for tasks such as crop scouting, spraying, and mapping. Autonomous ground vehicles equipped with cameras and sensors can navigate between rows of trees or vines, collecting data on plant health, growth, and yield [65]. They can also be used for targeted spraying of pesticides and fertilizers, reducing chemical use and minimizing drift [66]. Drones equipped with high-resolution cameras and multispectral sensors can provide detailed maps of canopy vigor, disease incidence, and nutrient status, enabling precision management and early detection of problems [67].

4.4 Field Vegetables and Row Crops

Field vegetables and row crops, such as lettuce, carrots, potatoes, and onions, are important components of the horticulture industry, providing a wide range of fresh and processed products. These crops are typically grown on a large scale in open fields, presenting challenges for automation and robotics due to the variable and unstructured nature of the environment [68].

One of the main applications of automation in field vegetables and row crops is precision planting and seeding. Automated planters and seeders equipped with GPS and sensing technologies can precisely place seeds or seedlings at the optimal depth and spacing, reducing labor requirements and ensuring uniform crop establishment [69]. Variable rate planting systems can adjust the seeding rate based on soil properties and other factors, optimizing plant density and improving resource use efficiency [70].

Robotic systems are being developed for various tasks in field vegetables and row crops, such as weeding, thinning, and harvesting. Robotic weeders equipped with computer vision and mechanical or thermal tools can selectively remove weeds while leaving the crop plants unharmed, reducing the need for manual weeding and minimizing herbicide use [71]. Robotic thinners can precisely remove excess plants to achieve the desired spacing and optimize crop yield and quality [72]. Robotic harvesters with advanced sensing and manipulation capabilities can selectively harvest mature vegetables, such as lettuce, broccoli, and cauliflower, reducing labor requirements and maintaining product quality [73].

Autonomous vehicles and drones are also being used in field vegetables and row crops for tasks such as crop monitoring, scouting, and mapping. Autonomous ground vehicles equipped with sensors and imaging systems can collect data on plant health, growth, and yield, enabling precision management and early detection of problems [74]. Drones equipped with high-resolution cameras and multispectral sensors can provide detailed maps of crop vigor, stress, and nutrient status, enabling variable rate application of inputs and targeted interventions [75].

5. Socio-Economic Implications and Workforce Considerations

5.1 Impact on Labor and Employment

The adoption of automation and robotics in horticulture has significant implications for labor and employment in the industry. While these technologies have the potential to reduce labor requirements and improve productivity, they also raise concerns about job displacement and the need for new skills and training [76].

On one hand, automation and robotics can help address the challenges of labor shortages and rising labor costs in the horticulture industry. By replacing or augmenting human workers in tasks such as planting, harvesting, and handling, these technologies can reduce the need for manual labor and improve the efficiency and consistency of operations [77]. This can help horticulture businesses remain competitive and sustainable in the face of increasing global competition and market pressures.

On the other hand, the adoption of automation and robotics can lead to job losses and displacement, particularly for low-skilled and seasonal workers who perform manual tasks in the industry [78]. This can have significant social and economic impacts on rural communities and vulnerable populations who depend on horticulture for their livelihoods. Addressing these impacts requires proactive strategies and policies to support affected workers and communities, such as retraining programs, social safety nets, and alternative employment opportunities [79].

Furthermore, the adoption of automation and robotics in horticulture creates new skill requirements and job opportunities in areas such as robotics, data science, and precision agriculture. Workers will need to acquire new technical and digital skills to operate and maintain advanced technologies, and businesses will need to invest in training and upskilling programs to prepare their workforce for the future [80]. Collaborative efforts between industry, education, and government can help develop the talent pipeline and ensure that the benefits of automation are shared broadly across the workforce [81].

5.2 Socio-Economic Benefits and Challenges

The adoption of automation and robotics in horticulture presents both socio-economic benefits and challenges that need to be carefully considered and managed. On the positive side, these technologies can contribute to improved food security, sustainability, and rural development by increasing productivity, reducing waste, and enabling more efficient use of resources [82]. Automated systems and robots can help produce more food with less land, water, and inputs, reducing the environmental impact of horticulture and improving the resilience of food systems to climate change and other shocks [83].

Moreover, automation and robotics can improve the quality, safety, and traceability of horticultural products, benefiting both producers and consumers. Automated monitoring and control systems can ensure optimal growing conditions and reduce the risk of contamination and foodborne illnesses [84]. Robotic systems can handle products with greater care and consistency, reducing damage and extending shelf life [85]. Digital technologies, such as blockchain and IoT, can enable end-to-end traceability and transparency in the supply chain, improving food safety and consumer trust [86].

However, the adoption of automation and robotics in horticulture also presents socio-economic challenges that need to be addressed. One of the main challenges is the high upfront costs and investments required to implement these technologies, which can be a barrier for small and medium-sized producers who may lack access to capital and financing [87]. This can lead to a widening technology gap and unequal distribution of benefits, with larger and more well-resourced operations being able to adopt and benefit from these technologies more quickly [88].

Another challenge is the potential for automation and robotics to exacerbate existing inequalities and power imbalances in the horticulture industry. The concentration of ownership and control of these technologies in the hands of a few large corporations or investors can lead to greater market consolidation and reduced bargaining power for smaller producers and workers [89]. Ensuring that the benefits of automation are shared equitably and that the rights and interests of all stakeholders are protected will require inclusive governance mechanisms and policies that promote fair competition, transparency, and accountability [90].

5.3 Engaging and Upskilling the Workforce

Engaging and upskilling the workforce is critical for the successful adoption and integration of automation and robotics in horticulture. As these technologies transform the nature of work in the industry, it is important to involve workers in the process of technological change and provide them with the skills and support needed to adapt and thrive in the new environment [91].

One key strategy is to foster a culture of lifelong learning and continuous skill development in the horticulture workforce. This requires investing in education and training programs that enable workers to acquire the technical, digital, and soft skills needed to work with advanced technologies [92]. Collaborative partnerships between industry, education providers, and government can help develop targeted training programs that meet the evolving needs of the industry and provide workers with recognized credentials and career pathways [93].

Another important strategy is to promote participatory and inclusive approaches to technology adoption that engage workers in the design, implementation, and evaluation of new systems and processes. This can help ensure that the perspectives and needs of workers are taken into account and that the benefits of automation are shared fairly [94]. Involving workers in pilot projects, user testing, and feedback loops can help identify and address potential challenges and unintended consequences early on, improving the effectiveness and acceptability of new technologies [95].

Moreover, supporting the workforce through the transition to automation requires providing access to social protection, safety nets, and support services. This includes measures such as income support, retraining assistance, and job placement services for workers who may be displaced or need to transition to new roles [96]. It also involves ensuring that the working conditions and rights of workers who remain in the industry are protected and that they have access to fair wages, benefits, and social dialogue [97].

Finally, promoting diversity, equity, and inclusion in the horticulture workforce can help ensure that the benefits of automation are shared broadly and that the industry can tap into the full potential of its human capital. This involves addressing barriers to entry and advancement for underrepresented groups, such as women, youth, and minorities, and creating inclusive workplaces that value and respect diversity [98]. Investing in programs that promote STEM education, entrepreneurship, and leadership development for these groups can help build a more diverse and resilient workforce for the future [99].

6. Future Directions and Opportunities

6.1 Research and Development Priorities

Advancing automation and robotics in horticulture requires ongoing research and development efforts to address the technical, operational, and socio-economic challenges and opportunities presented by these technologies. Some key research and development priorities include:

1. Improving the adaptability and robustness of robotic systems to operate in complex and variable horticultural environments, such as open fields, orchards, and greenhouses [100].
2. Developing advanced sensing, perception, and manipulation capabilities to enable robots to handle delicate and variable plant materials with greater dexterity and efficiency [101].
3. Enhancing the interoperability and integration of different automation and robotic systems, as well as their compatibility with existing horticultural equipment and practices [102].
4. Optimizing the design and control of automated systems and robots for specific horticultural tasks and crops, taking into account factors such as plant physiology, growth stages, and quality requirements [103].
5. Developing new applications of automation and robotics in horticulture, such as precision pollination, pest and disease detection, and postharvest handling and processing [104].
6. Investigating the social, economic, and environmental impacts of automation and robotics in horticulture, and developing strategies and policies to ensure their responsible and equitable adoption [105].
7. Exploring the potential of emerging technologies, such as artificial intelligence, machine learning, and blockchain, to enhance the performance and impact of automation and robotics in horticulture [106].

Addressing these research and development priorities will require collaborative efforts between academia, industry, and government, as well as interdisciplinary approaches that bring together expertise from fields such as robotics, plant science, computer science, and social science [107].

6.2 Collaborative Ecosystems and Partnerships

Fostering collaborative ecosystems and partnerships is essential for accelerating the development and adoption of automation and robotics in horticulture. These collaborations can take many forms, such as:

1. Industry-academia partnerships that bring together the technical expertise of robotics and automation companies with the domain knowledge of horticultural researchers and practitioners to develop and test new technologies and applications [108].

2. Public-private partnerships that leverage the resources and capabilities of government agencies, research institutions, and private sector actors to support the development and deployment of automation and robotics in horticulture, such as through funding, infrastructure, and policy support [109].
3. International collaborations that enable the sharing of knowledge, best practices, and resources across different countries and regions to address common challenges and opportunities in horticultural automation and robotics [110].
4. Multi-stakeholder platforms and networks that bring together diverse actors, such as producers, workers, technology providers, investors, and civil society organizations, to engage in dialogue, coordination, and collective action around the responsible and inclusive adoption of automation and robotics in horticulture [111].

Strengthening these collaborative ecosystems and partnerships can help mobilize the necessary resources, expertise, and support to drive innovation, scale up solutions, and ensure that the benefits of automation and robotics are shared broadly across the horticulture value chain [112].

6.3 Policy and Regulatory Frameworks

Developing appropriate policy and regulatory frameworks is critical for creating an enabling environment for the responsible and sustainable adoption of automation and robotics in horticulture. Some key policy and regulatory considerations include:

1. Establishing safety and performance standards for automated systems and robots used in horticulture to ensure their reliability, efficiency, and compatibility with existing regulations and best practices [113].
2. Developing data governance and privacy frameworks to ensure the secure and ethical collection, sharing, and use of data generated by automated systems and robots in horticulture, and to protect the rights and interests of stakeholders [114].
3. Providing financial and technical support to small and medium-sized horticultural producers to enable them to adopt and benefit from automation and robotics, such as through grants, loans, tax incentives, and extension services [115].
4. Reforming education and training systems to provide workers with the skills and qualifications needed to work with advanced technologies in horticulture, and to promote lifelong learning and upskilling [116].
5. Strengthening social protection and labor market policies to support workers affected by automation and robotics in horticulture, such as through income support, retraining, and job placement services [117].
6. Promoting inclusive innovation and technology governance approaches that engage diverse stakeholders, including workers and communities, in the design, implementation, and evaluation of automation and robotics policies and programs in horticulture [118].

Developing these policy and regulatory frameworks will require proactive and adaptive approaches that balance the need for innovation and efficiency with the need for social inclusion, sustainability, and resilience [119]. It will also require policy coherence and coordination across different sectors and levels of government, as well as international cooperation to address transboundary issues and promote technology transfer and capacity building [120].

7. Conclusion

Automation and robotics are transforming the horticulture industry, offering new opportunities and solutions for improving productivity, sustainability, and competitiveness. From robotic harvesters and autonomous vehicles to precision irrigation and intelligent greenhouses, these technologies are enabling growers to produce more with less, while enhancing the quality, safety, and traceability of horticultural products. However, the adoption of automation and robotics in horticulture also presents significant challenges and risks, particularly in terms of the social and economic impacts on workers and communities. Ensuring that the benefits of these technologies are shared equitably and that the rights and interests of all stakeholders are protected will require inclusive and responsible approaches to technology governance and workforce development. Looking ahead, the future of automation and robotics in horticulture will depend on continued research and development efforts to improve the adaptability, robustness, and interoperability of these technologies, as well as on collaborative ecosystems and partnerships that bring together diverse actors to drive innovation and scale up solutions. It will also require appropriate policy and regulatory frameworks that create an enabling environment for the responsible and sustainable adoption of these technologies, while promoting social inclusion, resilience, and sustainability.

References

1. Duckett, T., Pearson, S., Blackmore, S., & Grieve, B. (2018). Agricultural robotics: The future of robotic agriculture. UK-RAS White Papers, 1-27.
2. Shamshiri, R. R., Weltzien, C., Hameed, I. A., Yule, I. J., Grift, T. E., Balasundram, S. K., ... & Chowdhary, G. (2018). Research and development in agricultural robotics: A perspective of digital farming. International Journal of Agricultural and Biological Engineering, 11(4), 1-14.
3. Lowenberg-DeBoer, J., Huang, I. Y., Grigoriadis, V., & Blackmore, S. (2020). Economics of robots and automation in field crop production. Precision Agriculture, 21(2), 278-299.
4. Bechar, A., & Vigneault, C. (2016). Agricultural robots for field operations: Concepts and components. Biosystems Engineering, 149, 94-111.
5. Bechar, A., & Vigneault, C. (2017). Agricultural robots for field operations. Part 2: Operations and systems. Biosystems Engineering, 153, 110-128.
6. Marinoudi, V., Sørensen, C. G., Pearson, S., & Bochtis, D. (2019). Robotics and labour in agriculture. A context consideration. Biosystems Engineering, 184, 111-121.
7. Gallardo, R. K., & Sauer, J. (2018). Adoption of labor-saving technologies in agriculture. Annual Review of Resource Economics, 10, 185-206.
8. De Clercq, M., Vats, A., & Biel, A. (2018). Agriculture 4.0: The future of farming technology. World Government Summit, Dubai, UAE, 11-13.
9. Gallardo, R. K., & Brady, M. P. (2015). Adoption of labor-enhancing technologies by specialty crop producers: The case of the Washington apple industry. Agricultural and Resource Economics Review, 44(1), 102-119.

10. Zhang, Z., & Noguchi, N. (2019). Development of a low-cost crop growth monitoring system using raspberry Pi and digital camera. Sensors, 19(14), 3108.

11. Khanna, A., & Kaur, S. (2019). Evolution of Internet of Things (IoT) and its significant impact in the field of Precision Agriculture. Computers and Electronics in Agriculture, 157, 218-231.

12. Zahid, A., Abbas, H. T., Ren, A., Zoha, A., Heidari, H., Shah, S. A., ... & Imran, M. A. (2019). Machine learning driven non-invasive approach of water content estimation in living plant leaves using terahertz waves. Plant Methods, 15(1), 1-13.

13. Wolfert, S., Ge, L., Verdouw, C., & Bogaardt, M. J. (2017). Big data in smart farming–a review. Agricultural Systems, 153, 69-80.

14. Lakkad, H., Borisagar, V., & Pradhan, S. (2020). Study and analysis of image processing techniques for grading of fruits. In Smart Intelligent Computing and Applications (pp. 603-611). Springer, Singapore.

15. Bhargava, A., & Bansal, A. (2018). Fruits and vegetables quality evaluation using computer vision: A review. Journal of King Saud University-Computer and Information Sciences.

16. Tian, H., Wang, T., Liu, Y., Qiao, X., & Li, Y. (2020). Computer vision technology in agricultural automation—A review. Information Processing in Agriculture, 7(1), 1-19.

17. Relf-Eckstein, J. A., Ballantyne, A. T., & Phillips, P. W. (2019). Farming Reimagined: A case study of autonomous farm equipment and creating an innovation opportunity space for broadacre smart farming. NJAS-Wageningen Journal of Life Sciences, 90, 100307.

18. Auat Cheein, F. A., & Carelli, R. (2013). Agricultural robotics: Unmanned robotic service units in agricultural tasks. IEEE industrial electronics magazine, 7(3), 48-58.

19. Rotz, S., Gravely, E., Mosby, I., Duncan, E., Finnis, E., Horgan, M., ... & Fraser, E. (2019). Automated pastures and the digital divide: How agricultural technologies are shaping labour and rural communities. Journal of Rural Studies, 68, 112-122.

20. Li, Y., Xia, C., & Lee, J. (2020). Vision-based pest detection and automatic spray of greenhouse plant. IEEE Access, 8, 35679-35689.

21. Santos, T. T., de Souza, L. L., dos Santos, A. A., & Avilar, S. (2020). Grape detection, segmentation and tracking using deep neural networks and three-dimensional association. Computers and Electronics in Agriculture, 170, 105247.

22. Huang, Y., Ren, Z., Wang, L., Zhang, B., Jiang, S., Xing, Y., & Wu, Q. (2020). Phenoliner: A New Field Phenotyping Platform for Grapevine Research. Sensors, 20(5), 1500.

23. Silwal, A., Davidson, J. R., Karkee, M., Mo, C., Zhang, Q., & Lewis, K. (2017). Design, integration, and field evaluation of a robotic apple harvester. Journal of Field Robotics, 34(6), 1140-1159.

24. Kamilaris, A., Kartakoullis, A., & Prenafeta-Boldú, F. X. (2017). A review on the practice of big data analysis in agriculture. Computers and Electronics in Agriculture, 143, 23-37.

25. Ojha, T., Misra, S., & Raghuwanshi, N. S. (2015). Wireless sensor networks for agriculture: The state-of-the-art in practice and future challenges. Computers and Electronics in Agriculture, 118, 66-84.

26. Jawad, H. M., Nordin, R., Gharghan, S. K., Jawad, A. M., & Ismail, M. (2017). Energy-efficient wireless sensor networks for precision agriculture: A review. Sensors, 17(8), 1781.

27. Tzounis, A., Katsoulas, N., Bartzanas, T., & Kittas, C. (2017). Internet of Things in agriculture, recent advances and future challenges. Biosystems Engineering, 164, 31-48.

28. Zambon, I., Cecchini, M., Egidi, G., Saporito, M. G., & Colantoni, A. (2019). Revolution 4.0: Industry vs. agriculture in a future development for SMEs. Processes, 7(1), 36.

29. Vu, Q., & Raghavan, V. (2019). Autonomous agricultural robot with plant health monitoring system. In 2019 IEEE Canadian Conference of Electrical and Computer Engineering (CCECE) (pp. 1-4). IEEE.

30. Eizicovits, D., van Tuijl, B., Berman, S., & Edan, Y. (2016). Integration of perception capabilities in gripper design using graspability maps. Biosystems Engineering, 146, 98-113.

31. Chen, B., Peng, X., Sun, M., Xiao, J., & Yan, Z. (2021). Review of plant-picking robots. Frontiers of Information Technology & Electronic Engineering, 22(3), 367-384.

32. Bechar, A., & Vigneault, C. (2017). Agricultural robots for field operations. Part 2: Operations and systems. Biosystems Engineering, 153, 110-128.

33. Tripicchio, P., Satler, M., Dabisias, G., Ruffaldi, E., & Avizzano, C. A. (2015). Towards smart farming and sustainable agriculture with drones. In 2015 International Conference on Intelligent Environments (pp. 140-143). IEEE.

34. Ren, Z., Huang, Y., Yang, W., Li, S., Luo, X., Jin, R., & Guo, Y. (2021). Towards fully autonomous agriculture: Designing and developing a novel autonomous vehicle for orchards and vineyards. Computers and Electronics in Agriculture, 182, 106005.

35. Lottes, P., Behley, J., Milioto, A., & Stachniss, C. (2018). Fully convolutional networks with sequential information for robust crop and weed detection in precision farming. IEEE Robotics and Automation Letters, 3(4), 2870-2877.

36. Liakos, K. G., Busato, P., Moshou, D., Pearson, S., & Bochtis, D. (2018). Machine learning in agriculture: A review. Sensors, 18(8), 2674.

37. Kamilaris, A., & Prenafeta-Boldú, F. X. (2018). Deep learning in agriculture: A survey. Computers and electronics in agriculture, 147, 70-90.

38. Navarro, E., Costa, N., & Pereira, A. (2020). A systematic review of IoT solutions for smart farming. Sensors, 20(15), 4231.

39. Schor, N., Bechar, A., Ignat, T., Dombrovsky, A., Elad, Y., & Berman, S. (2016). Robotic disease detection in greenhouses: Combined detection of powdery mildew and tomato spotted wilt virus. IEEE Robotics and Automation Letters, 1(1), 354-360.

40. Cadena, C., Carlone, L., Carrillo, H., Latif, Y., Scaramuzza, D., Neira, J., ... & Leonard, J. J. (2016). Past, present, and future of simultaneous localization and mapping: Toward the robust-perception age. IEEE Transactions on robotics, 32(6), 1309-1332.

41. Saiz-Rubio, V., & Rovira-Más, F. (2020). From smart farming towards agriculture 5.0: A review on crop data management. Agronomy, 10(2), 207.

42. Wuest, T., Weimer, D., Irgens, C., & Thoben, K. D. (2016). Machine learning in manufacturing: Advantages, challenges, and applications. Production & Manufacturing Research, 4(1), 23-45.

43. Boursianis, A. D., Papadopoulou, M. S., Diamantoulakis, P., Liopa-Tsakalidi, A., Barouchas, P., Salahas, G., ... & Goudos, S. K. (2020). Internet of Things (IoT) and Agricultural Unmanned Aerial Vehicles (UAVs) in smart farming: A comprehensive review. Internet of Things, 100187.

44. Elijah, O., Rahman, T. A., Orikumhi, I., Leow, C. Y., & Hindia, M. N. (2018). An overview of Internet of Things (IoT) and data analytics in agriculture: Benefits and challenges. IEEE Internet of Things Journal, 5(5), 3758-3773.

45. Fountas, S., Mylonas, N., Malounas, I., Rodias, E., Hellmann Santos, C., & Pekkeriet, E. (2020). Agricultural robotics for field operations. Sensors, 20(9), 2672.

46. Hayashi, S., Yamamoto, S., Saito, S., Ochiai, Y., Kamata, J., Kurita, M., & Yamamoto, K. (2014). Field operation of a movable strawberry-harvesting robot using a travel platform. Japan Agricultural Research Quarterly: JARQ, 48(3), 307-316.

47. Shafiekhani, A., Kadam, S., Fritschi, F. B., & DeSouza, G. N. (2017). Vinobot and vinoculer: Two robotic platforms for high-throughput field phenotyping. Sensors, 17(1), 214.

48. Zhang, Z., Maes, T., Vangeyte, J., Van Huylenbroeck, J., & Van Huylenbroeck, G. (2021). Co-robotic harvest-aiding platforms in modern greenhouse production–Current status and future outlook. Computers and Electronics in Agriculture, 190, 106415.

49. Drenjanac, D., Tomic, S. D. K., Klausner, L., & Kühn, E. (2014, November). Harnessing coherence of area decomposition and semantic shared spaces for task allocation in a robotic fleet. In International Conference on Industrial Applications of Holonic and Multi-Agent Systems (pp. 166-177). Springer, Cham.

50. Pekkeriet, E., & van Henten, E. (2011). Current developments of high-tech robotic and mechatronic systems in horticulture and challenges for the future. In IV International Symposium on Applications of Precision Agriculture to Sostenible Agricultural Systems 1152 (pp. 85-94).

51. Despommier, D. (2009). The rise of vertical farms. Scientific American, 301(5), 80-87.

52. Al-Chalabi, M. (2015). Vertical farming: Skyscraper sustainability?. Sustainable Cities and Society, 18, 74-77.

53. Kozai, T., Ohyama, K., & Chun, C. (2006). Commercialized closed systems with artificial lighting for plant production. In V International Symposium on Artificial Lighting in Horticulture 711 (pp. 61-70).

54. Beacham, A. M., Vickers, L. H., & Monaghan, J. M. (2019). Vertical farming: A summary of approaches to growing skywards. The Journal of Horticultural Science and Biotechnology, 94(3), 277-283.

55. Wang, B., & Xu, G. (2020). Intelligent precision agriculture based on Internet of Things. Journal of Physics: Conference Series, 1693(1), 012111.

56. Touliatos, D., Dodd, I. C., & McAinsh, M. (2016). Vertical farming increases lettuce yield per unit area compared to conventional horizontal hydroponics. Food and energy security, 5(3), 184-191.

57. Nakamura, S., Kawano, M., Morii, K., & Hoshi, T. (2020). Three-dimensional environment modeling using a mobile robot with RGB-D camera in a vertical farm. Journal of Robotics and Mechatronics, 32(5), 910-920.

58. Murase, H. (2002). The latest greenhouse technologies that utilize computers. Computers and electronics in agriculture, 18(2-3), 133-146.

59. McBratney, A., Whelan, B., Ancev, T., & Bouma, J. (2005). Future directions of precision agriculture. Precision agriculture, 6(1), 7-23.

60. Peteinatos, G. G., Weis, M., Andújar, D., Rueda Ayala, V., & Gerhards, R. (2014). Potential use of ground-based sensor technologies for weed detection. Pest management science, 70(2), 190-199.

61. Naik, N. S., Shete, V. V., & Danve, S. R. (2016). Precision agriculture robot for seeding function. In 2016 International Conference on Inventive Computation Technologies (ICICT) (Vol. 2, pp. 1-3). IEEE.

62. Medeiros, A. A., Chattha, M. U., Jani, K., & Cetinkaya, O. (2020). Design and implementation of a smart spraying robot for precision horticulture. In 2020 IEEE International Symposium on Safety, Security, and Rescue Robotics (SSRR) (pp. 279-284). IEEE.

63. Bac, C. W., Hemming, J., & Van Henten, E. J. (2014). Stem localization of sweet-pepper plants using the support wire as a visual cue. Computers and electronics in agriculture, 105, 111-120.

64. Arad, B., Balendonck, J., Barth, R., Ben-Shahar, O., Edan, Y., Hellström, T., ... & Vougioukas, S. (2020). Development of a sweet pepper harvesting robot. Journal of Field Robotics, 37(6), 1027-1039.

65. Pilli, S. K., Nallathambi, B., George, S. J., & Diwanji, V. (2014). eAGROBOT-A robot for early crop disease detection using image processing. In 2014 International Conference on Electronics and Communication Systems (ICECS) (pp. 1-6). IEEE.

66. Oberti, R., Marchi, M., Tirelli, P., Calcante, A., Iriti, M., & Hočevar, M. (2013). Selective spraying of grapevine's diseases by a modular agricultural robot. Journal of Agricultural Engineering, 44(s2), e29-e29.

67. Das, P. K., Laxman, B., & Rao, S. V. C. K. (2021). Artificial Intelligence and Robotics in Agriculture: Current trends and Future Perspectives. In Artificial Intelligence and Robotics in Agriculture (pp. 1-16). CRC Press.

68. Zhang, T., Huang, J., Lin, J., Jiang, G., & Xu, L. (2021). Robotics and automation in the sugar industry: the past, present and future. International Journal of Agricultural and Biological Engineering, 14(1), 1-15.

69. Deng, X., Zhang, Z., Fang, H., Peng, H., Xue, L., & Yu, X. (2021). Review of rice planting robots. International Journal of Agricultural and Biological Engineering, 14(1), 16-31.

70. Gonzalez-de-Santos, P., Fernández, R., Sepúlveda, D., Navas, E., Armada, M., & Emmi, L. (2020). Unmanned ground vehicles for smart farms. In Agronomy-Climate Change & Food Security. IntechOpen.

71. Raja, R., Nguyen, T. T., Slaughter, D. C., & Fennimore, S. A. (2020). Real-time robotic weed knife control system for tomato and lettuce based on geometric appearance of plant labels. Biosystems Engineering, 194, 152-164.

72. Xiong, Y., Ge, Y., Grimstad, L., & From, P. J. (2020). An autonomous strawberry-harvesting robot: Design, development, integration, and field evaluation. Journal of Field Robotics, 37(2), 202-224.

73. Birrell, S., Hughes, J., Cai, J. Y., & Iida, F. (2020). A field-tested robotic harvesting system for iceberg lettuce. Journal of Field Robotics, 37(2), 225-245.

74. Roldán, J. J., del Cerro, J., Garzón-Ramos, D., Garcia-Aunon, P., Garzón, M., de León, J., & Barrientos, A. (2018). Robots in agriculture: State of art and practical experiences. In Service robots. IntechOpen.

75. Mammarella, M., Comba, L., Biglia, A., Dabbene, F., & Gay, P. (2020). Cooperation of unmanned systems for agricultural applications: A theoretical framework. Biosystems Engineering, 188, 163-177.

76. Frey, C. B., & Osborne, M. A. (2017). The future of employment: How susceptible are jobs to computerisation?. Technological forecasting and social change, 114, 254-280.

77. Marinoudi, V., Sørensen, C. G., Pearson, S., & Bochtis, D. (2019). Robotics and labour in agriculture. A context consideration. Biosystems Engineering, 184, 111-121.

78. Hertz, T., & Zahniser, S. (2013). Is there a farm labor shortage?. American Journal of Agricultural Economics, 95(2), 476-481.

79. Rotz, S., Gravely, E., Mosby, I., Duncan, E., Finnis, E., Horgan, M., ... & Pant, L. (2019). Automated pastures and the digital divide: How agricultural technologies are shaping labour and rural communities. Journal of Rural Studies, 68, 112-122.

80. Kritikos, M. (2017). Precision agriculture in Europe. Legal, social and ethical considerations. European Parliament Research Services.

81. Reddy, P. P. (2016). Sustainable intensification of crop production. Springer.

82. Finger, R., Swinton, S. M., El Benni, N., & Walter, A. (2019). Precision farming at the nexus of agricultural production and the environment. Annual Review of Resource Economics, 11, 313-335.

83. Klerkx, L., Jakku, E., & Labarthe, P. (2019). A review of social science on digital agriculture, smart farming and agriculture 4.0: New contributions and a future research agenda. NJAS-Wageningen Journal of Life Sciences, 90, 100315.

84. Benos, L., Bechar, A., & Bochtis, D. (2020). Safety and ergonomics in human-robot interactive agricultural operations. Biosystems Engineering, 200, 55-72.

85. Salampasis, M., & Theodoridis, A. (2013). Information and communication technology in agricultural development. Procedia Technology, 8, 1-3.

86. Welte, J. T., Ault, A., Bowman, C., Ellis, S., Buckmaster, D. R., Ess, D., & Krogmeier, J. V. (2013). An approach to farm management information systems using task-specific, collaborative mobile apps and cloud storage services. In 2013 Kansas City, Missouri, July 21-July 24, 2013 (p. 1). American Society of Agricultural and Biological Engineers.

87. Lowenberg-DeBoer, J., & Erickson, B. (2019). How does European adoption of precision agriculture compare to worldwide trends?. In Precision agriculture'19 (pp. 7-20). Wageningen Academic Publishers.

88. Bramley, R. G. V., & Ouzman, J. (2019). Farmer attitudes to the use of sensors and automation in fertilizer decision-making: Nitrogen fertilization in the Australian grains sector. Precision Agriculture, 20(1), 157-175.

89. Bronson, K., & Knezevic, I. (2016). Big Data in food and agriculture. Big Data & Society, 3(1), 2053951716648174.

90. Kamilaris, A., Kartakoullis, A., & Prenafeta-Boldú, F. X. (2017). A review on the practice of big data analysis in agriculture. Computers and Electronics in Agriculture, 143, 23-37.

91. R. Berenstein and Y. Edan, "Human-robot collaborative site-specific sprayer," Journal of Field Robotics, vol. 34, no. 8, pp. 1519–1530, 2017.

92. Diacono, M., Persiani, A., Fiore, A., Montemurro, F., & Canali, S. (2021). Agro-Ecological Practices for Sustainable Agriculture: A Review. Agronomy, 11(8), 1527.

93. Pretty, J., & Bharucha, Z. P. (2014). Sustainable intensification in agricultural systems. Annals of botany, 114(8), 1571-1596.

94. Klerkx, L., Rose, D. (2020). Dealing with the game-changing technologies of Agriculture 4.0: How do we manage diversity and responsibility in food system transition pathways?. Global Food Security, 24, 100347.

95. Fleming, A., Jakku, E., Lim-Camacho, L., Taylor, B., & Thorburn, P. (2018). Is big data for big farming or for everyone? Perceptions in the Australian grains industry. Agronomy for sustainable development, 38(3), 1-10.

96. Barnes, A. P., Soto, I., Eory, V., Beck, B., Balafoutis, A., Sánchez, B., ... & Gómez-Barbero, M. (2019). Exploring the adoption of precision agricultural technologies: A cross regional study of EU farmers. Land use policy, 80, 163-174.

97. Regan, Á. (2019). 'Smart farming' in Ireland: A risk perception study with key governance actors. NJAS-Wageningen Journal of Life Sciences, 90, 100292.

98. Eastwood, C., Klerkx, L., Ayre, M., & Rue, B. D. (2019). Managing socio-ethical challenges in the development of smart farming: from a fragmented to a comprehensive approach for responsible research and innovation. Journal of Agricultural and Environmental Ethics, 32(5), 741-768.

99. Fielke, S., Taylor, B., & Jakku, E. (2020). Digitalisation of agricultural knowledge and advice networks: A state-of-the-art review. Agricultural Systems, 180, 102763.

100. Driessen, C., & Heutinck, L. F. (2015). Cows desiring to be milked? Milking robots and the co-evolution of ethics and technology on Dutch dairy farms. Agriculture and Human Values, 32(1), 3-20.

101. Bos, A. P., Groot Koerkamp, P. W., Gosselink, J. M., & Bokma, S. (2009). Reflexive interactive design and its application in a project on sustainable dairy husbandry systems. Outlook on agriculture, 38(2), 137-145.

102. Duncan, E., Glaros, A., Ross, D. Z., & Nost, E. (2021). New but for whom? Discourses of innovation in precision agriculture. Agriculture and Human Values, 1-16.

103. Klerkx, L., & Rose, D. (2020). Dealing with the game-changing technologies of Agriculture 4.0: How do we manage diversity and responsibility in food system transition pathways?. Global Food Security, 24, 100347.

104. Berthet, E. T., Hickey, G. M., & Klerkx, L. (2018). Opening design and innovation processes in agriculture: Insights from design and management sciences and future directions. Agricultural systems, 165, 111-115.

105. Jakku, E., Taylor, B., Fleming, A., Mason, C., Fielke, S., Sounness, C., & Thorburn, P. (2019). "If they don't tell us what they do with it, why would we trust them?" Trust, transparency and benefit-sharing in Smart Farming. NJAS-Wageningen Journal of Life Sciences, 90, 100285.

106. Rose, D. C., Wheeler, R., Winter, M., Lobley, M., & Chivers, C. A. (2021). Agriculture 4.0: Making it work for people, production, and the planet. Land Use Policy, 100, 104933.

107. Kuch, D., Kearnes, M., & Gulson, K. (2020). The promise of precision: datafication in medicine, agriculture and education. Policy Studies, 41(5), 527-546.

108. Sparrow, R., & Howard, M. (2021). Robots in agriculture: prospects, impacts, ethics, and policy. Precision Agriculture, 22(3), 818-833.

109. Henriette, H., Bosch, J., Veraart, F., van der Maarl, A. (2021). Responsible digitalization in the agri-food sector with PL4.0 technologies: Investigating ethical challenges using the dilemma cube for responsible innovation. Precision livestock farming '21, 471.

110. Carolan, M. (2020). Automated agrifood futures: robotics, labor and the distributive politics of digital agriculture. The Journal of Peasant Studies, 47(1), 184-207.

111. Araújo, S. O., Peres, R. S., Barata, J., Lidon, F., & Ramalho, J. C. (2021). Characterising the Agriculture 4.0 Landscape—Emerging Trends, Challenges and Opportunities. Agronomy, 11(4), 667.

112. Bronson, K. (2018). Smart farming: including rights holders for responsible agricultural innovation. Technology innovation management review, 8(2).

113. Wiseman, L., Sanderson, J., Zhang, A., & Jakku, E. (2019). Farmers and their data: An examination of farmers' reluctance to share their data through the lens of the laws impacting smart farming. NJAS-Wageningen Journal of Life Sciences, 90, 100301.

114. Ryan, M., & Stahl, B. C. (2021). Artificial intelligence ethics guidelines for developers and users: Clarifying their content and normative implications. Journal of Information, Communication and Ethics in Society.

115. Lajoie-O'Malley, A., Bronson, K., van der Burg, S., & Klerkx, L. (2020). The future(s) of digital agriculture and sustainable food systems: An analysis of high-level policy documents. Ecosystem Services, 45, 101183.

116. van der Burg, S., Bogaardt, M. J., & Wolfert, S. (2019). Ethics of smart farming: Current questions and directions for responsible innovation towards the future. NJAS-Wageningen Journal of Life Sciences, 90, 100289.

117. Lioutas, E. D., & Charatsari, C. (2021). Enhancing the ability of agriculture to cope with major crises or disasters: What the experience of COVID-19 teaches us. Agricultural Systems, 187, 103023.

118. Jouanjean, M. A., Casalini, F., Wiseman, L., & Gray, E. (2020). Issues around data governance in the digital transformation of agriculture: The farmers' perspective. OECD Food, Agriculture and Fisheries Papers, No. 146, OECD Publishing, Paris.

119. Prause, L., Hackfort, S., & Lindgren, M. (2021). Digitalization and the third food regime. Agriculture and Human Values, 38(3), 641-655.

120. Ofori, M., El-Gayar, O., & Siambi, M. (2021). Towards responsible adoption of digital agriculture for sustainable development in Africa: A synthesis of the evidence. Information Processing in Agriculture.

CHAPTER - 4

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Novel Approaches to Pest and Disease Management in Vegetable Crops

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Abstract

Effective management of pests and diseases is crucial for sustainable vegetable production. Traditional methods heavily reliant on chemical pesticides face challenges due to the development of resistance, environmental concerns, and consumer demand for safer produce. This chapter explores novel approaches to pest and disease management in vegetable crops, focusing on integrated strategies that combine cultural practices, biological control, and targeted use of biopesticides and plant activators. Cultural practices such as crop rotation, intercropping, and adjusting planting dates can disrupt pest and disease cycles. Promoting soil health through organic amendments, cover cropping, and reduced tillage enhances the natural suppressive capacity of soils against soilborne pathogens. Advances in protected cultivation, including insect-proof netting and hydroponic systems, create barriers against pests and diseases.

Biological control, utilizing natural enemies such as predators, parasitoids, and antagonistic microbes, offers an eco-friendly approach to managing pests and diseases. Conservation biological control involves manipulating the agroecosystem to favor these beneficial organisms. Augmentative releases of commercially available biocontrol agents can supplement natural populations. Biopesticides derived from microorganisms, plant extracts, and other natural sources provide targeted control with minimal impact on non-target organisms.

Plant activators and resistance inducers stimulate the plant's own defense mechanisms, enhancing their resilience against pests and diseases. Compounds such as salicylic acid, jasmonic acid, and beta-aminobutyric acid (BABA) have shown promise in inducing systemic acquired resistance (SAR) and induced systemic resistance (ISR). Genetic engineering techniques enable the development of transgenic vegetable varieties with enhanced resistance to specific pests and diseases. Successful implementation of these novel approaches requires a systems-level understanding of the complex interactions among crops, pests, diseases, and their environment. Integration of multiple strategies, coupled with regular monitoring and decision support tools, can optimize the efficacy of pest and disease management while minimizing reliance on chemical interventions. Continued research and extension efforts are essential to refine and promote the adoption of these innovative approaches in vegetable production systems worldwide.

Keywords: Integrated Pest Management, Biological Control, Biopesticides, Plant Activators, Host Plant Resistance

Vegetable crops are an essential component of global food security and nutrition, providing a diverse array of vitamins, minerals, and phytochemicals crucial for human health [1]. However, the intensive cultivation of vegetable crops often leads to the proliferation of pests and diseases, which can cause significant yield losses and compromise produce quality [2]. Traditionally, the management of pests and diseases in vegetable production has heavily relied on the use of synthetic chemical pesticides. While these pesticides have played a critical role in protecting crops, their extensive and indiscriminate use has led to several challenges, including the development of resistance in target organisms, adverse effects on beneficial insects and other non-target species, environmental contamination, and concerns over human health risks associated with pesticide residues in food [3].

In response to these challenges, there has been a growing interest in developing and implementing novel approaches to pest and disease management in vegetable crops. These approaches aim to reduce the reliance on chemical pesticides while maintaining effective control of pests and diseases. They encompass a wide range of strategies, including cultural practices, biological control, the use of biopesticides and natural products, plant activators and resistance inducers, and genetic engineering techniques [4]. The adoption of these novel approaches requires a paradigm shift from the conventional "silver bullet" mentality to a more holistic, systems-based approach that takes into account the complex interactions among crops, pests, diseases, and their environment.

The importance of integrated pest and disease management (IPDM) strategies is highlighted, emphasizing the need for a holistic approach that combines multiple tactics based on a thorough understanding of the agroecosystem. The chapter discusses the principles and components of IPDM, the role of monitoring and decision support tools, and presents case studies of successful IPDM implementation in vegetable production systems.

Finally, the chapter addresses the challenges and future perspectives related to the adoption of novel approaches to pest and disease management in vegetable crops. These include issues such as resistance management, regulatory and policy considerations, technology transfer and adoption by farmers, and the identification of research priorities and knowledge gaps. The chapter concludes by emphasizing the need for continued research, extension, and stakeholder engagement to refine and promote these innovative approaches, with the ultimate goal of achieving sustainable and resilient vegetable production systems that can meet the growing global demand for safe and nutritious food.

2. Cultural Practices for Pest and Disease Management

Cultural practices play a fundamental role in the prevention and management of pests and diseases in vegetable crops. These practices involve the manipulation of the crop environment to create conditions that are less favorable for the development and spread of pests and diseases, while promoting the growth and health of the crop. By implementing appropriate cultural practices, farmers can reduce the need for chemical interventions and enhance the overall sustainability of their production systems. This section discusses several key cultural practices that can be employed for effective pest and disease management in vegetable crops.

2.1. Crop Rotation and Intercropping: Crop rotation is a time-tested practice that involves the sequential planting of different crops in the same field over multiple growing seasons. By alternating host and non-host crops, crop rotation can disrupt the life cycles of pests and diseases, reducing their population buildup and carryover from one season to the next [5]. For example, rotating solanaceous crops like tomatoes and potatoes with non-solanaceous crops can help manage soilborne diseases such as verticillium wilt and bacterial wilt [6]. Similarly, rotating brassica crops with non-brassica crops can reduce the incidence of clubroot disease caused by *Plasmodiophora brassicae* [7]. When planning crop rotations, it is essential to consider the specific pests and diseases affecting the crops, their host ranges, and the length of their survival in the absence of host plants.

Intercropping, the practice of growing two or more crops simultaneously in the same field, can also contribute to pest and disease management. By increasing crop diversity, intercropping can create a more complex and resilient agroecosystem that is less conducive to the proliferation of pests and diseases [8]. For instance, intercropping tomatoes with companion crops like basil or marigolds has been shown to reduce the incidence of whiteflies and tomato yellow leaf curl virus (TYLCV) [9]. The mechanisms underlying the benefits of intercropping include the disruption of pest host-finding behavior, the provision of alternative hosts for natural enemies, and the alteration of the microclimate within the crop canopy [10].

2.2. Adjusting Planting Dates and: Densities The timing of planting and the density at which crops are grown can have significant implications for pest and disease management. By adjusting planting dates, farmers can avoid or reduce the exposure of vulnerable crop stages to peak pest and disease pressure. For example, delaying the planting of cucurbit crops until after the peak activity of striped cucumber beetles (*Acalymma vittatum*) can minimize the risk of bacterial wilt transmission [11]. Similarly, planting brassica crops early in the season can help them escape the peak population of diamondback moth (*Plutella xylostella*) [12]. However, the effectiveness of these strategies depends on a thorough understanding of the biology and phenology of the target pests and diseases, as well as the local climate and cropping patterns.

Manipulating planting densities can also influence pest and disease dynamics. In general, higher planting densities can create a microclimate that favors the development and spread of certain pests and diseases, particularly those that thrive in humid conditions [13]. On the other hand, lower planting densities can reduce the spread of pests and diseases by increasing the distance between plants and improving air circulation within the crop canopy [14]. However, the optimal planting density for pest and disease management must be balanced with the need to maintain yield and quality, as excessively low densities can result in reduced productivity.

2.3. Sanitation and Removal of Infected Plant Material: Sanitation is a critical component of pest and disease management in vegetable crops. It involves the removal and proper disposal of infected plant material, crop residues, and other sources of inoculum that can harbor pests and diseases. By reducing the initial inoculum load, sanitation practices can delay the onset and slow the spread of pests and diseases within the crop [15]. For example, promptly removing and destroying plants infected with tomato spotted wilt virus (TSWV) can help prevent the spread of the virus by thrips vectors to healthy plants [16]. Similarly, the removal and destruction of crop residues after harvest can reduce the overwintering populations of pests and diseases, thereby minimizing their impact on subsequent crops [17].

Effective sanitation also extends to the cleaning and disinfection of tools, equipment, and other surfaces that may come into contact with infected plant material. This is particularly important for managing bacterial and viral diseases that can be easily transmitted through mechanical means [18]. The use of appropriate disinfectants, such as bleach or quaternary ammonium compounds, can help eliminate pathogens from contaminated surfaces. Additionally, implementing strict hygiene protocols for workers, such as handwashing and the use of disposable gloves, can further reduce the risk of disease transmission.

2.4. Soil Health Management Maintaining: soil health is fundamental to the prevention and management of soilborne pests and diseases in vegetable crops. A healthy soil harbors a diverse and active community of beneficial microorganisms that can suppress the growth and activity of plant pathogens through various mechanisms, such as competition, antibiosis, and induced systemic resistance [19]. Therefore, practices that promote soil health, such as the application of organic amendments, cover cropping, and reduced tillage, can enhance the natural suppressive capacity of soils against pests and diseases.

Organic amendments, such as compost, animal manures, and green manures, can improve soil structure, fertility, and biological activity, creating conditions that favor the growth of beneficial microorganisms while suppressing plant pathogens [20]. For example, the incorporation of compost has been shown to reduce the incidence of soilborne diseases like *Pythium* and *Rhizoctonia* in various vegetable crops [21]. Cover cropping, the practice of growing non-cash crops for the purpose of soil improvement, can also contribute to soil health and pest and disease management. Cover crops can help suppress weeds, which can act as alternate hosts for pests and diseases, and can also provide habitat for beneficial insects and other natural enemies [22].

Reduced tillage systems, such as no-till or strip-till, can promote soil health by minimizing soil disturbance and preserving the integrity of soil aggregates and pore networks [23]. This can foster the development of a more diverse and stable soil microbial community, which can enhance the suppression of soilborne pathogens. However, the adoption of reduced tillage systems in vegetable production may require adjustments in other management practices, such as the use of specialized planting equipment and the management of crop residues.

2.5. Protected Cultivation: Techniques Protected cultivation techniques, such as the use of greenhouses, high tunnels, and insect-proof netting, can create physical barriers that prevent or reduce the entry of pests and diseases into the crop environment. These structures can also modify the microclimate within the crop canopy, creating conditions that are less favorable for the development and spread of certain pests and diseases [24]. For example, the use of insect-proof netting can effectively exclude major pests like whiteflies, thrips, and aphids from vegetable crops, thereby reducing the need for insecticide applications [25].

In addition to acting as physical barriers, protected cultivation techniques can also facilitate the implementation of other pest and disease management strategies. For instance, the controlled environment of a greenhouse allows for the precise application of biological control agents, such as predators and parasitoids, without the risk of them being dispersed by wind or rain [26]. Similarly, the use of hydroponic systems in protected cultivation can minimize the exposure of crops to soilborne pests and diseases, as the growing medium is typically free of pathogens [27].

However, the adoption of protected cultivation techniques also presents certain challenges. The initial investment costs for the construction and maintenance of these structures can be high, and they may require specialized skills and knowledge for their proper management. Moreover, the modified microclimate within protected structures can sometimes favor the development of certain pests and diseases if not properly managed, such as powdery mildew in greenhouse-grown cucurbits [28]. Therefore, the successful use of protected cultivation for pest and disease management requires a comprehensive understanding of the crop, the target pests and diseases, and the specific environmental conditions within the protected structure.

3. **Biological Control Strategies**

Biological control is an eco-friendly approach to managing pests and diseases in vegetable crops by utilizing living organisms to suppress the populations of harmful ones. This strategy leverages the natural relationships among organisms in the agroecosystem, such as predation, parasitism, and competition, to maintain pest and disease populations below economically damaging levels. Biological control can be implemented through three main approaches: conservation biological control, augmentative biological control, and classical biological control. This section focuses on conservation and augmentative biological control strategies, as they are more commonly employed in vegetable production systems.

3.1. Conservation Biological Control Conservation biological control involves modifying the environment to favor the survival, reproduction, and effectiveness of natural enemies that are already present in the agroecosystem. This approach aims to enhance the natural regulation of pests and diseases by providing essential resources and reducing factors that may hinder the performance of beneficial organisms [29]. Key strategies for conservation biological control include:

a. Habitat management: This involves the manipulation of the crop environment to provide food, shelter, and reproductive sites for natural enemies. For example, planting flower strips or hedgerows along field margins can provide nectar and pollen sources for adult parasitoids and predators, enhancing their longevity and fecundity [30]. Similarly, the inclusion of non-crop vegetation within the field, such as intercropping or cover cropping, can create a more diverse habitat that supports a higher abundance and diversity of natural enemies [31].

b. Selective use of pesticides: The indiscriminate use of broad-spectrum pesticides can have detrimental effects on natural enemy populations, disrupting their ability to control pests and diseases. Conservation biological control emphasizes the selective use of pesticides that are less toxic to beneficial organisms, such as biopesticides or narrow-spectrum insecticides [32]. When chemical interventions are necessary, they should be applied in a manner that minimizes the exposure of natural enemies, such as using targeted sprays or timing applications to coincide with periods of low natural enemy activity.

c. Provision of alternative prey or hosts: Some natural enemies require alternative prey or hosts to sustain their populations when the target pest is scarce. Providing these alternative resources can help maintain stable populations of natural enemies in the agroecosystem. For example, planting banker plants that harbor non-pest aphids can provide a continuous supply of alternative prey for aphid predators, ensuring their persistence in the crop environment [33].

3.2. Augmentative Biological Control Augmentative biological control involves the supplemental release of natural enemies to enhance the biological control of pests and diseases. This approach is particularly useful when the natural populations of beneficial organisms are insufficient to provide adequate control, or when the timing of their activity does not coincide with the critical stages of pest or disease development. Augmentative releases can be further classified into two categories: inoculative releases and inundative releases.

Inoculative releases involve the periodic introduction of small numbers of natural enemies with the expectation that they will establish and reproduce in the crop environment, providing long-term pest or disease suppression [34]. This approach is more suitable for pests or diseases that have a relatively low reproductive rate and a long crop cycle. Inundative releases, on the other hand, involve the mass release of large numbers of natural enemies for the rapid and short-term suppression of pests or diseases [35]. This approach is more appropriate for pests or diseases that have a high reproductive rate and a short crop cycle, or when the natural enemies are not expected to establish and reproduce in the crop environment.

The success of augmentative biological control depends on several factors, including the selection of the appropriate natural enemy species, the quality and quantity of the released organisms, the timing and frequency of releases, and the compatibility of the released organisms with other management practices. Some common examples of commercially available natural enemies used in augmentative biological control of vegetable pests and diseases include:

3.2.1. Predators

- Ladybird beetles (*Coccinellidae*) for the control of aphids, mealybugs, and other soft-bodied insects [36].
- Lacewings (*Chrysopidae*) for the control of aphids, thrips, and other small insect pests [37].
- Predatory mites (*Phytoseiidae*) for the control of spider mites and other phytophagous mites [38].

3.2.2. Parasitoids

- *Encarsia formosa* and *Eretmocerus eremicus* for the control of whiteflies in greenhouse-grown vegetables [39].
- *Aphidius* spp. for the control of aphids in various vegetable crops [40].
- *Trichogramma* spp. for the control of lepidopteran pests, such as the European corn borer (*Ostrinia nubilalis*) and the tomato leafminer (*Tuta absoluta*) [41].

3.3.3. Antagonistic Microbes

- *Trichoderma* spp. for the control of soilborne fungal pathogens, such as *Pythium*, *Rhizoctonia*, and *Fusarium* [42].
- *Bacillus subtilis* and other *Bacillus* spp. for the control of various fungal and bacterial diseases in vegetable crops [43].
- *Pseudomonas fluorescens* and other plant growth-promoting rhizobacteria (PGPR) for the suppression of soilborne diseases and the induction of systemic resistance in plants [44].

3.3. Challenges and Opportunities in Biological Control Despite the numerous benefits of biological control, there are several challenges that need to be addressed to ensure its successful implementation in vegetable production systems. One of the main challenges is the variability in the performance of biological control agents under different environmental conditions. Natural enemies are living organisms that are sensitive to factors such as temperature, humidity, and the presence of pesticide residues, which can affect their survival, reproduction, and efficacy [45]. Therefore, the selection of biological control agents must take into account the specific environmental conditions of the cropping system, and the agents must be able to tolerate the prevailing conditions to provide effective pest or disease suppression.

Another challenge is the potential for unintended consequences associated with the introduction of non-native biological control agents. In some cases, introduced natural enemies may have negative impacts on non-target organisms or may themselves become invasive pests [46]. To minimize these risks, rigorous screening and risk assessment procedures must be in place before the release of any non-native biological control agents. Additionally, the use of native or locally adapted natural enemies should be prioritized whenever possible.

The successful implementation of biological control also requires a good understanding of the biology and ecology of the target pests or diseases, as well as the natural enemies. This knowledge is essential for developing effective release strategies, such as determining the optimal timing, frequency, and density of releases [47]. Moreover, the integration of biological control with other pest and disease management tactics, such as cultural practices and the use of biopesticides, requires careful planning and coordination to avoid potential conflicts and maximize synergies [48].

Despite these challenges, biological control presents numerous opportunities for sustainable pest and disease management in vegetable crops. Advances in technology, such as the use of molecular tools for the identification and characterization of natural enemies, and the development of improved formulations and delivery systems for biological control agents, are opening up new possibilities for enhancing the efficacy and reliability of biological control [49]. Furthermore, the growing demand for organic and sustainably produced vegetables is creating a strong market incentive for the adoption of biological control and other eco-friendly pest and disease management strategies [50].

To fully realize the potential of biological control in vegetable production systems, continued research and extension efforts are needed. This includes the identification and evaluation of new biological control agents, the optimization of production and release methods, and the development of decision support tools to assist farmers in the implementation of biological control strategies. Additionally, the promotion of farmer-to-farmer knowledge exchange and the strengthening of collaborations among researchers, extension agents, and the private sector can help foster the wider adoption of biological control and other innovative pest and disease management approaches.

4. Biopesticides and Natural Products

Biopesticides and natural products have emerged as promising alternatives to synthetic chemical pesticides for the management of pests and diseases in vegetable crops. These substances are derived from living organisms or natural sources and are generally considered to be safer for human health and the environment compared to conventional pesticides. Biopesticides can be classified into three main categories: microbial pesticides, biochemical pesticides, and plant-incorporated protectants (PIPs) [51]. This section focuses on microbial biopesticides and botanical pesticides, as they are the most widely used in vegetable production systems.

4.1. Microbial Biopesticides Microbial biopesticides are formulations that contain living microorganisms, such as bacteria, fungi, viruses, or nematodes, as the active ingredients. These microorganisms can suppress pests and diseases through various modes of action, including antibiosis, competition, parasitism, and the induction of host plant resistance [52]. The specificity of microbial biopesticides to their target pests or pathogens makes them less likely to harm non-target organisms, including beneficial insects and other natural enemies.

4.1.1. Bacterial Biopesticides Bacterial biopesticides are the most widely used type of microbial biopesticides in vegetable production. The most common bacterial agents used in these formulations belong to the genera *Bacillus*, *Pseudomonas*, and *Streptomyces*. *Bacillus thuringiensis* (Bt) is a well-known example of a bacterial biopesticide that has been successfully used for the control of lepidopteran pests in various vegetable crops [53]. Bt produces crystal proteins (Cry toxins) that are toxic to specific groups of insects, such as caterpillars and beetles, but are harmless to most other organisms. Different strains of Bt have been developed to target specific insect pests, such as *B. thuringiensis* subsp. *kurstaki* for the control of the diamondback moth (*Plutella xylostella*) in brassica crops [54].

Other bacterial biopesticides, such as *Pseudomonas fluorescens* and *Bacillus subtilis*, have been shown to be effective against various fungal and bacterial diseases in vegetable crops. These bacteria can suppress plant pathogens through the production of antimicrobial compounds, competition for nutrients and space, and the induction of systemic resistance in the host plant [55]. For example, the application of *P. fluorescens* has been found to reduce the incidence of bacterial spot (*Xanthomonas campestris* pv. *vesicatoria*) in tomato and pepper [56], while *B. subtilis* has been shown to control powdery mildew (*Podosphaera xanthii*) in cucurbits [57].

4.1.2. Fungal Biopesticides Fungal biopesticides are formulations that contain fungal spores or mycelium as the active ingredients. These fungi can infect and kill insect pests or suppress plant pathogens through various mechanisms, such as the production of toxins, enzymes, and other metabolites [58]. Some of the most commonly used fungal biopesticides in vegetable production include *Beauveria bassiana*, *Metarhizium anisopliae*, and *Trichoderma* spp.

Beauveria bassiana and *Metarhizium anisopliae* are entomopathogenic fungi that can infect and kill a wide range of insect pests, including whiteflies, thrips, and aphids [59]. These fungi can penetrate the insect cuticle and proliferate within the body cavity, eventually causing death. The application of these fungal biopesticides can provide effective control of insect pests in various vegetable crops, such as tomatoes, peppers, and cucurbits [60].

Trichoderma spp., on the other hand, are antagonistic fungi that can suppress plant pathogenic fungi through competition, mycoparasitism, and antibiosis [61]. These fungi can also induce systemic resistance in host plants, enhancing their defense against various pathogens. The application of *Trichoderma* biopesticides has been found to be effective against a range of soilborne fungal diseases, such as *Pythium*, *Rhizoctonia*, and *Fusarium*, in various vegetable crops [62].

4.1.3. Viral Biopesticides Viral biopesticides, also known as baculoviruses, are formulations that contain insect-specific viruses as the active ingredients. These viruses can infect and kill specific groups of insect pests, particularly lepidopteran larvae, without harming beneficial insects or other non-target organisms [63]. The most commonly used viral biopesticides in vegetable production are nucleopolyhedroviruses (NPVs) and granuloviruses (GVs).

NPVs have been successfully used for the control of various lepidopteran pests in vegetable crops, such as the beet armyworm (*Spodoptera exigua*) in tomatoes and the cabbage looper (*Trichoplusia ni*) in brassicas [64]. Similarly, GVs have been found to be effective against the codling moth (*Cydia pomonella*) in various fruit crops [65]. The application of viral biopesticides can provide long-term suppression of insect pests, as the viruses can persist in the environment and spread to subsequent generations of the target pests.

4.2. Botanical Pesticides and Plant Extracts Botanical pesticides and plant extracts are natural products derived from plants that have insecticidal, fungicidal, or nematicidal properties. These substances can be obtained from various plant parts, such as leaves, stems, roots, flowers, and seeds, and can be used in the form of aqueous extracts, essential oils, or powders [66]. Botanical pesticides offer several advantages over synthetic chemical pesticides, including lower toxicity to non-target organisms, rapid degradation in the environment, and reduced risk of resistance development in target pests and pathogens.

Some of the most commonly used botanical pesticides in vegetable production include neem (*Azadirachta indica*), pyrethrum (*Chrysanthemum cinerariifolium*), and garlic (*Allium sativum*). Neem extracts, particularly azadirachtin, have been found to be effective against a wide range of insect pests, such as whiteflies, thrips, and leafminers, as well as against various fungal diseases [67]. Pyrethrum, which contains pyrethrins, has been used for the control of aphids, beetles, and other insect pests in various vegetable crops [68]. Garlic extracts have been shown to have insecticidal and fungicidal properties and have been used for the management of pests and diseases in tomatoes, cucurbits, and other vegetables [69].

Other plant extracts that have shown promise for pest and disease management in vegetable crops include chitosan (derived from crustacean shells), plant essential oils (e.g., thyme, rosemary, and peppermint), and plant growth regulators (e.g., salicylic acid and jasmonic acid) [70]. These substances can act as insect repellents, antifeedants, or toxicants, or can induce plant defense responses against pests and pathogens.

4.3. Other Natural Products and Formulations In addition to microbial and botanical pesticides, several other natural products and formulations have been investigated for their potential use in pest and disease management in vegetable crops. These include:

- **Semiochemicals:** These are naturally occurring chemical signals that mediate interactions between organisms, such as pheromones and allelochemicals. Semiochemicals can be used for monitoring, mass trapping, or mating disruption of insect pests [71]. For example, sex pheromone traps have been successfully used for the monitoring and management of the tomato leafminer (*Tuta absoluta*) in tomato crops [72].

- **Inorganic compounds:** Some naturally occurring inorganic compounds, such as sulfur, copper, and potassium bicarbonate, have been used for the control of fungal diseases in vegetable crops [73]. These substances can act as contact fungicides or can induce plant defense responses against pathogens.
- **Biopesticide formulations:** The efficacy and stability of biopesticides can be enhanced through the development of appropriate formulations, such as microencapsulation, granulation, and oil-based formulations [74]. These formulations can improve the shelf life, field persistence, and delivery of the active ingredients to the target pests or pathogens.

5. Plant Activators and Resistance Inducers

Plant activators and resistance inducers are compounds that can stimulate the plant's own defense mechanisms against pests and diseases, without directly acting on the target organisms. These substances can be of natural or synthetic origin and can induce resistance through various signaling pathways, such as the salicylic acid (SA), jasmonic acid (JA), and ethylene (ET) pathways [75]. The induced resistance can be either local or systemic and can provide broad-spectrum protection against a range of pests and pathogens.

5.1. Salicylic Acid and Its Derivatives Salicylic acid (SA) is a plant hormone that plays a key role in the activation of systemic acquired resistance (SAR) against biotrophic pathogens, such as powdery mildews and rusts [76]. SAR is a broad-spectrum, long-lasting resistance that is induced by a localized infection and provides protection against subsequent attacks by the same or different pathogens [77]. The application of exogenous SA or its functional analogs, such as benzothiadiazole (BTH) and 2,6-dichloroisonicotinic acid (INA), has been shown to induce SAR in various vegetable crops, including tomatoes, cucurbits, and brassicas [78].

BTH, marketed under the trade name Actigard or Bion, is one of the most widely used SAR inducers in vegetable production. It has been shown to provide protection against a range of fungal, bacterial, and viral diseases, such as tomato spotted wilt virus (TSWV) in tomatoes [79], bacterial spot (*Xanthomonas campestris* pv. *vesicatoria*) in peppers [80], and downy mildew (*Pseudoperonospora cubensis*) in cucurbits [81]. The application of BTH can also enhance the plant's resistance to certain insect pests, such as the silverleaf whitefly (*Bemisia tabaci*) in tomatoes [82].

5.2. Jasmonic Acid and Related Compounds Jasmonic acid (JA) and its derivatives, such as methyl jasmonate (MeJA) and cis-jasmone, are plant hormones that are involved in the activation of induced systemic resistance (ISR) against necrotrophic pathogens and herbivorous insects [83]. ISR is a broad-spectrum resistance that is induced by non-pathogenic root-colonizing bacteria, such as plant growth-promoting rhizobacteria (PGPR), and provides protection against subsequent attacks by pests and pathogens [84].

The application of exogenous JA or its derivatives has been found to induce ISR in various vegetable crops. For example, the foliar application of MeJA has been shown to reduce the incidence of gray mold (*Botrytis cinerea*) in tomatoes [85] and the severity of bacterial wilt (*Ralstonia solanacearum*) in eggplants [86]. Similarly, the application of cis-jasmone has been found to induce resistance against the two-spotted spider mite (*Tetranychus urticae*) in tomatoes [87] and the diamondback moth (*Plutella xylostella*) in brassicas [88].

5.3. Beta-Aminobutyric Acid (BABA) Beta-aminobutyric acid (BABA) is a non-protein amino acid that can induce resistance against a wide range of pests and pathogens in plants, including fungi, bacteria, viruses, and nematodes [89]. BABA-induced resistance is mediated through both the SA and JA/ET signaling pathways and can provide long-lasting protection against multiple stresses [90].

In vegetable crops, the application of BABA has been shown to induce resistance against various diseases, such as downy mildew (*Bremia lactucae*) in lettuce [91], powdery mildew (*Leveillula taurica*) in tomatoes [92], and Fusarium wilt (*Fusarium oxysporum* f. sp. *melonis*) in cucurbits [93]. BABA can also enhance the plant's resistance to insect pests, such as the green peach aphid (*Myzus persicae*) in peppers [94] and the whitefly (*Bemisia tabaci*) in tomatoes [95].

5.4. Other Plant Activators and Elicitors In addition to SA, JA, and BABA, several other plant activators and elicitors have been investigated for their potential use in pest and disease management in vegetable crops. These include:

- **Chitosan**: Chitosan is a natural biopolymer derived from the chitin of crustacean shells that can induce plant defense responses against various pests and pathogens [96]. The application of chitosan has been found to reduce the incidence of gray mold (*Botrytis cinerea*) in tomatoes [97] and the severity of bacterial wilt (*Ralstonia solanacearum*) in potatoes [98].
- **Harpin proteins**: Harpin proteins are bacterial elicitors that can induce SAR and ISR in plants [99]. The application of harpin proteins has been shown to reduce the incidence of bacterial spot (*Xanthomonas campestris* pv. *vesicatoria*) in tomatoes [100] and the severity of powdery mildew (*Podosphaera xanthii*) in cucurbits [101].
- **Plant extracts**: Some plant extracts, such as those derived from giant knotweed (*Reynoutria sachalinensis*) and seaweed (*Ascophyllum nodosum*), have been found to induce plant defense responses against various pests and pathogens [102]. For example, the application of giant knotweed extract has been shown to reduce the incidence of powdery mildew (*Oidium neolycopersici*) in tomatoes [103], while seaweed extract has been found to enhance the plant's resistance to the root-knot nematode (*Meloidogyne incognita*) in peppers [104].

The use of plant activators and resistance inducers offers a promising approach for the management of pests and diseases in vegetable crops, as they can provide broad-spectrum and long-lasting protection without directly targeting the pests or pathogens. However, the efficacy of these compounds can be influenced by various factors, such as the crop species, the target pest or pathogen, the application timing and method, and the environmental conditions [105]. Therefore, the successful implementation of plant activators and resistance inducers in vegetable production systems requires a good understanding of their modes of action, compatibility with other management practices, and optimal use strategies.

6. Genetic Engineering for Pest and Disease Resistance: Genetic engineering has emerged as a powerful tool for developing vegetable varieties with enhanced resistance to pests and diseases. This approach involves the introduction of foreign genes or the modification of existing genes in the plant genome to confer specific traits, such as insect resistance or disease resistance [106]. The use of genetic engineering can complement traditional breeding methods and provide a more targeted and efficient way of developing resistant varieties.

6.1. Transgenic Approaches: Transgenic approaches involve the introduction of genes from other organisms, such as bacteria or other plant species, into the target vegetable crop. These genes can encode for proteins that confer resistance to specific pests or pathogens, such as insecticidal proteins or pathogen-derived resistance genes [107].

One of the most well-known examples of transgenic pest resistance in vegetable crops is the use of *Bacillus thuringiensis* (Bt) genes to confer resistance against lepidopteran pests. Bt genes encode for insecticidal proteins that are toxic to specific groups of insects, such as moths and butterflies, but are harmless to other organisms [108]. Transgenic Bt vegetable crops, such as Bt eggplant and Bt tomato, have been developed and commercialized in some countries, providing effective control of target pests like the eggplant fruit and shoot borer (*Leucinodes orbonalis*) and the tomato fruit borer (*Helicoverpa armigera*) [109].

Transgenic approaches have also been used to develop vegetable varieties with resistance to viral diseases. For example, the introduction of viral coat protein genes or viral replicase genes into the plant genome can confer resistance to the corresponding virus through mechanisms such as coat protein-mediated resistance or RNA silencing [110]. Transgenic vegetable crops with resistance to viruses such as cucumber mosaic virus (CMV), tomato yellow leaf curl virus (TYLCV), and papaya ringspot virus (PRSV) have been developed and tested in various countries [111].

6.2. RNA Interference (RNAi) Technology: RNA interference (RNAi) is a gene silencing mechanism that can be exploited for the development of pest- and disease-resistant vegetable varieties. RNAi involves the use of double-stranded RNA (dsRNA) to trigger the degradation of complementary mRNA, thereby preventing the expression of target genes [112]. By designing dsRNA constructs that target essential genes in pests or pathogens, RNAi can be used to confer specific and effective resistance in vegetable crops.

In the case of insect pests, RNAi has been used to target genes involved in the insect's growth, development, and survival, such as those encoding for digestive enzymes, hormones, or structural proteins [113]. For example, the silencing of the *Acetylcholinesterase* gene in the Colorado potato beetle (*Leptinotarsa decemlineata*) using RNAi has been shown to reduce the insect's survival and feeding damage on potato plants [114]. Similarly, the silencing of the *Ecdysone receptor* gene in the diamondback moth (*Plutella xylostella*) using

RNAi has been found to disrupt the insect's molting and development, leading to increased mortality [115].

RNAi has also been applied for the control of fungal and oomycete pathogens in vegetable crops. By targeting essential genes involved in the pathogen's virulence, growth, or development, RNAi can provide effective and specific disease resistance [116]. For instance, the silencing of the *Cellulose synthase* gene in the oomycete pathogen *Phytophthora infestans* using RNAi has been shown to reduce the pathogen's ability to infect potato plants [117]. Similarly, the silencing of the *Chitin synthase* gene in the fungal pathogen *Fusarium oxysporum* f. sp. *lycopersici* using RNAi has been found to enhance the resistance of tomato plants to Fusarium wilt [118].

6.3. Genome Editing Techniques (CRISPR/Cas9): Genome editing techniques, such as the CRISPR/Cas9 system, have revolutionized the field of plant breeding by enabling the precise and efficient modification of plant genomes [119]. CRISPR/Cas9 is a bacterial defense system that has been adapted for use in plant genetic engineering. It consists of a guide RNA (gRNA) that directs the Cas9 endonuclease to a specific target site in the genome, where it creates a double-stranded break (DSB) [120]. This DSB can be repaired through either non-homologous end joining (NHEJ) or homology-directed repair (HDR), resulting in targeted gene modifications, such as gene knockouts, gene insertions, or gene replacements [121].

The CRISPR/Cas9 system has been used to develop pest- and disease-resistant vegetable varieties by targeting genes involved in plant susceptibility or pathogen virulence. For example, the knockout of the *Mildew Locus O* (*MLO*) gene in tomato using CRISPR/Cas9 has been shown to confer resistance to powdery mildew (*Oidium neolycopersici*) [122]. Similarly, the knockout of the *Eukaryotic translation initiation factor 4E* (*eIF4E*) gene in cucumber using CRISPR/Cas9 has been found to provide resistance to several potyviruses, including zucchini yellow mosaic virus (ZYMV) and papaya ringspot virus (PRSV) [123].

CRISPR/Cas9 has also been applied for the development of insect-resistant vegetable varieties by targeting genes essential for insect survival or reproduction. For instance, the knockout of the *Abdominal-A* (*Abd-A*) gene in the cotton bollworm (*Helicoverpa armigera*) using CRISPR/Cas9 has been shown to disrupt the insect's development and reduce its survival on tomato plants [124].

The use of genetic engineering techniques, such as transgenic approaches, RNAi, and CRISPR/Cas9, offers a powerful tool for developing pest- and disease-resistant vegetable varieties. However, the successful application of these techniques requires a thorough understanding of the target pest or pathogen biology, the identification of suitable target genes, and the development of efficient transformation and regeneration protocols for the target vegetable crop [125]. Furthermore, the regulatory and public acceptance issues associated with genetically modified crops need to be addressed to facilitate the widespread adoption of these technologies in vegetable production systems.

7. Integrated Pest and Disease Management (IPDM) Strategies:Integrated pest and disease management (IPDM) is a holistic approach that combines various strategies, such as cultural practices, biological control, biopesticides, plant activators, and genetic resistance, to manage pests and diseases in vegetable crops while minimizing the reliance on chemical pesticides [126]. IPDM aims to maintain pest and disease populations below economically damaging levels, promote the sustainable use of natural resources, and ensure the safety of food and the environment [127].

7.1. Principles and Components of IPDM The key principles of IPDM include:

1. **Prevention**: The use of cultural practices, such as crop rotation, sanitation, and resistant varieties, to prevent or reduce the incidence of pests and diseases.
2. **Monitoring**: The regular surveillance of pest and disease populations using various methods, such as visual inspection, traps, and diagnostic tools, to inform management decisions.
3. **Intervention**: The use of various control tactics, such as biological control, biopesticides, and plant activators, to suppress pest and disease populations when they exceed economic thresholds.
4. **Integration**: The combination of multiple control tactics in a coordinated and complementary manner to achieve optimal pest and disease management.
5. **Evaluation**: The continuous assessment of the effectiveness and sustainability of IPDM strategies to inform future management decisions and improvements [128].

The main components of IPDM in vegetable crops include:

- **Cultural control**: The use of practices such as crop rotation, intercropping, sanitation, and resistant varieties to create an environment that is less favorable for pests and diseases.
- **Biological control**: The use of natural enemies, such as predators, parasitoids, and antagonistic microbes, to suppress pest and disease populations.
- **Biopesticides**: The use of natural products, such as microbial pesticides, botanical extracts, and semiochemicals, to control pests and diseases.
- **Plant activators**: The use of compounds, such as salicylic acid, jasmonic acid, and beta-aminobutyric acid (BABA), to induce the plant's natural defense mechanisms against pests and diseases.
- **Genetic resistance**: The use of resistant varieties, developed through traditional breeding or genetic engineering, to minimize the impact of pests and diseases.
- **Chemical control**: The judicious use of synthetic pesticides, based on economic thresholds and in combination with other control tactics, to manage pests and diseases when necessary [129].

7.2. Monitoring and Decision Support Tools Effective IPDM relies on the accurate and timely monitoring of pest and disease populations to inform management decisions. Various monitoring methods and decision support tools have been developed to assist farmers and extension agents in implementing IPDM strategies in vegetable crops.

- **Pest and disease forecasting models**: These models use weather data, crop phenology, and pest and disease biology to predict the risk of pest and disease outbreaks and inform the timing of control interventions [130]. Examples include the TOM-CAST model for tomato early blight and septoria leaf spot [131] and the MELCAST model for cucumber downy mildew [132].
- **Trap-based monitoring**: The use of various types of traps, such as pheromone traps, sticky traps, and light traps, to monitor the presence and abundance of insect pests in the field [133]. The data collected from these traps can be used to determine the need for and timing of control interventions.
- **Diagnostic tools**: The use of various diagnostic methods, such as visual inspection, serological tests (e.g., ELISA), and molecular techniques (e.g., PCR), to identify and quantify pest and disease populations in the field [134]. These tools can help in the early detection of pests and diseases and the selection of appropriate control tactics.
- **Remote sensing**: The use of satellite imagery, aerial photography, and unmanned aerial vehicles (UAVs) to monitor crop health and detect pest and disease outbreaks over large areas [135]. These technologies can provide valuable information for precision pest and disease management and the optimization of control interventions.
- **Decision support systems (DSS)**: The use of computer-based tools that integrate various sources of information, such as weather data, crop growth models, and pest and disease forecasts, to provide recommendations for IPDM decision-making [136]. Examples include the VegSyst DSS for vegetable crops [137] and the DESSAC DSS for greenhouse tomato production [138].

7.3. Case Studies of Successful IPDM Implementation There are numerous examples of successful IPDM implementation in vegetable production systems worldwide. These case studies demonstrate the potential of IPDM to reduce pesticide use, improve crop yield and quality, and enhance the sustainability of vegetable production.

- **Tomato production in California, USA**: An IPDM program for tomato production in California, which included the use of resistant varieties, crop rotation, monitoring, and targeted pesticide applications, resulted in a 50% reduction in pesticide use and a 25% increase in yield compared to conventional practices [139].
- **Brassica production in Indonesia**: An IPDM program for cabbage and cauliflower production in Indonesia, which incorporated the use of resistant varieties, cultural practices, biological control, and reduced pesticide applications, led to a 60% reduction in pesticide use and a 20% increase in farmer income [140].

- **Cucumber production in China**: An IPDM program for cucumber production in China, which combined the use of grafting, biological control, and targeted pesticide applications, resulted in a 70% reduction in pesticide use and a 30% increase in yield compared to conventional practices [141].
- **Eggplant production in Bangladesh**: An IPDM program for eggplant production in Bangladesh, which included the use of Bt eggplant varieties, cultural practices, and reduced pesticide applications, led to a 80% reduction in pesticide use and a 40% increase in farmer income [142].

These case studies highlight the importance of adapting IPDM strategies to the specific needs and constraints of each cropping system and the need for participatory approaches that engage farmers, researchers, and extension agents in the development and implementation of IPDM programs.

8. Challenges and Future Perspectives Despite the significant advances in the development and application of novel approaches to pest and disease management in vegetable crops, several challenges and opportunities remain to be addressed to ensure the widespread adoption and sustainability of these strategies.

8.1. Resistance Management The development of resistance to pesticides, biopesticides, and plant activators by pests and pathogens is a major challenge facing the long-term sustainability of these management strategies. Resistance can evolve rapidly, especially when a single control tactic is used repeatedly without rotation or integration with other tactics [143]. To prevent or delay the development of resistance, it is essential to implement resistance management strategies, such as:

- **Rotation of control tactics**: The alternation of pesticides, biopesticides, and plant activators with different modes of action to reduce the selection pressure on pests and pathogens [144].
- **Combination of control tactics**: The use of multiple control tactics, such as cultural practices, biological control, and genetic resistance, in addition to pesticides and biopesticides, to diversify the selection pressure on pests and pathogens [145].
- **Monitoring of resistance**: The regular surveillance of pest and pathogen populations for signs of resistance development using bioassays, molecular markers, and field observations [146].
- **Implementation of refuge strategies**: The maintenance of untreated or susceptible pest and pathogen populations to reduce the selection pressure for resistance and preserve the effectiveness of control tactics [147].

8.2. Regulatory and Policy Issues The development and commercialization of novel pest and disease management products, such as biopesticides, plant activators, and genetically engineered crops, are subject to various regulatory and policy issues that can affect their adoption and use in vegetable production systems [148]. These issues include:

- **Registration and approval processes**: The time and cost associated with the registration and approval of new pest and disease management products can be significant, especially for small and medium-sized enterprises [149].

- **Intellectual property rights**: The protection of intellectual property rights, such as patents and plant breeders' rights, can affect the accessibility and affordability of novel pest and disease management products for farmers [150].
- **Public perception and acceptance**: The public perception and acceptance of novel pest and disease management strategies, particularly genetically engineered crops, can vary widely across different regions and cultures, affecting their adoption and use [151].

To address these issues, it is essential to foster dialogue and collaboration among researchers, industry, policymakers, and the public to develop transparent, science-based, and inclusive regulatory frameworks that balance innovation, safety, and accessibility of novel pest and disease management strategies [152].

8.3. Adoption and Technology Transfer The successful adoption and implementation of novel pest and disease management strategies in vegetable production systems require effective technology transfer and capacity building efforts targeting farmers, extension agents, and other stakeholders [153]. Some of the key challenges and opportunities in this area include:

- **Awareness and knowledge**: The lack of awareness and knowledge about novel pest and disease management strategies among farmers and extension agents can hinder their adoption and use. Efforts to disseminate information and provide training on these strategies are essential to overcome this challenge [154].
- **Adaptability and compatibility**: The adaptability and compatibility of novel pest and disease management strategies to the specific needs and constraints of each cropping system and region can affect their adoption and use. Participatory research and development approaches that engage farmers and other stakeholders in the design and testing of these strategies can help ensure their relevance and applicability [155].
- **Access and affordability**: The access and affordability of novel pest and disease management products and technologies can be a significant barrier to their adoption and use, especially for small-scale and resource-poor farmers. Efforts to develop and promote low-cost, locally available, and culturally acceptable solutions are essential to address this challenge [156].
- **Enabling policies and institutions**: The presence of enabling policies and institutions, such as extension services, farmer organizations, and input supply chains, can facilitate the adoption and use of novel pest and disease management strategies. Strengthening these policies and institutions through capacity building, partnerships, and investments is crucial for the successful scaling up and sustainability of these strategies [157].

8.4. Research Priorities and Knowledge Gaps: Despite the significant progress made in the development and application of novel pest and disease management strategies in vegetable crops, several research priorities and knowledge gaps remain to be addressed to further advance and optimize these strategies. Some of the key research priorities and knowledge gaps include:

- **Fundamental biology and ecology of pests and pathogens**: A better understanding of the biology, ecology, and population dynamics of pests and pathogens is essential to develop more effective and sustainable management strategies. This includes research on the genetic diversity, host range, dispersal mechanisms, and environmental adaptations of pests and pathogens [158].
- **Mechanisms of plant resistance and immunity**: Elucidating the molecular and physiological mechanisms underlying plant resistance and immunity to pests and pathogens is crucial for the development of resistant varieties and the optimization of plant activator and elicitor treatments. This includes research on the genetic basis of resistance, the signaling pathways involved in plant defense responses, and the interactions between plants, pests, and pathogens [159].
- **Microbial ecology and plant-microbe interactions**: A deeper understanding of the microbial ecology and plant-microbe interactions in the phytobiome is essential to develop more effective and robust biological control and biopesticide strategies. This includes research on the diversity, functions, and dynamics of microbial communities associated with plants, as well as the mechanisms of microbial antagonism, competition, and induced systemic resistance [160].
- **Integrated and systems-level approaches**: The development and optimization of integrated and systems-level approaches that combine multiple pest and disease management strategies, such as cultural practices, biological control, biopesticides, plant activators, and genetic resistance, is a key research priority. This includes research on the compatibility, synergy, and trade-offs among different strategies, as well as the modeling and decision support tools needed to guide their implementation [161].
- **Impact assessment and economic analysis**: Assessing the agronomic, environmental, and economic impacts of novel pest and disease management strategies is essential to inform their adoption and use by farmers and policymakers. This includes research on the efficacy, sustainability, and cost-effectiveness of these strategies, as well as their effects on crop yield, quality, and ecosystem services [162].

9. Conclusion: The sustainable management of pests and diseases is a critical challenge facing vegetable production systems worldwide. The overreliance on chemical pesticides has led to numerous problems, including the development of resistance, environmental contamination, and human health risks. Novel approaches to pest and disease management, such as cultural practices, biological control, biopesticides, plant activators, and genetic resistance, offer promising alternatives to reduce the dependence on chemical pesticides and improve the sustainability of vegetable production.

The adoption and implementation of these novel approaches require a systems-level understanding of the complex interactions among crops, pests, diseases, and their environment. Integrated pest and disease management (IPDM) strategies that combine multiple control tactics based on this understanding have shown great potential to reduce pesticide use, improve crop yield and quality, and enhance the profitability and resilience of vegetable production systems.

However, several challenges remain to be addressed to ensure the widespread adoption and sustainability of these novel approaches. These include the development of resistance, regulatory and policy issues, technology transfer and capacity building, and research priorities and knowledge gaps. Overcoming these challenges will require concerted efforts and collaborations among researchers, farmers, industry, and policymakers to develop and promote innovative, science-based, and stakeholder-driven solutions.

The future of pest and disease management in vegetable crops lies in the continued development and integration of novel approaches that are effective, sustainable, and adaptable to the changing needs and contexts of vegetable production systems. This will require a paradigm shift from a focus on short-term pest and disease control to a holistic and long-term approach that prioritizes the health and resilience of the entire agroecosystem. By embracing this paradigm shift and investing in the research, development, and adoption of novel pest and disease management strategies, we can ensure the sustainable production of safe, nutritious, and abundant vegetable crops for future generations.

References

1. [1] Food and Agriculture Organization of the United Nations. (2019). FAOSTAT database. Retrieved from http://www.fao.org/faostat/en/#data/QC
2. [2] Oerke, E. C. (2006). Crop losses to pests. The Journal of Agricultural Science, 144(1), 31-43. https://doi.org/10.1017/S0021859605005708
3. [3] Carvalho, F. P. (2017). Pesticides, environment, and food safety. Food and Energy Security, 6(2), 48-60. https://doi.org/10.1002/fes3.108
4. [4] Barzman, M., Bàrberi, P., Birch, A. N. E., Boonekamp, P., Dachbrodt-Saaydeh, S., Graf, B., ... & Sattin, M. (2015). Eight principles of integrated pest management. Agronomy for Sustainable Development, 35(4), 1199-1215. https://doi.org/10.1007/s13593-015-0327-9
5. [5] Mohler, C. L., & Johnson, S. E. (Eds.). (2009). Crop rotation on organic farms: a planning manual. Natural Resource, Agriculture, and Engineering Service (NRAES).
6. [6] Larkin, R. P. (2015). Soil health paradigms and implications for disease management. Annual Review of Phytopathology, 53, 199-221. https://doi.org/10.1146/annurev-phyto-080614-120357
7. [7] Hwang, S. F., Strelkov, S. E., Feng, J., Gossen, B. D., & Howard, R. J. (2012). Plasmodiophora brassicae: a review of an emerging pathogen of the Canadian canola (Brassica napus) crop. Molecular Plant Pathology, 13(2), 105-113. https://doi.org/10.1111/j.1364-3703.2011.00729.x
8. [8] Boudreau, M. A. (2013). Diseases in intercropping systems. Annual Review of Phytopathology, 51, 499-519. https://doi.org/10.1146/annurev-phyto-082712-102246
9. [9] Srinivasan, R., Alvarez, J. M., Cervantes, F., Alatorre-Rosas, R., & Loera-Alvarado, E. (2012). Effectiveness of seven commercial biorational insecticides for managing the primary vector of tomato yellow leaf curl virus, Bemisia tabaci (Hemiptera: Aleyrodidae). Journal of Economic Entomology, 105(6), 2116-2124. https://doi.org/10.1603/EC12080
10. [10] Letourneau, D. K., Armbrecht, I., Rivera, B. S., Lerma, J. M., Carmona, E. J., Daza, M. C., ... & Trujillo, A. R. (2011). Does plant diversity benefit agroecosystems? A synthetic review. Ecological Applications, 21(1), 9-21. https://doi.org/10.1890/09-2026.1
11. [11] Shapiro, L. R., Seidl-Adams, I., De Moraes, C. M., Stephenson, A. G., & Mescher, M. C. (2014). Dynamics of short-and long-term association between a bacterial plant pathogen and its arthropod vector. Scientific Reports, 4(1), 1-7. https://doi.org/10.1038/srep04155

12. [12] Sarfraz, M., Keddie, A. B., & Dosdall, L. M. (2005). Biological control of the diamondback moth, Plutella xylostella: a review. Biocontrol Science and Technology, 15(8), 763-789. https://doi.org/10.1080/09583150500136956
13. [13] Schoeny, A., Menat, J., Darsonval, A., Rouault, F., Jumel, S., & Tivoli, B. (2008). Effect of pea canopy architecture on splash dispersal of Mycosphaerella pinodes conidia. Plant Pathology, 57(6), 1073-1085. https://doi.org/10.1111/j.1365-3059.2008.01888.x
14. [14] Perez, C., Dill-Macky, R., & Kinkel, L. L. (2008). Management of soil microbial communities to enhance populations of Fusarium graminearum-antagonists in soil. Plant and Soil, 302(1), 53-69. https://doi.org/10.1007/s11104-007-9455-6
15. [15] Choudhary, D. K., Prakash, A., & Johri, B. N. (2007). Induced systemic resistance (ISR) in plants: mechanism of action. Indian Journal of Microbiology, 47(4), 289-297. https://doi.org/10.1007/s12088-007-0054-2
16. [16] Pappu, H. R., Jones, R. A., & Jain, R. K. (2009). Global status of tospovirus epidemics in diverse cropping systems: successes achieved and challenges ahead. Virus Research, 141(2), 219-236. https://doi.org/10.1016/j.virusres.2009.01.009
17. [17] Krupinsky, J. M., Bailey, K. L., McMullen, M. P., Gossen, B. D., & Turkington, T. K. (2002). Managing plant disease risk in diversified cropping systems. Agronomy Journal, 94(2), 198-209. https://doi.org/10.2134/agronj2002.1980
18. [18] Miller, S. A., Beed, F. D., & Harmon, C. L. (2009). Plant disease diagnostic capabilities and networks. Annual Review of Phytopathology, 47, 15-38. https://doi.org/10.1146/annurev-phyto-080508-081743
19. [19] Raaijmakers, J. M., Paulitz, T. C., Steinberg, C., Alabouvette, C., & Moënne-Loccoz, Y. (2009). The rhizosphere: a playground and battlefield for soilborne pathogens and beneficial microorganisms. Plant and Soil, 321(1), 341-361. https://doi.org/10.1007/s11104-008-9568-6
20. [20] Bonanomi, G., Antignani, V., Pane, C., & Scala, F. (2007). Suppression of soilborne fungal diseases with organic amendments. Journal of Plant Pathology, 89(3), 311-324.
21. [21\
22. [20] Bonanomi, G., Antignani, V., Pane, C., & Scala, F. (2007). Suppression of soilborne fungal diseases with organic amendments. Journal of Plant Pathology, 89(3), 311-324.
23.] Noble, R., & Coventry, E. (2005). Suppression of soil-borne plant diseases with composts: a review. Biocontrol Science and Technology, 15(1), 3-20. https://doi.org/10.1080/09583150400015904
24. [22] Abawi, G. S., & Widmer, T. L. (2000). Impact of soil health management practices on soilborne pathogens, nematodes and root diseases of vegetable crops. Applied Soil Ecology, 15(1), 37-47. https://doi.org/10.1016/S0929-1393(00)00070-6
25. [23] Mathew, R. P., Feng, Y., Githinji, L., Ankumah, R., & Balkcom, K. S. (2012). Impact of no-tillage and conventional tillage systems on soil microbial communities. Applied and Environmental Soil Science, 2012. https://doi.org/10.1155/2012/548620
26. [24] Gruda, N. (2005). Impact of environmental factors on product quality of greenhouse vegetables for fresh consumption. Critical Reviews in Plant Sciences, 24(3), 227-247. https://doi.org/10.1080/07352680591008628
27. [25] Weintraub, P. G. (2009). Physical control: an important tool in pest management programs. In Biorational Control of Arthropod Pests (pp. 317-324). Springer, Dordrecht. https://doi.org/10.1007/978-90-481-2316-2_12
28. [26] Van Lenteren, J. C. (2000). A greenhouse without pesticides: fact or fantasy?. Crop Protection, 19(6), 375-384. https://doi.org/10.1016/S0261-2194(00)00038-7
29. [27] Postma, J., Willemsen-de Klein, M. J., & van Elsas, J. D. (2000). Effect of the indigenous microflora on the development of root and crown rot caused by Pythium aphanidermatum in cucumber grown on rockwool. Phytopathology, 90(2), 125-133. https://doi.org/10.1094/PHYTO.2000.90.2.125
30. [28] Paulitz, T. C., & Bélanger, R. R. (2001). Biological control in greenhouse systems. Annual Review of Phytopathology, 39(1), 103-133. https://doi.org/10.1146/annurev.phyto.39.1.103

31. [29] Landis, D. A., Wratten, S. D., & Gurr, G. M. (2000). Habitat management to conserve natural enemies of arthropod pests in agriculture. Annual Review of Entomology, 45(1), 175-201. https://doi.org/10.1146/annurev.ento.45.1.175
32. [30] Gurr, G. M., Wratten, S. D., Landis, D. A., & You, M. (2017). Habitat management to suppress pest populations: progress and prospects. Annual Review of Entomology, 62, 91-109. https://doi.org/10.1146/annurev-ento-031616-035050
33. [31] Ratnadass, A., Fernandes, P., Avelino, J., & Habib, R. (2012). Plant species diversity for sustainable management of crop pests and diseases in agroecosystems: a review. Agronomy for Sustainable Development, 32(1), 273-303. https://doi.org/10.1007/s13593-011-0022-4
34. [32] Gentz, M. C., Murdoch, G., & King, G. F. (2010). Tandem use of selective insecticides and natural enemies for effective, reduced-risk pest management. Biological Control, 52(3), 208-215. https://doi.org/10.1016/j.biocontrol.2009.07.012
35. [33] Huang, N., Enkegaard, A., Osborne, L. S., Ramakers, P. M., Messelink, G. J., Pijnakker, J., & Murphy, G. (2011). The banker plant method in biological control. Critical Reviews in Plant Sciences, 30(3), 259-278. https://doi.org/10.1080/07352689.2011.572055
36. [34] Van Driesche, R., Hoddle, M., & Center, T. (2008). Control of pests and weeds by natural enemies: an introduction to biological control. John Wiley & Sons.
37. [35] Van Lenteren, J. C. (2012). The state of commercial augmentative biological control: plenty of natural enemies, but a frustrating lack of uptake. BioControl, 57(1), 1-20. https://doi.org/10.1007/s10526-011-9395-1
38. [36] Obrycki, J. J., Harwood, J. D., Kring, T. J., & O'Neil, R. J. (2009). Aphidophagy by Coccinellidae: application of biological control in agroecosystems. Biological Control, 51(2), 244-254. https://doi.org/10.1016/j.biocontrol.2009.05.009
39. [37] McEwen, P., New, T. R., & Whittington, A. E. (Eds.). (2007). Lacewings in the crop environment. Cambridge University Press.
40. [38] McMurtry, J. A., De Moraes, G. J., & Sourassou, N. F. (2013). Revision of the lifestyles of phytoseiid mites (Acari: Phytoseiidae) and implications for biological control strategies. Systematic and Applied Acarology, 18(4), 297-320. https://doi.org/10.11158/saa.18.4.1
41. [39] Hoddle, M. S., Van Driesche, R. G., & Sanderson, J. P. (1998). Biology and use of the whitefly parasitoid Encarsia formosa. Annual Review of Entomology, 43(1), 645-669. https://doi.org/10.1146/annurev.ento.43.1.645
42. [40] Boivin, G., Hance, T., & Brodeur, J. (2012). Aphid parasitoids in biological control. Canadian Journal of Plant Science, 92(1), 1-12. https://doi.org/10.4141/cjps2011-045
43. [41] Smith, S. M. (1996). Biological control with Trichogramma: advances, successes, and potential of their use. Annual Review of Entomology, 41(1), 375-406. https://doi.org/10.1146/annurev.en.41.010196.002111
44. [42] Harman, G. E. (2006). Overview of mechanisms and uses of Trichoderma spp. Phytopathology, 96(2), 190-194. https://doi.org/10.1094/PHYTO-96-0190
45. [43] Ongena, M., & Jacques, P. (2008). Bacillus lipopeptides: versatile weapons for plant disease biocontrol. Trends in Microbiology, 16(3), 115-125. https://doi.org/10.1016/j.tim.2007.12.009
46. [44] Kloepper, J. W., Ryu, C. M., & Zhang, S. (2004). Induced systemic resistance and promotion of plant growth by Bacillus spp. Phytopathology, 94(11), 1259-1266. https://doi.org/10.1094/PHYTO.2004.94.11.1259
47. [45] Inglis, G. D., Goettel, M. S., Butt, T. M., & Strasser, H. (2001). Use of hyphomycetous fungi for managing insect pests. In T. M. Butt, C. Jackson, & N. Magan (Eds.), Fungi as biocontrol agents: Progress, problems and potential (pp. 23-69). CABI Publishing. https://doi.org/10.1079/9780851993560.0023
48. [46] Louda, S. M., Pemberton, R. W., Johnson, M. T., & Follett, P. A. (2003). Nontarget effects—the Achilles' heel of biological control? Retrospective analyses to reduce risk associated with biocontrol introductions. Annual Review of Entomology, 48(1), 365-396. https://doi.org/10.1146/annurev.ento.48.060402.102800
49. [47] Van Driesche, R. G., & Bellows, T. S. (1996). Biological Control. Springer Science & Business Media.

50. [48] Chandler, D., Bailey, A. S., Tatchell, G. M., Davidson, G., Greaves, J., & Grant, W. P. (2011). The development, regulation and use of biopesticides for integrated pest management. Philosophical Transactions of the Royal Society B: Biological Sciences, 366(1573), 1987-1998. https://doi.org/10.1098/rstb.2010.0390
51. [49] Lacey, L. A., Frutos, R., Kaya, H. K., & Vail, P. (2001). Insect pathogens as biological control agents: do they have a future?. Biological Control, 21(3), 230-248. https://doi.org/10.1006/bcon.2001.0938
52. [50] Collier, T., & Van Steenwyk, R. (2004). A critical evaluation of augmentative biological control. Biological Control, 31(2), 245-256. https://doi.org/10.1016/j.biocontrol.2004.05.001
53. [51] Copping, L. G., & Menn, J. J. (2000). Biopesticides: a review of their action, applications and efficacy. Pest Management Science: formerly Pesticide Science, 56(8), 651-676. https://doi.org/10.1002/1526-4998(200008)56:8<651::AID-PS201>3.0.CO;2-U
54. [52] Glare, T., Caradus, J., Gelernter, W., Jackson, T., Keyhani, N., Köhl, J., ... & Stewart, A. (2012). Have biopesticides come of age?. Trends in Biotechnology, 30(5), 250-258. https://doi.org/10.1016/j.tibtech.2012.01.003
55. [53] Bravo, A., Likitvivatanavong, S., Gill, S. S., & Soberón, M. (2011). Bacillus thuringiensis: a story of a successful bioinsecticide. Insect Biochemistry and Molecular Biology, 41(7), 423-431. https://doi.org/10.1016/j.ibmb.2011.02.006
56. [54] Shelton, A. M., Zhao, J. Z., & Roush, R. T. (2002). Economic, ecological, food safety, and social consequences of the deployment of Bt transgenic plants. Annual Review of Entomology, 47(1), 845-881. https://doi.org/10.1146/annurev.ento.47.091201.145309
57. [55] Haas, D., & Défago, G. (2005). Biological control of soil-borne pathogens by fluorescent pseudomonads. Nature Reviews Microbiology, 3(4), 307-319. https://doi.org/10.1038/nrmicro1129
58. [56] Ji, P., Campbell, H. L., Kloepper, J. W., Jones, J. B., Suslow, T. V., & Wilson, M. (2006). Integrated biological control of bacterial speck and spot of tomato under field conditions using foliar biological control agents and plant growth-promoting rhizobacteria. Biological Control, 36(3), 358-367. https://doi.org/10.1016/j.biocontrol.2005.09.003
59. [57] Romero, A. M., Kousik, C. S., & Ritchie, D. F. (2001). Resistance to bacterial spot in bell pepper induced by acibenzolar-S-methyl. Plant Disease, 85(2), 189-194. https://doi.org/10.1094/PDIS.2001.85.2.189
60. [58] Butt, T. M., Jackson, C., & Magan, N. (Eds.). (2001). Fungi as biocontrol agents: progress problems and potential. CABI.
61. [59] Faria, M. R. D., & Wraight, S. P. (2007). Mycoinsecticides and mycoacaricides: a comprehensive list with worldwide coverage and international classification of formulation types. Biological Control, 43(3), 237-256. https://doi.org/10.1016/j.biocontrol.2007.08.001
62. [60] Shah, P. A., & Pell, J. K. (2003). Entomopathogenic fungi as biological control agents. Applied Microbiology and Biotechnology, 61(5), 413-423. https://doi.org/10.1007/s00253-003-1240-8
63. [61] Harman, G. E., Howell, C. R., Viterbo, A., Chet, I., & Lorito, M. (2004). Trichoderma species—opportunistic, avirulent plant symbionts. Nature Reviews Microbiology, 2(1), 43-56. https://doi.org/10.1038/nrmicro797
64. [62] Benítez, T., Rincón, A. M., Limón, M. C., & Codón, A. C. (2004). Biocontrol mechanisms of Trichoderma strains. International Microbiology, 7(4), 249-260.
65. [63] Szewczyk, B., Hoyos-Carvajal, L., Paluszek, M., Skrzecz, I., & Lobo de Souza, M. (2006). Baculoviruses—re-emerging biopesticides. Biotechnology Advances, 24(2), 143-160. https://doi.org/10.1016/j.biotechadv.2005.09.001
66. [64] Moscardi, F. (1999). Assessment of the application of baculoviruses for control of Lepidoptera. Annual Review of Entomology, 44(1), 257-289. https://doi.org/10.1146/annurev.ento.44.1.257
67. [65] Lacey, L. A., Thomson, D., Vincent, C., & Arthurs, S. P. (2008). Codling moth granulovirus: a comprehensive review. Biocontrol Science and Technology, 18(7), 639-663. https://doi.org/10.1080/09583150802267046

68. [66] Isman, M. B. (2006). Botanical insecticides, deterrents, and repellents in modern agriculture and an increasingly regulated world. Annual Review of Entomology, 51, 45-66. https://doi.org/10.1146/annurev.ento.51.110104.151146
69. [67] Schmutterer, H. (1990). Properties and potential of natural pesticides from the neem tree, Azadirachta indica. Annual Review of Entomology, 35(1), 271-297. https://doi.org/10.1146/annurev.en.35.010190.001415
70. [68] Casida, J. E. (1980). Pyrethrum flowers and pyrethroid insecticides. Environmental Health Perspectives, 34, 189-202. https://doi.org/10.1289/ehp.8034189
71. [69] Ankri, S., & Mirelman, D. (1999). Antimicrobial properties of allicin from garlic. Microbes and Infection, 1(2), 125-129. https://doi.org/10.1016/S1286-4579(99)80003-3
72. [70] El Hadrami, A., Adam, L. R., El Hadrami, I., & Daayf, F. (2010). Chitosan in plant protection. Marine Drugs, 8(4), 968-987. https://doi.org/10.3390/md8040968
73. [71] Witzgall, P., Kirsch, P., & Cork, A. (2010). Sex pheromones and their impact on pest management. Journal of Chemical Ecology, 36(1), 80-100. https://doi.org/10.1007/s10886-009-9737-y
74. [72] Witzgall, P., Stelinski, L., Gut, L., & Thomson, D. (2008). Codling moth management and chemical ecology. Annual Review of Entomology, 53, 503-522. https://doi.org/10.1146/annurev.ento.53.103106.093323
75. [73] Deliopoulos, T., Kettlewell, P. S., & Hare, M. C. (2010). Fungal disease suppression by inorganic salts: a review. Crop Protection, 29(10), 1059-1075. https://doi.org/10.1016/j.cropro.2010.05.011
76. [74] Sporleder, M., & Lacey, L. A. (2013). Biopesticides. In A. Alyokhin, C. Vincent, & P. Giordanengo (Eds.), Insect pests of potato (pp. 463-497). Academic Press. https://doi.org/10.1016/B978-0-12-386895-4.00016-8
77. [75] Vallad, G. E., & Goodman, R. M. (2004). Systemic acquired resistance and induced systemic resistance in conventional agriculture. Crop Science, 44(6), 1920-1934. https://doi.org/10.2135/cropsci2004.1920
78. [76] Durrant, W. E., & Dong, X. (2004). Systemic acquired resistance. Annual Review of Phytopathology, 42, 185-209. https://doi.org/10.1146/annurev.phyto.42.040803.140421
79. [77] Fu, Z. Q., & Dong, X. (2013). Systemic acquired resistance: turning local infection into global defense. Annual Review of Plant Biology, 64, 839-863. https://doi.org/10.1146/annurev-arplant-042811-105606
80. [78] Gozzo, F., & Faoro, F. (2013). Systemic acquired resistance (50 years after discovery): moving from the lab to the field. Journal of Agricultural and Food Chemistry, 61(51), 12473-12491. https://doi.org/10.1021/jf404156x
81. [79] Csinos, A. S., Pappu, H. R., McPherson, R. M., & Stephenson, M. G. (2001). Management of Tomato spotted wilt virus in flue-cured tobacco with acibenzolar-S-methyl and imidacloprid. Plant Disease, 85(3), 292-296. https://doi.org/10.1094/PDIS.2001.85.3.292
82. [80] Louws, F. J., Wilson, M., Campbell, H. L., Cuppels, D. A., Jones, J. B., Shoemaker, P. B., ... & Miller, S. A. (2001). Field control of bacterial spot and bacterial speck of tomato using a plant activator. Plant Disease, 85(5), 481-488. https://doi.org/10.1094/PDIS.2001.85.5.481
83. [81] Ishii, H., Fraaije, B. A., Sugiyama, T., Noguchi, K., Nishimura, K., Takeda, T., ... & Hollomon, D. W. (2001). Occurrence and molecular characterization of strobilurin resistance in cucumber powdery mildew and downy mildew. Phytopathology, 91(12), 1166-1171. https://doi.org/10.1094/PHYTO.2001.91.12.1166
84. [82] Inbar, M., Doostdar, H., Sonoda, R. M., Leibee, G. L., & Mayer, R. T. (1998). Elicitors of plant defensive systems reduce insect densities and disease incidence. Journal of Chemical Ecology, 24(1), 135-149. https://doi.org/10.1023/A:1022397130895
85. [83] Glazebrook, J. (2005). Contrasting mechanisms of defense against biotrophic and necrotrophic pathogens. Annual Review of Phytopathology, 43, 205-227. https://doi.org/10.1146/annurev.phyto.43.040204.135923
86. [84] Pieterse, C. M., Zamioudis, C., Berendsen, R. L., Weller, D. M., Van Wees, S. C., & Bakker, P. A. (2014). Induced systemic resistance by beneficial microbes. Annual Review of Phytopathology, 52, 347-375. https://doi.org/10.1146/annurev-phyto-082712-102340

87. [85] Metraux, J. P., Signer, H., Ryals, J., Ward, E., Wyss-Benz, M., Gaudin, J., ... & Inverardi, B. (1990). Increase in salicylic acid at the onset of systemic acquired resistance in cucumber. Science, 250(4983), 1004-1006. https://doi.org/10.1126/science.250.4983.1004
88. [86] Mandal, B., Mandal, S., Csinos, A. S., Martinez, N., Culbreath, A. K., & Pappu, H. R. (2008). Biological and molecular analyses of the acibenzolar-S-methyl-induced systemic acquired resistance in flue-cured tobacco against Tomato spotted wilt virus. Phytopathology, 98(2), 196-204. https://doi.org/10.1094/PHYTO-98-2-0196
89. [87] Thaler, J. S., Owen, B., & Higgins, V. J. (2004). The role of the jasmonate response in plant susceptibility to diverse pathogens with a range of lifestyles. Plant Physiology, 135(1), 530-538. https://doi.org/10.1104/pp.104.041566
90. [88] Birkett, M. A., Campbell, C. A., Chamberlain, K., Guerrieri, E., Hick, A. J., Martin, J. L., ... & Wadhams, L. J. (2000). New roles for cis-jasmone as an insect semiochemical and in plant defense. Proceedings of the National Academy of Sciences, 97(16), 9329-9334. https://doi.org/10.1073/pnas.160241697
91. [89] Cohen, Y. R. (2002). β-aminobutyric acid-induced resistance against plant pathogens. Plant Disease, 86(5), 448-457. https://doi.org/10.1094/PDIS.2002.86.5.448
92. [90] Jakab, G., Cottier, V., Toquin, V., Rigoli, G., Zimmerli, L., Métraux, J. P., & Mauch-Mani, B. (2001). β-Aminobutyric acid-induced resistance in plants. European Journal of Plant Pathology, 107(1), 29-37. https://doi.org/10.1023/A:1008730721037
93. [91] Cohen, Y., Rubin, A. E., & Kilfin, G. (2010). Mechanisms of induced resistance in lettuce against Bremia lactucae by DL-β-amino-butyric acid (BABA). European Journal of Plant Pathology, 126(4), 553-573. https://doi.org/10.1007/s10658-009-9564-6
94. [92] Silue, D., Pajot, E., & Cohen, Y. (2002). Induction of resistance to downy mildew (Peronospora parasitica) in cauliflower by DL-β-amino-n-butanoic acid (BABA). Plant Pathology, 51(1), 97-102. https://doi.org/10.1046/j.1365-3059.2002.00664.x
95. [93] Cohen, Y., Rubin, A. E., Galperin, M., Schuster, S., & Temkin, R. (2010). Protection against foliar diseases in cucumber, pepper and tomato by DL-3-amino-n-butanoic acid (BABA). Phytoparasitica, 38(5), 439-448. https://doi.org/10.1007/s12600-010-0118-4
96. [94] Cohen, Y., & Gisi, U. (1994). Systemic translocation of 14C-DL-3-aminobutyric acid in tomato plants in relation to induced resistance against Phytophthora infestans. Physiological and Molecular Plant Pathology, 45(6), 441-456. https://doi.org/10.1016/S0885-5765(05)80041-9
97. [95] Pappu, H. R., Csinos, A. S., McPherson, R. M., Jones, D. C., & Stephenson, M. G. (2000). Effect of acibenzolar-S-methyl and imidacloprid on suppression of tomato spotted wilt Tospovirus in flue-cured tobacco. Crop Protection, 19(5), 349-354. https://doi.org/10.1016/S0261-2194(00)00028-6
98. [96] Hadwiger, L. A. (2013). Multiple effects of chitosan on plant systems: solid science or hype. Plant Science, 208, 42-49. https://doi.org/10.1016/j.plantsci.2013.03.007
99. [97] Jayaraj, J., Wan, A., Rahman, M., & Punja, Z. K. (2008). Seaweed extract reduces foliar fungal diseases on carrot. Crop Protection, 27(10), 1360-1366. https://doi.org/10.1016/j.cropro.2008.05.005
100. [98] Daayf, F., Ongena, M., Boulanger, R., El Hadrami, I., & Bélanger, R. R. (2000). Induction of phenolic compounds in two cultivars of cucumber by treatment of healthy and powdery mildew-infected plants with extracts of Reynoutria sachalinensis. Journal of Chemical Ecology, 26(7), 1579-1593. https://doi.org/10.1023/A:1005578510954
101. [99] Wei, G., Kloepper, J. W., & Tuzun, S. (1996). Induced systemic resistance to cucumber diseases and increased plant growth by plant growth-promoting rhizobacteria under field conditions. Phytopathology, 86(2), 221-224. https://doi.org/10.1094/Phyto-86-221
102. [100] Jones, J. B., Bouzar, H., Stall, R. E., Almira, E. C., Roberts, P. D., Bowen, B. W., ... & Chun, J. (2000). Systematic analysis of xanthomonads (Xanthomonas spp.) associated with pepper and tomato lesions. International Journal of Systematic and Evolutionary Microbiology, 50(3), 1211-1219. https://doi.org/10.1099/00207713-50-3-1211
103. [101] McGrath, M. T. (2001). Fungicide resistance in cucurbit powdery mildew: experiences and challenges. Plant Disease, 85(3), 236-245. https://doi.org/10.1094/PDIS.2001.85.3.236

104. [102] Schmitt, A., Kunz, S., Nandi, S., Seddon, B., & Ernst, A. (2002). Use of Reynoutria sachalinensis plant extracts, clay preparations and Brevibacillus brevis against fungal diseases of grape berries. In 10th International Conference on Cultivation Technique and Phytopathological Problems in Organic Fruit-Growing and Viticulture. Proceedings of a conference. Weinsberg, Germany, 4-7 February 2002. (pp. 146-151). Fördergemeinschaft Ökologischer Obstbau eV (FÖKO).
105. [103] Konstantinidou-Doltsinis, S., & Schmitt, A. (1998). Impact of treatment with plant extracts from Reynoutria sachalinensis (F. Schmidt) Nakai on intensity of powdery mildew severity and yield in cucumber under high disease pressure. Crop Protection, 17(8), 649-656. https://doi.org/10.1016/S0261-2194(98)00066-0
106. [104] Sultana, B., Anwar, F., & Przybylski, R. (2007). Antioxidant activity of phenolic components present in barks of Azadirachta indica, Terminalia arjuna, Acacia nilotica, and Eugenia jambolana Lam. trees. Food Chemistry, 104(3), 1106-1114. https://doi.org/10.1016/j.foodchem.2007.01.019
107. [105] Walters, D., Walsh, D., Newton, A., & Lyon, G. (2005). Induced resistance for plant disease control: maximizing the efficacy of resistance elicitors. Phytopathology, 95(12), 1368-1373. https://doi.org/10.1094/PHYTO-95-1368
108. [106] Collinge, D. B., Jørgensen, H. J., Lund, O. S., & Lyngkjær, M. F. (2010). Engineering pathogen resistance in crop plants: current trends and future prospects. Annual Review of Phytopathology, 48, 269-291. https://doi.org/10.1146/annurev-phyto-073009-114430
109. [107] Punja, Z. K. (2001). Genetic engineering of plants to enhance resistance to fungal pathogens—a review of progress and future prospects. Canadian Journal of Plant Pathology, 23(3), 216-235. https://doi.org/10.1080/07060660109506935
110. [108] Dangl, J. L., Horvath, D. M., & Staskawicz, B. J. (2013). Pivoting the plant immune system from dissection to deployment. Science, 341(6147), 746-751. https://doi.org/10.1126/science.1236011
111. [109] Shelton, A. M., Hossain, M. J., Paranjape, V., Azad, A. K., Rahman, M. L., Khan, A. S. M. M. R., ... & McCandless, L. (2018).

CHAPTER - 5

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Edible landscaping and its benefits

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Abstract

Edible landscaping is simply a way of growing of vegetables, fruits, herbs and flowers that will perform multiple functions used for food, flavor, and ornamental appearance. Edible landscaping is an alternative to standard landscaping that produces vegetables, fruits, and herbs for domestic use. Foods that are edible can be planted separately or combined with ornamentals to create aesthetically beautiful designs in already existing yards and gardens. Edibles perform perfectly in the environment, such as the date palm, which is often employed as a big tree, the low-growing perennial hedge made with rosemary, and the perfect substitute for dark-leaved annuals for pot cultivation is purple basil. Due to the raising urbanization and population, the demand for edible landscaping is garnering greater attention because it serves for many purposes. To that end, we will discuss the advantages and application techniques for edible ornamentals in this chapter.

Keywords: Edible landscaping, Edible ornamentals, Edible landscape designs and Vegetable gardens

Plants that can be used for food production are considered as edible. Both food plants and ornamental plants can be used in landscaping that is edible. The utilization of edible plants as landscaping accents is known as edible landscaping. These plants are utilized both for food and for aesthetic purposes. A progressive food systems strategy known as edible landscaping, often known as foodscaping, encourages everyone to promote local food in their homes, businesses, and public areas (Thompson and Sokolowski, 2016).

Food-producing plants are used in home landscaping as part of edible landscaping. It creates aesthetically beautiful designs out of fruit and nut trees, berry bushes, vegetables, herbs, edible flowers, and other ornamental plants. Large agricultural landscapes, urban settings (such as sidewalks, rooftops, and indoor spaces), community gardens, and one's own backyard are all possible locations and designs for these gardens (Mackalvie, 2014).

Simply defined, edible landscaping involves replacing just decorative plants with food-producing ones. The use of edible landscaping will enable the development of a multipurpose landscape that yields fruits, vegetables, and other produce in exchange for the use of water, fertilizer, and labor. An edible landscape can be just as lovely as a conventional one; in fact, many edibles' bright fruits and foliage are extremely lovely. In addition to fruits and vegetables, edible landscapes can also feature medicinal and aromatic plants like geranium, peppermint, Thyme, Rosemary, sage, Echinacea, and even contain kiwi, apple, cherry, fig, pear, strawberry, black berry, and other berries (Filiz Celik, 2017)

According to Worden and Brown (2007), these designs can incorporate 1–100% edible species and can adopt any garden style. The practical integration of food plants into an aesthetic or decorative setting is known as edible landscaping. In edible landscaping, almost any herb can be used (Creasy, 2010).

The Benefits of Edible Landscapes

Improved Taste and Nutrition of Food:

Most of the plants have their highest nutrient and taste content right after harvest. Fresh foods from the edible landscape can be consumed immediately after harvesting, as opposed to days or weeks afterward. Additionally, farmers of edible landscapes have access to a wide range of remarkable and tasty cultivars that are unavailable at food shops.

Increased Food Security:

By creating an edible landscape, you may lessen your reliance on unreliable foreign food sources.

Reduced Food Costs:

Some foods are very productive and cost-effective to produce at home rather than buy.

Convenience:

It may be easier to prepare meals when you have fresher, healthier items nearby , which can help you include them in your diet.

Fun and Exercise:

Growing your own food may be fulfilling and enjoyable, and the exercise you get from it can keep you in shape.

Sustainability:

Using less energy and conserving the environment can be accomplished in large part by eating locally sourced food.

By adding a distinctive ornamental element with added health, aesthetic, and financial benefits, using edibles in landscape design can improve a garden (Creasy, 2010). There are numerous benefits to including food plants in residential landscaping. These consist of:

- To experience the flavor and freshness of home-grown, fully ripened fruits and vegetables,
- To grow unusual varieties not available in stores,

- To get outside, interact with the natural world, and have fun (Beck and Quigley, 2001),
- To enable people to develop a food community around them and become more connected to their land and food, as well as to share locally grown foods with their friends and neighbors (Worden and Brown, 2007).

Functions of Edible Landscaping:

Production

Non-commercial cultivation of food for local communities. Gardening which is edible Landscape design for sustainable productivity and resource efficiency.

Energy management

Local food production saves energy used in packing, chilling, and shipping. Create transportation networks for a more efficient food delivery system.

Waste management

Organic waste recycling for compost generation and safe food development Create a garbage collecting and composting system for your community.

Biodiversity

Landscape design can accommodate a diverse array of native and imported plant species. Reshaping the landscape allocation to include more gardens and farms.

Microclimate control

Landscape typically modifies the microclimate by controlling humidity, providing wind protection, and offering shade. Establishing an edible habitat that allows for air movement in order to avoid climate warming conditions.

Economic revitalization

Edible ornamentals provide additional employment in areas with low incomes. Develop a social network to connect residents with new possibilities for employment.

Community socialization

Gardening and the exchange of food items promote socialization among people living there. Integration of farming and other forms of social activity

Public health

Residents' health and physical activity are frequently improved when they have free access to fresh fruits and vegetables and other natural locations. Explore the possibility of healthy lifestyle improvement via community programming.

Cultural heritage

Edible landscaping plants may provide access to traditional ethnic foods that are often unavailable to immigrant residents. Providing communal edible landscaping to communities with a large immigrant population

Education

During summer holidays, gardening education programs should be held to teach children and adults about food production, crops, nutrition, the environment, and other cultures.

The Importance of Edible Landscaping for Urban Environments

54% of today's world population living in urban areas that is expected to increase to 66% by 2050. According to projections, the population of cities could increase by 2.5 billion people by 2050 as a result of urbanization and global population growth. The global urban population has significantly increased, making managing urban areas one of the most significant development concerns of the twenty-first century (Filiz Celik, 2017)

Agriculture is the primary user of land resources in the majority of countries, and changes in agricultural land use are one of the key drivers of both local and global environmental change. Soil sealing, the process of turning agricultural land into artificial surfaces, can have a variety of negative environmental effects on water, soil, and biodiversity resources. As a result of increasing demand for urban, industrial, and infrastructural regions, amenity areas, and partly as a result of land abandonment, industrialized countries have seen a general decline in agricultural areas over the past few decades. Land use changes from agricultural land to artificial surfaces like transportation infrastructure (highways, railroads, etc.), urban sprawl (housing and industrial complexes), tourism and recreational amenities. The ecology and agricultural landscapes are significantly impacted by increased land development, which also frequently raises property prices. When compared to the instance of land abandonment, the impact of changing urban land is certainly far more diverse. (Filiz Celik, 2017)

Table 1: Plants suitable for edible landscaping and its functions

S.No.	Crop	Scientific Name	Utilization in Landscaping
1.	Strawberry	*Fragaria sps*	Strawberry can be planted in the landscape in a variety of forms, including as a slope ground cover, in hanging baskets, and vertically.
2.	Mint	*Mentha sps*	Mint is regarded as the ideal ground cover since it grows very quickly and comes back after being cut multiple times throughout the year. It is also appropriate for hanging baskets and containers.
3.	Asparagus	*Asparagus officinalis*	Because it grows similarly to decorative asparagus, asparagus can be cultivated in garden beds and garden borders.
4.	Sage	*Salvia officinalis*	In recognition of the decorative value of its leaves and blossoms, sage plants are commonly used in gardens. Sage can be cultivated in flower beds or as a tiny biennial hedge.
5.	Rosemary	*Rosmarinus officinalis*	Because it is drought-tolerant, the plant has a long tradition in landscaping as a tiny hedge, or flower border, and can be cultivated in outdoor pots.
6.	Sweet basil	*Ocimum basilicum*	Sweet basil, either green or purple, is an excellent plant for small hedges, borders, or growing as a

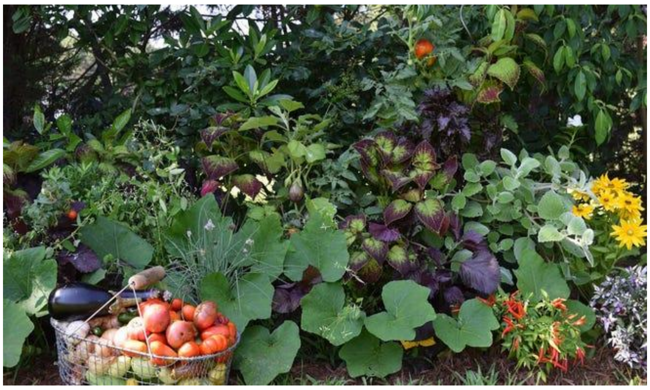
			container display.
7.	Kale	*Brassica oleracea var. acephala*	Kale is an excellent bedding plant that may be used for creating colorful beds of various shapes or as a single plant in containers.
8.	Blackberry	*Rubus allegheniensis*	During the flowering and fruiting seasons, the plants are visually appealing. Blackberry canes can be used to make wire fences to divide areas.
9.	Red Raspberry	*Rubus idaeus*	It can be employed as a single shrub or in a group in shaded regions under an ancient tree with an extended canopy, based on its wild growth patterns.
10.	Blueberry	*Vaccinium corymbosum*	Blueberry shrubs are good for the establishment of low hedges.
11.	Pomegranate	*Punica granatum*	The edible pomegranate is an excellent choice for growth in poor soil conditions since it is drought and salinity-tolerant and produces a huge red blossom for an extended period of time. The blossom of edible pomegranate is identical to that of ornamental types that do not bear fruits.
12.	Cashew	*Anacardium occidentale*	Cashew is a well-known nut, and the fruit is quite tasty, containing one seed that is famous for being roasted before eating.
13.	Custard apple	*Annona squamosa*	Due to its small stature, the tree can be grown in a straight path to separate areas. It can also be cultivated as a single plant over lawns.
14.	Mulberry	*Morus alba, Morus nigra*	Mulberry is a deciduous tree, thus it is best grown away from swimming pools in the garden. It can be utilized as a shade tree in the summer and to enjoy the sun in the winter.
15.	Papaya	*Carica papaya*	Papaya has a palm-like structure, it is an ideal option for planting exclusive trees in the center of flower beds, groups in a corner, and sometimes in a row.
16.	Hazelnut	*Corylus species*	Because this little bush grows quickly, it is appropriate for use as a fence or adjacent to tree lines.
17.	Citrus	*Citrus sps*	Citrus trees cultivated in pots were popular in historical gardens during the seventeenth and eighteenth centuries due to their powerful perfume and delicious fruits. Until recently, most private gardens had to feature at least one citrus species, and most owners preferred lemon trees. Trees can be grown in pots, either individually or in groups.

18.	Peach	*Prunus persica*	Peach trees are popular in landscaping because of their pink blooms that develop on the wood before the leaves. It is also ideal for containers and is appreciated by Bonsai enthusiasts.
19.	Prickly pear cactus	*Opuntia species*	Opuntia is commonly used in rock gardens and sandy cliffs due to its arid tolerance. It may not require watering after it gets established in the soil.
20.	Lotus	*Nelumbo species*	Nelumbo is mostly utilized in landscape ponds for its beautiful leaves and blossoms, and it was employed by ancient Egyptians, Japanese, and Chinese.
21.	Water lily	*Nymphaea odorata*	Nymphaea is another example of an edible aesthetically pleasing plant that, like Nelumbo, is utilized in landscape in ponds for its beautiful leaves and flowers.
22.	Canna lily	*Canna indica*	Canna is a common landscaping plant that is placed in flower beds or along tree lines because of its glossy leaves and lovely flowers.
23.	Hops	*Humulus lupulus*	Hops vines are traditional vines used to cover arches and pergolas.
24.	Kiwi	*Actinidia deliciosa*	The deciduous vine will be an excellent substitute for traditional landscaping climber plants.
25.	Lemongras s	*Cymbopogon citratus*	It has a nice lemony aroma and may be grown in pots. It is used in food preparation, beverages, natural remedies, household products, and personal-care products.
26.	Onion chives	*Allium schoenoprasum*	Chives can also be utilized for landscaping as beds.
27.	Coriander	*Coriandrum sativum*	Coriander is a cool-season annual planted for its aromatic seeds and leaves. It can be cultivated in both pots and beds.
28.	Ginger	*Zingiber officinale*	Used to make food and drinks, medications, and personal-care products. Grown in pots, the rhizomes are harvested 9-12 months after seeding.
29.	Lettuce		

Impact of Covid-19

However, since 2020, there has been a steady increase in the number of literature on issues related to edible landscaping (Clouse, 2022). The effect of COVID-19 was exponentially significant on home gardening and edible landscaping. Consumers are in fact prefer alternate methods of obtaining food and are moving toward foraging, home gardening, and self-sufficiency (Rombach et al., 2022). Studies on horticulture and food have shown that COVID-19 has made consumers concerned about the quality and cost of food, with one effect being a recession and an increase in food prices globally two years after the Covid-19 pandemic began (Cleary and Chenarides, 2022).

Covid-19 has led consumers to change their food-purchasing methods or channels. This is largely a result of the demand and supply imbalance, which includes rising grocery demand and decreasing demand for food consumed away from home (Lusk and McFadden, 2021). Other instances of supply shocks owing to labor concerns including employee illnesses were seen in the food service industry as well as in production and processing. Increased interest in seeds and other horticultural materials required for food production, horticultural YouTube videos, and horticultural influences are signs of this propensity toward food growing (Bulgari et al., 2021). Consumer research indicates rising tendencies in domestic fruit and vegetable production, beekeeping, raising animals, baking, and food processing.



Conclusion

- Residential landscaping, community gardens, and urban green spaces can all include edible landscapes.
- Reintroducing food to urban areas and re-establishing connections between people and their food systems to encourage a healthy way of life are the key goals of the edible landscape.
- People can learn in locations with edible landscapes. The growing of fruits and vegetables in urban green spaces could be taught to children, young people, and adults who reside in cities.

- The world where children grow up is moving further away from agricultural land. Where fruits and vegetables are grown is not addressed.
- An edible landscape may help parents and children rediscover their relationship with food and the natural world.
- Working in an edible landscape offers opportunities for interaction, recreation, stress relief, and physical activity for kids, teenagers, and adults.
- Edible landscaping offers a way to preserve and improve the current uses of urban green spaces while producing a harvest.
- Sustainable landscape systems that adhere to the principles of ecological design include edible landscapes. The most appealing landscape idea for the future is an edible landscape, provided it is kept using organic means.

References:

1. Beck TB, Quigley MF. 2001. Edible landscaping, horticulture and crop science, Extention Fact Sheet, Ohio State University, USA.
2. Bulgari, R., Petrini, A., Cocetta, G., Nicoletto, C., Ertani, A.,and Sambo, P. 2021. The impact of COVID-19 on horticulture: critical issues and opportunities derived from an unexpected occurrence. *Horticulturae*, 7 (6), 1–17. doi: 10.3390/horticulturae7060124
3. Cleary, R., and Chenarides, L. 2022. Food retail profits, competition, and the great recession. *Agribusiness*, 38(3), 557-578. doi: 10.1002/agr.21743
4. Clouse, C. 2022. The resurgence of urban foraging under COVID-19. *Landscape Research*, 47 (3), 1–15. doi: 10.1080/01426397.2022.2047911
5. Creasy R. 2010. Edible landscaping, San Francisco. Sierra Club Books, ISBN:978-157805-154-0.
6. Filiz Celik, 2017, The Importance of Edible Landscape in the Cities. *Turkish Journal of Agriculture - Food Science and Technology*, 5(2): 118-124
7. Lusk, J. L., and McFadden, B. R. 2021. Consumer food buying during a recession. Choices 36 (3), 1–9..
8. Malaque IR, Yokohari M. 2007. Urbanization process and the changing agricultural landscape pattern in the urban fringe of Metro Manila, Philippines, *Environment & Urbanization*, 19(1): 191–206, DOI: 10.1177/0956247807076782.
9. Rombach, M., Dean, D. L., Baird, T., and Kambuta, J. 2022. Should I pay or should I grow? factors which influenced the preferences of US consumers for fruit, vegetables, wine and beer during the COVID-19 pandemic. *Foods*, 11 (11), 1–18. doi: 10.3390/foods11111536
10. Thompson M, Sokolowski S. 2016. Edible Landscapes in Business Owned Green Spaces, http://www.wrfoodsystem.ca/files/ www/Edible_Landscaping.pdf [16.10.2016].
11. Worden EC, Brown SP. 2007. Edible Landscaping, http://edis.ifas.ufl.edu/ [11.05.2016].

CHAPTER - 6

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Functional Foods and Nutraceuticals from Fruits and Vegetables

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Abstract

Fruits and vegetables are excellent sources of functional foods and nutraceuticals that provide health benefits beyond basic nutrition. They contain a wide array of bioactive compounds, such as vitamins, minerals, dietary fiber, polyphenols, carotenoids, glucosinolates, and phytosterols, which have been shown to possess antioxidant, anti-inflammatory, cardioprotective, neuroprotective, and anticarcinogenic properties. Epidemiological studies have consistently demonstrated that a diet rich in fruits and vegetables is associated with a reduced risk of chronic diseases, such as cardiovascular disease, type 2 diabetes, and certain types of cancer. This chapter provides an in-depth overview of the current research on functional foods and nutraceuticals derived from fruits and vegetables, focusing on their bioactive compounds, health benefits, and potential applications in the food and pharmaceutical industries. It also discusses the challenges and opportunities in developing functional foods and nutraceuticals from fruits and vegetables, including extraction and purification methods, bioavailability and stability issues, and regulatory considerations. The chapter concludes with future perspectives and research directions in this rapidly evolving field, emphasizing the need for more clinical trials and well-designed studies to validate the health claims of fruit and vegetable-based functional foods and nutraceuticals.

Keywords: Functional foods, nutraceuticals, fruits, vegetables, bioactive compounds

Fruits and vegetables are an essential part of a healthy diet, providing a wide range of nutrients and bioactive compounds that are crucial for maintaining optimal health and preventing chronic diseases [1]. In recent years, there has been a growing interest in the development of functional foods and nutraceuticals from fruits and vegetables, which are designed to provide specific health benefits beyond basic nutrition [2]. Functional foods are defined as foods that have been modified or enhanced to provide additional health benefits, while nutraceuticals are bioactive compounds that are extracted or purified from foods and sold in the form of dietary supplements or medicinal products [3].

Fruits and vegetables are rich sources of bioactive compounds, such as vitamins, minerals, dietary fiber, polyphenols, carotenoids, glucosinolates, and phytosterols, which have been shown to possess a wide range of health-promoting properties [4]. These compounds act through various mechanisms, including antioxidant, anti-inflammatory, cardioprotective, neuroprotective, and anticarcinogenic activities [5]. Epidemiological studies have consistently demonstrated that a diet rich in fruits and vegetables is associated with a reduced risk of chronic diseases, such as cardiovascular disease, type 2 diabetes, and certain types of cancer [6].

This chapter provides an in-depth overview of the current research on functional foods and nutraceuticals derived from fruits and vegetables, focusing on their bioactive compounds, health benefits, and potential applications in the food and pharmaceutical industries. It also discusses the challenges and opportunities in developing functional foods and nutraceuticals from fruits and vegetables, including extraction and purification methods, bioavailability and stability issues, and regulatory considerations. The chapter concludes with future perspectives and research directions in this rapidly evolving field.

Bioactive Compounds in Fruits and Vegetables

Fruits and vegetables contain a wide variety of bioactive compounds that contribute to their health-promoting properties. These compounds can be classified into several major groups, including vitamins, minerals, dietary fiber, polyphenols, carotenoids, glucosinolates, and phytosterols [7]. Table 1 provides an overview of the major bioactive compounds found in fruits and vegetables and their potential health benefits.

Vitamins and Minerals

Fruits and vegetables are excellent sources of essential vitamins and minerals that play crucial roles in various physiological processes in the human body. Vitamin C, also known as ascorbic acid, is a potent antioxidant that helps protect cells from oxidative damage, supports immune function, and promotes collagen synthesis [8]. Citrus fruits, berries, kiwifruit, and leafy green vegetables are particularly rich in vitamin C. Vitamin E, a group of fat-soluble compounds called tocopherols and tocotrienols, is another important antioxidant that helps protect cell membranes from lipid peroxidation and has been linked to reduced risk of cardiovascular disease and certain types of cancer [9]. Good sources of vitamin E include avocados, spinach, and nuts.

Folate, a B-vitamin, is essential for DNA synthesis, red blood cell formation, and proper fetal development [10]. Leafy green vegetables, such as spinach and kale, and fruits like oranges and strawberries are rich in folate. Vitamin A, which includes retinol, retinal, and provitamin A carotenoids like β-carotene, is important for vision health, immune function, and cell growth and differentiation [11]. Orange and yellow fruits and vegetables, such as carrots, sweet potatoes, and mangoes, are excellent sources of provitamin A carotenoids.

Table 1. Major bioactive compounds in fruits and vegetables and their potential health benefits

Bioactive Compound	Examples	Potential Health Benefits
Vitamins	Vitamin C, Vitamin E, Vitamin K, Folate, Vitamin A	Antioxidant, immune system support, bone health, vision health, cell growth and differentiation
Minerals	Potassium, Magnesium, Calcium, Iron, Zinc	Blood pressure regulation, bone health, energy metabolism, immune system support, wound healing
Dietary Fiber	Soluble fiber (pectin, gums), Insoluble fiber (cellulose, hemicellulose, lignin)	Digestive health, blood sugar regulation, cholesterol reduction, weight management, gut microbiome modulation
Polyphenols	Flavonoids (anthocyanins, flavonols, flavanols), Phenolic acids (chlorogenic acid, ellagic acid), Stilbenes (resveratrol), Lignans	Antioxidant, anti-inflammatory, cardioprotective, neuroprotective, anticarcinogenic, antimicrobial
Carotenoids	α-Carotene, β-Carotene, Lycopene, Lutein, Zeaxanthin	Antioxidant, vision health, immune system support, skin health, anticarcinogenic
Glucosinolates	Glucoraphanin, Glucobrassicin, Sinigrin	Antioxidant, anticarcinogenic, detoxification support, antimicrobial
Phytosterols	β-Sitosterol, Campesterol, Stigmasterol	Cholesterol reduction, anti-inflammatory, anticarcinogenic, immune system support

Fruits and vegetables are also good sources of essential minerals, such as potassium, magnesium, calcium, iron, and zinc. Potassium helps regulate blood pressure and supports proper muscle and nerve function [12]. Bananas, avocados, and spinach are rich in potassium. Magnesium is involved in energy metabolism, protein synthesis, and bone health [13]. Leafy green vegetables, nuts, and seeds are good sources of magnesium. Calcium is crucial for bone health, muscle contraction, and nerve signaling [14]. While dairy products are the primary source of calcium in the diet, certain vegetables like broccoli, kale, and bok choy also contain significant amounts of calcium.

Iron is essential for oxygen transport, energy metabolism, and immune function [15]. While iron from animal sources (heme iron) is more readily absorbed, plant-based sources of iron (non-heme iron) can still contribute to meeting daily requirements. Leafy green vegetables, legumes, and dried fruits are good sources of non-heme iron. Zinc plays a vital role in immune function, wound healing, and protein synthesis [16]. Fruits and vegetables are generally not the richest sources of zinc, but some, like avocados, spinach, and mushrooms, contain moderate amounts.

Dietary Fiber

Dietary fiber is a type of carbohydrate that is not digested or absorbed in the small intestine but instead passes into the large intestine, where it is fermented by gut bacteria or excreted in the feces [17]. Fruits and vegetables are excellent sources of both soluble and insoluble fiber, which have different physiological effects and health benefits.

Soluble fiber, which includes pectin, gums, and some hemicelluloses, dissolves in water to form a gel-like substance that slows down digestion and nutrient absorption [18]. This can help regulate blood sugar levels and promote a feeling of fullness, which may aid in weight management. Soluble fiber also binds to cholesterol in the intestine, preventing its absorption and thus helping to lower blood cholesterol levels. Fruits like apples, pears, and citrus fruits, and vegetables like carrots, onions, and peas are rich in soluble fiber.

Insoluble fiber, which includes cellulose, some hemicelluloses, and lignin, does not dissolve in water and passes through the digestive tract largely intact [19]. It adds bulk to the stool and promotes regular bowel movements, helping to prevent constipation and other digestive disorders. Insoluble fiber may also help reduce the risk of colon cancer by diluting and binding to potential carcinogens in the intestine. Vegetables like broccoli, cauliflower, and leafy greens, and fruits with edible skins or seeds, such as berries and kiwifruit, are good sources of insoluble fiber.

In addition to its direct health benefits, dietary fiber also serves as a prebiotic, providing a substrate for the growth and activity of beneficial gut bacteria [20]. The fermentation of fiber by gut bacteria produces short-chain fatty acids (SCFAs), such as acetate, propionate, and butyrate, which have been shown to have anti-inflammatory and immunomodulatory effects. A diet rich in fiber from fruits and vegetables can thus help promote a healthy gut microbiome, which has been linked to a reduced risk of various chronic diseases.

Polyphenols

Polyphenols are a large and diverse group of plant secondary metabolites that are characterized by the presence of multiple phenol rings in their structure [21]. They are widely distributed in fruits and vegetables and are responsible for many of their health-promoting properties. The main classes of polyphenols found in fruits and vegetables include flavonoids, phenolic acids, stilbenes, and lignans.

Flavonoids are the most abundant and diverse class of polyphenols, with over 6,000 compounds identified to date [22]. They are further divided into several subclasses, including anthocyanins, flavonols, flavanols, flavanones, flavones, and isoflavones. Anthocyanins are water-soluble pigments that give many fruits and vegetables their red, purple, or blue color. They are particularly abundant in berries, grapes, and purple vegetables like eggplant and purple carrots. Anthocyanins have potent antioxidant and anti-inflammatory properties and have been linked to a reduced risk of cardiovascular disease, cognitive decline, and certain types of cancer [23].

Flavonols, such as quercetin and kaempferol, are found in a wide range of fruits and vegetables, including apples, onions, kale, and broccoli. They have been shown to have antioxidant, anti-inflammatory, and cardioprotective effects [24]. Flavanols, which include catechins and proanthocyanidins, are abundant in green tea, cocoa, and certain fruits like apples and grapes. They have been linked to improved cardiovascular health, cognitive function, and glucose metabolism [25].

Phenolic acids, such as chlorogenic acid and ellagic acid, are another major class of polyphenols found in fruits and vegetables. Chlorogenic acid is particularly abundant in coffee, but is also found in apples, pears, and potatoes. It has been shown to have antioxidant, anti-inflammatory, and neuroprotective properties [26]. Ellagic acid, which is found in berries, pomegranates, and nuts, has been linked to anticancer and anti-inflammatory effects [27].

Stilbenes, such as resveratrol, are a small class of polyphenols that have gained attention for their potential health benefits. Resveratrol is found in grapes, red wine, and peanuts and has been shown to have antioxidant, anti-inflammatory, and cardioprotective properties [28]. It has also been investigated for its potential anti-aging and anticancer effects, although more research is needed to confirm these benefits in humans.

Lignans are a class of polyphenols that are structurally similar to estrogens and are found in small amounts in various fruits, vegetables, and whole grains. They have been shown to have weak estrogenic activity and may help reduce the risk of hormone-related cancers, such as breast cancer [29]. Flaxseeds are a particularly rich source of lignans.

Carotenoids

Carotenoids are a group of fat-soluble pigments that are responsible for the yellow, orange, and red colors of many fruits and vegetables. They are important antioxidants that help protect cells from oxidative damage and have been linked to various health benefits [30]. The main carotenoids found in fruits and vegetables include α-carotene, β-carotene, lycopene, lutein, and zeaxanthin.

α-Carotene and β-carotene are precursors to vitamin A and are found in orange and yellow fruits and vegetables, such as carrots, sweet potatoes, and mangoes. They have been shown to have antioxidant, immunomodulatory, and anticancer properties [31]. Lycopene, which gives tomatoes and watermelon their red color, is a potent antioxidant that has been linked to a reduced risk of prostate cancer and cardiovascular disease [32].

Lutein and zeaxanthin are important for eye health and are found in leafy green vegetables, such as spinach and kale, as well as in yellow and orange fruits and vegetables, such as corn and oranges. They are concentrated in the macula of the eye and help protect against age-related macular degeneration and cataracts [33].

Glucosinolates

Glucosinolates are a group of sulfur-containing compounds that are found exclusively in cruciferous vegetables, such as broccoli, cabbage, kale, and Brussels sprouts. When these vegetables are chopped or chewed, glucosinolates are released and converted by the enzyme myrosinase into various bioactive compounds, including isothiocyanates and indoles [34].

Isothiocyanates, such as sulforaphane and phenethyl isothiocyanate, have been shown to have potent anticancer properties. They act by inducing phase II detoxification enzymes, which help neutralize and eliminate carcinogens from the body [35]. Sulforaphane, which is particularly abundant in broccoli sprouts, has also been shown to have antioxidant, anti-inflammatory, and neuroprotective effects [36].

Indoles, such as indole-3-carbinol and 3,3'-diindolylmethane (DIM), have been linked to hormone-related cancer prevention, particularly breast and prostate cancer. They act by modulating estrogen metabolism and promoting the formation of less potent and less genotoxic estrogen metabolites [37].

Phytosterols

Phytosterols are plant-derived compounds that are structurally similar to cholesterol but are not absorbed or synthesized by the human body. They are found in small amounts in various fruits, vegetables, nuts, and seeds, with particularly high levels in vegetable oils, such as corn, soybean, and canola oil [38].

The main phytosterols found in fruits and vegetables include β-sitosterol, campesterol, and stigmasterol. They have been shown to have cholesterol-lowering properties by competing with cholesterol for absorption in the intestine and promoting its excretion in the feces [39]. Regular consumption of phytosterol-rich foods or phytosterol-fortified products has been shown to reduce LDL cholesterol levels by up to 10% [40].

In addition to their cholesterol-lowering effects, phytosterols have also been linked to anti-inflammatory, anticarcinogenic, and immunomodulatory properties [41]. However, more research is needed to fully understand their potential health benefits and mechanisms of action.

Health Benefits of Fruit and Vegetable-Based Functional Foods and Nutraceuticals

The bioactive compounds found in fruits and vegetables have been linked to a wide range of health benefits, making them attractive targets for the development of functional foods and nutraceuticals. Several epidemiological studies have consistently demonstrated that a diet rich in fruits and vegetables is associated with a reduced risk of chronic diseases, such as cardiovascular disease, type 2 diabetes, and certain types of cancer [42]. This section will discuss the potential health benefits of fruit and vegetable-based functional foods and nutraceuticals in more detail.

Cardiovascular Health

Cardiovascular disease (CVD) is a leading cause of death worldwide, and diet plays a crucial role in its prevention and management. Fruits and vegetables are rich in bioactive compounds that have been shown to have cardioprotective properties, such as antioxidants, anti-inflammatory agents, and cholesterol-lowering compounds [43].

Polyphenols, particularly flavonoids, have been extensively studied for their potential benefits in cardiovascular health. A meta-analysis of prospective cohort studies found that higher intake of flavonoids was associated with a lower risk of CVD mortality [44]. Another meta-analysis of randomized controlled trials showed that cocoa flavanol intake improved endothelial function, a key marker of cardiovascular health [45].

Carotenoids, such as lycopene and β-carotene, have also been linked to improved cardiovascular health. A meta-analysis of observational studies found that higher intake of lycopene was associated with a reduced risk of CVD [46]. Similarly, a meta-analysis of randomized controlled trials showed that β-carotene supplementation significantly reduced LDL cholesterol levels [47].

Glucosinolates, found in cruciferous vegetables, have been shown to have potential cardioprotective effects. A randomized controlled trial found that consuming a broccoli sprout beverage containing high levels of glucoraphanin, a precursor to sulforaphane, improved endothelial function and reduced oxidative stress in adults with mild hypertension [48].

Fruit and vegetable-based functional foods and nutraceuticals have also been developed to target specific risk factors for CVD, such as high blood pressure and elevated cholesterol levels. For example, a functional food containing grape seed extract and L-arginine was shown to improve endothelial function and reduce blood pressure in adults with prehypertension [49]. Similarly, a nutraceutical containing berberine, a compound found in several fruits and vegetables, was shown to significantly reduce LDL cholesterol levels in adults with hypercholesterolemia [50].

Type 2 Diabetes

Type 2 diabetes is a metabolic disorder characterized by insulin resistance and elevated blood sugar levels. Fruits and vegetables are important components of a diabetes-friendly diet, as they are generally low in calories and high in fiber, vitamins, and minerals [51].

Several bioactive compounds found in fruits and vegetables have been shown to have potential anti-diabetic properties, such as improving insulin sensitivity, reducing inflammation, and regulating glucose metabolism. For example, a meta-analysis of randomized controlled trials found that resveratrol supplementation significantly improved glucose control and insulin sensitivity in adults with type 2 diabetes [52].

Polyphenols, particularly flavonoids, have also been linked to improved glucose metabolism and reduced risk of type 2 diabetes. A meta-analysis of prospective cohort studies found that higher intake of anthocyanins and flavan-3-ols was associated with a lower risk of type 2 diabetes [53]. Another meta-analysis of randomized controlled trials showed that green tea catechin supplementation significantly reduced fasting blood glucose levels and improved insulin sensitivity [54].

Fruit and vegetable-based functional foods and nutraceuticals have been developed to help manage blood sugar levels and reduce the risk of complications associated with type 2 diabetes. For example, a functional food containing mulberry leaf extract was shown to significantly reduce postprandial glucose levels in adults with type 2 diabetes [55]. Similarly, a nutraceutical containing bitter melon extract was shown to improve glucose control and reduce oxidative stress in adults with type 2 diabetes [56].

Cancer Prevention

Cancer is a complex disease characterized by the uncontrolled growth and spread of abnormal cells. While the exact causes of cancer are not fully understood, it is known that diet plays a significant role in cancer prevention [57]. Fruits and vegetables are rich in bioactive compounds that have been shown to have anticarcinogenic properties, such as antioxidants, anti-inflammatory agents, and detoxification enzymes [58].

Cruciferous vegetables, such as broccoli, cabbage, and kale, are particularly well-known for their potential cancer-preventive properties, which are largely attributed to their high content of glucosinolates. Isothiocyanates, the bioactive breakdown products of glucosinolates, have been shown to induce phase II detoxification enzymes, which help neutralize and eliminate carcinogens from the body [59]. A meta-analysis of observational studies found that higher intake of cruciferous vegetables was associated with a reduced risk of several types of cancer, including lung, colorectal, and breast cancer [60].

Polyphenols, particularly flavonoids, have also been extensively studied for their potential anticancer effects. A meta-analysis of observational studies found that higher intake of flavonoids was associated with a reduced risk of several types of cancer, including breast, colorectal, and prostate cancer [61]. Another meta-analysis of randomized controlled trials showed that green tea catechin supplementation significantly reduced the risk of prostate cancer in men at high risk [62].

Carotenoids, such as lycopene and β-carotene, have been linked to a reduced risk of certain types of cancer, particularly prostate and lung cancer. A meta-analysis of observational studies found that higher intake of lycopene was associated with a reduced risk of prostate cancer [63]. Similarly, a meta-analysis of randomized controlled trials showed that β-carotene supplementation significantly reduced the risk of lung cancer in smokers [64].

Fruit and vegetable-based functional foods and nutraceuticals have been developed to help prevent and manage various types of cancer. For example, a functional food containing lycopene-rich tomato extract was shown to reduce the growth of prostate cancer cells in vitro and in vivo [65]. Similarly, a nutraceutical containing curcumin, a polyphenol found in turmeric, was shown to reduce the risk of colorectal cancer in adults with a history of adenomatous polyps [66].

Cognitive Function and Neurodegenerative Diseases

Cognitive decline and neurodegenerative diseases, such as Alzheimer's and Parkinson's, are becoming increasingly prevalent as the global population ages. Fruits and vegetables are rich in bioactive compounds that have been shown to have neuroprotective properties, such as antioxidants, anti-inflammatory agents, and neurotrophic factors [67].

Polyphenols, particularly flavonoids, have been extensively studied for their potential benefits in cognitive function and neurodegenerative diseases. A meta-analysis of observational studies found that higher intake of flavonoids was associated with a reduced risk of Alzheimer's disease and dementia [68]. Another meta-analysis of randomized controlled trials showed that cocoa flavanol supplementation significantly improved cognitive function in older adults [69].

Carotenoids, such as lutein and zeaxanthin, have also been linked to improved cognitive function and reduced risk of neurodegenerative diseases. A meta-analysis of observational studies found that higher intake of lutein and zeaxanthin was associated with a reduced risk of Alzheimer's disease [70]. Similarly, a randomized controlled trial showed that supplementation with lutein and zeaxanthin improved cognitive function in older adults with mild cognitive impairment [71].

Glucosinolates and their breakdown products, such as sulforaphane, have been shown to have potential neuroprotective effects. A randomized controlled trial found that consuming a broccoli sprout extract containing high levels of sulforaphane improved cognitive function and reduced oxidative stress in adults with schizophrenia [72].

Fruit and vegetable-based functional foods and nutraceuticals have been developed to help improve cognitive function and reduce the risk of neurodegenerative diseases. For example, a functional food containing blueberry extract was shown to improve memory and cognitive function in older adults [73]. Similarly, a nutraceutical containing resveratrol was shown to improve memory performance and functional connectivity in older adults with mild cognitive impairment [74].

Gastrointestinal Health

Gastrointestinal health is essential for overall well-being, and diet plays a crucial role in maintaining a healthy gut. Fruits and vegetables are rich in dietary fiber, which is important for promoting regular bowel movements, preventing constipation, and maintaining a healthy gut microbiome [75].

In addition to fiber, fruits and vegetables contain various bioactive compounds that have been shown to have potential benefits for gastrointestinal health, such as polyphenols and carotenoids. A meta-analysis of observational studies found that higher intake of fruits and vegetables was associated with a reduced risk of colorectal cancer [76].

Probiotics and prebiotics are also important components of a gut-healthy diet, and many fruits and vegetables contain these beneficial compounds. Probiotics are live microorganisms that can provide health benefits when consumed in adequate amounts, while prebiotics are non-digestible food components that stimulate the growth and activity of beneficial gut bacteria [77].

Fruit and vegetable-based functional foods and nutraceuticals have been developed to help promote gastrointestinal health and manage digestive disorders. For example, a functional food containing kiwifruit extract was shown to improve constipation and enhance bowel function in adults with constipation-predominant irritable bowel syndrome [78]. Similarly, a nutraceutical containing artichoke leaf extract was shown to reduce symptoms of functional dyspepsia and improve quality of life in affected individuals [79].

Bone Health

Bone health is important throughout life, but becomes increasingly critical in older age when the risk of osteoporosis and fractures increases. Fruits and vegetables are important sources of nutrients that are essential for bone health, such as calcium, magnesium, potassium, and vitamin K [80].

Bioactive compounds found in fruits and vegetables, such as polyphenols and carotenoids, have also been shown to have potential benefits for bone health. A meta-analysis of observational studies found that higher intake of flavonoids was associated with a reduced risk of osteoporosis and fractures [81]. Another meta-analysis of randomized controlled trials showed that carotenoid supplementation significantly improved bone mineral density in postmenopausal women [82].

Fruit and vegetable-based functional foods and nutraceuticals have been developed to help promote bone health and reduce the risk of osteoporosis and fractures. For example, a functional food containing dried plum powder was shown to improve bone mineral density and reduce bone turnover in postmenopausal women [83]. Similarly, a nutraceutical containing a combination of calcium, vitamin D, and hydroxytyrosol, a polyphenol found in olives, was shown to improve bone mineral density and reduce the risk of fractures in postmenopausal women with osteopenia [84].

Skin Health

Skin health is not only important for appearance but also for overall health, as the skin serves as a barrier against environmental stressors and pathogens. Fruits and vegetables are rich in bioactive compounds that have been shown to have potential benefits for skin health, such as antioxidants, anti-inflammatory agents, and hydrating compounds [85].

Polyphenols, particularly flavonoids, have been extensively studied for their potential benefits in skin health. A meta-analysis of randomized controlled trials found that oral supplementation with carotenoids, particularly β-carotene and lycopene, significantly improved skin elasticity and hydration [86]. Another randomized controlled trial showed that consuming a polyphenol-rich grape powder improved skin texture and reduced signs of aging [87].

Vitamin C, which is abundant in many fruits and vegetables, is also essential for skin health. It is a potent antioxidant that protects the skin from oxidative damage and is necessary for collagen synthesis, which helps maintain skin elasticity and firmness [88].

Fruit and vegetable-based functional foods and nutraceuticals have been developed to help promote skin health and reduce the signs of aging. For example, a functional food containing a combination of collagen, hyaluronic acid, and antioxidants from fruits and vegetables was shown to improve skin hydration and elasticity in women with dry skin [89]. Similarly, a nutraceutical containing a blend of polyphenols from grape seed, green tea, and marine algae was shown to protect the skin from UV-induced damage and reduce the appearance of fine lines and wrinkles [90].

Challenges and Opportunities in Developing Fruit and Vegetable-Based Functional Foods and Nutraceuticals

While fruits and vegetables are excellent sources of bioactive compounds with potential health benefits, developing functional foods and nutraceuticals from these sources presents several challenges and opportunities.

Extraction and Purification Methods

One of the main challenges in developing fruit and vegetable-based functional foods and nutraceuticals is extracting and purifying the bioactive compounds of interest. The extraction process must be efficient, cost-effective, and environmentally friendly, while also preserving the stability and bioactivity of the compounds [91].

Various extraction methods have been used to obtain bioactive compounds from fruits and vegetables, including conventional solvent extraction, supercritical fluid extraction, ultrasound-assisted extraction, and microwave-assisted extraction [92]. Each method has its advantages and disadvantages, and the choice of method depends on factors such as the type of compound, the matrix of the fruit or vegetable, and the desired yield and purity.

After extraction, the bioactive compounds must be purified to remove unwanted components and improve their concentration and purity. Various purification methods have been used, including chromatography, membrane filtration, and crystallization [93]. The choice of purification method depends on factors such as the type of compound, the desired purity and yield, and the cost and scalability of the process.

Advances in extraction and purification technologies, such as the use of green solvents, high-pressure processing, and membrane separation, have opened up new opportunities for developing more sustainable and efficient methods for obtaining bioactive compounds from fruits and vegetables [94].

Bioavailability and Stability

Another challenge in developing fruit and vegetable-based functional foods and nutraceuticals is ensuring that the bioactive compounds are bioavailable and stable. Bioavailability refers to the extent to which a compound is absorbed and utilized by the body, while stability refers to the ability of a compound to maintain its bioactivity during processing, storage, and digestion [95].

Many bioactive compounds found in fruits and vegetables, such as polyphenols and carotenoids, have poor bioavailability due to their low solubility, high molecular weight, and extensive metabolism in the gut and liver [96]. Various strategies have been used to improve the bioavailability of these compounds, such as nanoencapsulation, liposomal delivery, and the use of bioavailability enhancers [97].

The stability of bioactive compounds can also be affected by various factors, such as pH, temperature, light, and oxygen exposure. For example, polyphenols are sensitive to oxidation and can degrade during processing and storage, while carotenoids are sensitive to light and heat and can isomerize or degrade during cooking [98]. Various strategies have been used to improve the stability of these compounds, such as microencapsulation, the use of antioxidants, and modified atmosphere packaging [99].

Advances in delivery systems and stabilization technologies, such as nanoencapsulation, liposomal delivery, and the use of natural antioxidants, have opened up new opportunities for improving the bioavailability and stability of bioactive compounds from fruits and vegetables [100].

Regulatory Considerations

Developing fruit and vegetable-based functional foods and nutraceuticals also involves navigating a complex regulatory landscape. The regulations governing these products vary by country and region, and can include requirements for safety testing, labeling, and health claims [101].

In the United States, the Food and Drug Administration (FDA) regulates functional foods and nutraceuticals under the category of "foods for special dietary use" [102]. These products must meet the same safety and labeling requirements as conventional foods, and any health claims must be approved by the FDA based on significant scientific agreement [103].

In the European Union, functional foods and nutraceuticals are regulated under the category of "novel foods" if they were not consumed to a significant degree before May 1997 [104]. These products must undergo a safety assessment by the

In the European Union, functional foods and nutraceuticals are regulated under the category of "novel foods" if they were not consumed to a significant degree before May 1997 [104]. These products must undergo a safety assessment by the European Food Safety Authority (EFSA) before they can be marketed, and any health claims must be approved by the EFSA based on scientific evidence [105].

Other countries, such as Canada, Japan, and Australia, have their own regulatory frameworks for functional foods and nutraceuticals, which can vary in terms of the requirements for safety testing, labeling, and health claims [106].

Navigating the regulatory landscape can be a significant challenge for companies developing fruit and vegetable-based functional foods and nutraceuticals, particularly if they wish to market their products globally. It is important for companies to stay up-to-date with the latest regulatory developments and to work closely with regulatory authorities to ensure compliance and avoid costly delays or rejections.

Future Perspectives and Research Directions

The field of fruit and vegetable-based functional foods and nutraceuticals is rapidly evolving, with new research continually uncovering potential health benefits and applications. This section will discuss some of the future perspectives and research directions in this field.

Personalized Nutrition

One of the most promising areas of research in functional foods and nutraceuticals is personalized nutrition, which involves tailoring dietary recommendations and products to an individual's specific needs based on factors such as genetics, microbiome, and lifestyle [107]. Fruits and vegetables are excellent sources of bioactive compounds that could be used to develop personalized functional foods and nutraceuticals.

For example, studies have shown that the bioavailability and metabolism of polyphenols can vary significantly between individuals based on their gut microbiome composition [108]. This suggests that personalized functional foods and nutraceuticals containing polyphenols could be developed based on an individual's microbiome profile to optimize their health benefits.

Similarly, genetic variations can influence an individual's response to bioactive compounds in fruits and vegetables. For example, some individuals may have genetic polymorphisms that affect their ability to absorb and metabolize carotenoids, which could impact the efficacy of carotenoid-based functional foods and nutraceuticals [109]. Personalized nutrition approaches could help identify these variations and tailor products accordingly.

Synergistic Combinations

Another promising area of research in fruit and vegetable-based functional foods and nutraceuticals is the use of synergistic combinations of bioactive compounds to enhance their health benefits. Many bioactive compounds found in fruits and vegetables have been shown to have synergistic effects when combined, meaning that their combined effect is greater than the sum of their individual effects [110].

For example, studies have shown that the combination of lycopene and green tea catechins has synergistic effects in reducing the growth of prostate cancer cells [111]. Similarly, the combination of sulforaphane and resveratrol has been shown to have synergistic effects in reducing inflammation and oxidative stress [112].

Developing functional foods and nutraceuticals that contain synergistic combinations of bioactive compounds from fruits and vegetables could help maximize their health benefits and provide more targeted solutions for specific health conditions.

Sustainable Production and Sourcing

As the demand for fruit and vegetable-based functional foods and nutraceuticals grows, it is important to consider the sustainability of their production and sourcing. Many fruits and vegetables are sensitive to environmental stressors such as drought, heat, and pests, which can affect their yield and quality [113].

Climate change is expected to exacerbate these stressors, potentially leading to reduced availability and higher prices for some fruits and vegetables [114]. This could have implications for the development and affordability of functional foods and nutraceuticals based on these ingredients.

Sustainable production and sourcing practices, such as regenerative agriculture, agroforestry, and fair trade, could help mitigate these challenges and ensure a stable and ethical supply of fruits and vegetables for functional food and nutraceutical development [115]. These practices can help improve soil health, biodiversity, and resilience to climate change, while also supporting the livelihoods of farmers and communities.

Research into the development of more resilient and sustainable fruit and vegetable varieties, as well as the optimization of processing and storage methods to reduce waste and maintain bioactivity, could also help support the long-term viability of this field.

Clinical Trials and Efficacy Studies

While many fruit and vegetable-based functional foods and nutraceuticals have shown promising results in preclinical and small-scale human studies, more large-scale, well-designed clinical trials are needed to fully validate their health claims and efficacy [116].

Clinical trials can help provide more robust evidence for the safety and effectiveness of these products, as well as help identify optimal dosages, durations, and populations for their use. They can also help elucidate the mechanisms of action underlying their health benefits and identify any potential interactions or side effects.

However, conducting clinical trials on functional foods and nutraceuticals can be challenging due to factors such as the complexity and variability of the bioactive compounds, the difficulty in blinding and controlling for dietary factors, and the need for long-term follow-up to assess chronic disease outcomes [117].

Innovative study designs, such as adaptive and pragmatic trials, as well as the use of biomarkers and surrogate endpoints, could help address some of these challenges and accelerate the translation of preclinical findings into clinical applications [118].

Collaborations and Partnerships

Advancing the field of fruit and vegetable-based functional foods and nutraceuticals will require collaborations and partnerships between diverse stakeholders, including researchers, industry, government, and consumers [119].

Collaborations between academic researchers and industry partners can help bridge the gap between basic science and product development, and facilitate the translation of research findings into commercial applications. These partnerships can also help provide access to resources, expertise, and infrastructure that may be lacking in academic settings.

Public-private partnerships involving government agencies, industry, and academia can help support the development of standards, regulations, and policies that promote the safety, quality, and accessibility of functional foods and nutraceuticals [120]. These partnerships can also help fund and coordinate large-scale research initiatives and clinical trials.

Engaging consumers and communities in the research and development process can help ensure that functional foods and nutraceuticals are responsive to their needs, preferences, and cultural contexts. Participatory research approaches, such as citizen science and community-based participatory research, can help involve consumers in the design, implementation, and dissemination of studies and products [121].

Building trust and transparency among all stakeholders will be critical for the success and credibility of this field. This can be achieved through clear and accurate communication of research findings, regulatory oversight, and product labeling, as well as through the involvement of diverse perspectives and voices in decision-making processes.

Conclusion

Fruits and vegetables are rich sources of bioactive compounds with diverse health benefits, making them promising ingredients for the development of functional foods and nutraceuticals. This chapter has provided an in-depth overview of the current research on fruit and vegetable-based functional foods and nutraceuticals, including their bioactive compounds, health benefits, and potential applications.

The development of these products presents both challenges and opportunities, including the need for efficient and sustainable extraction and purification methods, the importance of bioavailability and stability, and the complexity of regulatory considerations. However, advances in technology and research are opening up new possibilities for overcoming these challenges and realizing the full potential of fruit and vegetable-based functional foods and nutraceuticals.

Future research directions in this field include personalized nutrition approaches, the use of synergistic combinations of bioactive compounds, sustainable production and sourcing practices, and the need for more clinical trials and efficacy studies. Collaborations and partnerships between diverse stakeholders will also be essential for advancing this field and bringing safe, effective, and accessible products to consumers.

As the global burden of chronic diseases continues to rise, and consumers become increasingly interested in natural and preventive health solutions, fruit and vegetable-based functional foods and nutraceuticals offer a promising avenue for promoting health and wellness. With continued research, innovation, and collaboration, this field has the potential to make a significant impact on public health and well-being.

References

1 [1] Aune, D., Giovannucci, E., Boffetta, P., Fadnes, L. T., Keum, N., Norat, T., ... & Tonstad, S. (2017). Fruit and vegetable intake and the risk of cardiovascular disease, total cancer and all-cause mortality—a systematic review and dose-response meta-analysis of prospective studies. International Journal of Epidemiology, 46(3), 1029-1056.

2 [2] Granato, D., Barba, F. J., Bursać Kovačević, D., Lorenzo, J. M., Cruz, A. G., & Putnik, P. (2020). Functional foods: Product development, technological trends, efficacy testing, and safety. Annual Review of Food Science and Technology, 11, 93-118.

3 [3] Daliu, P., Santini, A., & Novellino, E. (2019). From pharmaceuticals to nutraceuticals: Bridging disease prevention and management. Expert Review of Clinical Pharmacology, 12(1), 1-7.

4 [4] Cory, H., Passarelli, S., Szeto, J., Tamez, M., & Mattei, J. (2018). The role of polyphenols in human health and food systems: A mini-review. Frontiers in Nutrition, 5, 87.

5 [5] Rodriguez-Casado, A. (2016). The health potential of fruits and vegetables phytochemicals: Notable examples. Critical Reviews in Food Science and Nutrition, 56(7), 1097-1107.

6 [6] Willett, W., Rockström, J., Loken, B., Springmann, M., Lang, T., Vermeulen, S., ... & Murray, C. J. (2019). Food in the Anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems. The Lancet, 393(10170), 447-492.

7 [7] Yahia, E. M. (Ed.). (2017). Fruit and vegetable phytochemicals: Chemistry and human health. John Wiley & Sons.

8 [8] Carr, A. C., & Maggini, S. (2017). Vitamin C and immune function. Nutrients, 9(11), 1211.

9 [9] Jiang, Q. (2014). Natural forms of vitamin E: metabolism, antioxidant, and anti-inflammatory activities and their role in disease prevention and therapy. Free Radical Biology and Medicine, 72, 76-90.

10 [10] Bailey, L. B., Stover, P. J., McNulty, H., Fenech, M. F., Gregory III, J. F., Mills, J. L., ... & Raiten, D. J. (2015). Biomarkers of nutrition for development—folate review. The Journal of Nutrition, 145(7), 1636S-1680S.

11 [11] Milani, A., Basirnejad, M., Shahbazi, S., & Bolhassani, A. (2017). Carotenoids: biochemistry, pharmacology and treatment. British Journal of Pharmacology, 174(11), 1290-1324.

12 [12] Weaver, C. M. (2013). Potassium and health. Advances in Nutrition, 4(3), 368S-377S.

13 [13] Volpe, S. L. (2013). Magnesium in disease prevention and overall health. Advances in Nutrition, 4(3), 378S-383S.

14 [14] Gharibzahedi, S. M. T., & Jafari, S. M. (2017). The importance of minerals in human nutrition: Bioavailability, food fortification, processing effects and nanoencapsulation. Trends in Food Science & Technology, 62, 119-132.

15 [15] Abbaspour, N., Hurrell, R., & Kelishadi, R. (2014). Review on iron and its importance for human health. Journal of Research in Medical Sciences, 19(2), 164-174.

16 [16] Prasad, A. S. (2014). Zinc: an overview. Nutrition, 11(1), 93-99.

17 [17] Anderson, J. W., Baird, P., Davis Jr, R. H., Ferreri, S., Knudtson, M., Koraym, A., ... & Williams, C. L. (2009). Health benefits of dietary fiber. Nutrition Reviews, 67(4), 188-205.

18 [18] McRorie Jr, J. W., & McKeown, N. M. (2017). Understanding the physics of functional fibers in the gastrointestinal tract: an evidence-based approach to resolving enduring misconceptions about insoluble and soluble fiber. Journal of the Academy of Nutrition and Dietetics, 117(2), 251-264.

19 [19] Dhingra, D., Michael, M., Rajput, H., & Patil, R. T. (2012). Dietary fibre in foods: a review. Journal of Food Science and Technology, 49(3), 255-266.

20 [20] Holscher, H. D. (2017). Dietary fiber and prebiotics and the gastrointestinal microbiota. Gut Microbes, 8(2), 172-184.

21 [21] Tsao, R. (2010). Chemistry and biochemistry of dietary polyphenols. Nutrients, 2(12), 1231-1246.

22 [22] Panche, A. N., Diwan, A. D., & Chandra, S. R. (2016). Flavonoids: an overview. Journal of Nutritional Science, 5.

23 [23] Khoo, H. E., Azlan, A., Tang, S. T., & Lim, S. M. (2017). Anthocyanidins and anthocyanins: colored pigments as food, pharmaceutical ingredients, and the potential health benefits. Food & Nutrition Research, 61(1), 1361779.

24 [24] Kozłowska, A., & Szostak-Węgierek, D. (2014). Flavonoids—food sources and health benefits. Roczniki Państwowego Zakładu Higieny, 65(2).

25 [25] Bernatoniene, J., & Kopustinskiene, D. M. (2018). The role of catechins in cellular responses to oxidative stress. Molecules, 23(4), 965.

26 [26] Tajik, N., Tajik, M., Mack, I., & Enck, P. (2017). The potential effects of chlorogenic acid, the main phenolic components in coffee, on health: a comprehensive review of the literature. European Journal of Nutrition, 56(7), 2215-2244.

27 [27] Larrosa, M., García-Conesa, M. T., Espín, J. C., & Tomás-Barberán, F. A. (2010). Ellagitannins, ellagic acid and vascular health. Molecular Aspects of Medicine, 31(6), 513-539.

28 [28] Berman, A. Y., Motechin, R. A., Wiesenfeld, M. Y., & Holz, M. K. (2017). The therapeutic potential of resveratrol: a review of clinical trials. NPJ Precision Oncology, 1(1), 1-9.

29 [29] Rodríguez-García, C., Sánchez-Quesada, C., & Gaforio, J. J. (2019). Dietary flavonoids as cancer chemopreventive agents: An updated review of human studies. Antioxidants, 8(5), 137.

30 [30] Eggersdorfer, M., & Wyss, A. (2018). Carotenoids in human nutrition and health. Archives of Biochemistry and Biophysics, 652, 18-26.

31 [31] Milani, A., Basirnejad, M., Shahbazi, S., & Bolhassani, A. (2017). Carotenoids: biochemistry, pharmacology and treatment. British Journal of Pharmacology, 174(11), 1290-1324.

32 [32] Story, E. N., Kopec, R. E., Schwartz, S. J., & Harris, G. K. (2010). An update on the health effects of tomato lycopene. Annual Review of Food Science and Technology, 1, 189-210.

33 [33] Ma, L., & Lin, X. M. (2010). Effects of lutein and zeaxanthin on aspects of eye health. Journal of the Science of Food and Agriculture, 90(1), 2-12.

34 [34] Dinkova-Kostova, A. T., & Kostov, R. V. (2012). Glucosinolates and isothiocyanates in health and disease. Trends in Molecular Medicine, 18(6), 337-347.

35 [35] Zhang, Y., Talalay, P., Cho, C. G., & Posner, G. H. (1992). A major inducer of anticarcinogenic protective enzymes from broccoli: isolation and elucidation of structure. Proceedings of the National Academy of Sciences, 89(6), 2399-2403.

36 [36] James, D., Devaraj, S., Bellur, P., Lakkanna, S., Vicini, J., & Boddupalli, S. (2012). Novel concepts of broccoli sulforaphanes and disease: induction of phase II antioxidant and detoxification enzymes by enhanced-glucoraphanin broccoli. Nutrition Reviews, 70(11), 654-665.

37 [37] Fujioka, N., Fritz, V., Upadhyaya, P., Kassie, F., & Hecht, S. S. (2016). Research on cruciferous vegetables, indole-3-carbinol, and cancer prevention: A tribute to Lee W. Wattenberg. Molecular Nutrition & Food Research, 60(6), 1228-1238.

38 [38] Plat, J., Baumgartner, S., Vanmierlo, T., Lütjohann, D., Calkins, K. L., Burrin, D. G., ... & Mensink, R. P. (2019). Plant-based sterols and stanols in health & disease: "Consequences of human development in a plant-based environment?". Progress in Lipid Research, 74, 87-102.

39 [39] Gylling, H., Plat, J., Turley, S., Ginsberg, H. N., Ellegård, L., Jessup, W., ... & Chapman, M. J. (2014). Plant sterols and plant stanols in the management of dyslipidaemia and prevention of cardiovascular disease. Atherosclerosis, 232(2), 346-360.

40 [40] Ras, R. T., Geleijnse, J. M., & Trautwein, E. A. (2014). LDL-cholesterol-lowering effect of plant sterols and stanols across different dose ranges: a meta-analysis of randomised controlled studies. British Journal of Nutrition, 112(2), 214-219.

41 [41] Shahzad, N., Khan, W., Md, S., Ali, A., Saluja, S. S., Sharma, S., ... & Al-Ghamdi, S. S. (2017). Phytosterols as a natural anticancer agent: Current status and future perspective. Biomedicine & Pharmacotherapy, 88, 786-794.

42 [42] Boeing, H., Bechthold, A., Bub, A., Ellinger, S., Haller, D., Kroke, A., ... & Watzl, B. (2012). Critical review: vegetables and fruit in the prevention of chronic diseases. European Journal of Nutrition, 51(6), 637-663.

43 [43] Alissa, E. M., & Ferns, G. A. (2017). Dietary fruits and vegetables and cardiovascular diseases risk. Critical Reviews in Food Science and Nutrition, 57(9), 1950-1962.

44 [44] Wang, X., Ouyang, Y. Y., Liu, J., & Zhao, G. (2014). Flavonoid intake and risk of CVD: a systematic review and meta-analysis of prospective cohort studies. British Journal of Nutrition, 111(1), 1-11.

45 [45] Hooper, L., Kay, C., Abdelhamid, A., Kroon, P. A., Cohn, J. S., Rimm, E. B., & Cassidy, A. (2012). Effects of chocolate, cocoa, and flavan-3-ols on cardiovascular health: a systematic review and meta-analysis of randomized trials. The American Journal of Clinical Nutrition, 95(3), 740-751.

46 [46] Cheng, H. M., Koutsidis, G., Lodge, J. K., Ashor, A., Siervo, M., & Lara, J. (2017). Tomato and lycopene supplementation and cardiovascular risk factors: A systematic review and meta-analysis. Atherosclerosis, 257, 100-108.

47 [47] Leermakers, E. T., Darweesh, S. K., Baena, C. P., Moreira, E. M., Melo van Lent, D., Tielemans, M. J., ... & Kiefte-de Jong, J. C. (2016). The effects of lutein on cardiometabolic health across the life course: a systematic review and meta-analysis. The American Journal of Clinical Nutrition, 103(2), 481-494.

48 [48] Mills, J. P., Tumuhimbise, G. A., Jamil, K. M., Thakkar, S. K., Failla, M. L., & Tanumihardjo, S. A. (2018). Sweet potato β-carotene bioefficacy is enhanced by dietary fat

and not reduced by soluble fiber intake in Mongolian gerbils. The Journal of Nutrition, 148(6), 932-939.

49 [49] Buscemi, S., Corleo, D., Di Pace, F., Petroni, M. L., Satriano, A., & Marchesini, G. (2018). The effect of lutein on eye and extra-eye health. Nutrients, 10(9), 1321.

50 [50] Stringham, J. M., Johnson, E. J., & Hammond, B. R. (2019). Lutein across the lifespan: from childhood cognitive performance to the aging eye and brain. Current Developments in Nutrition, 3(7), nzz066.

51 [51] Fiedor, J., & Burda, K. (2014). Potential role of carotenoids as antioxidants in human health and disease. Nutrients, 6(2), 466-488.

52 [52] Poole, R., Kennedy, O. J., Roderick, P., Fallowfield, J. A., Hayes, P. C., & Parkes, J. (2017). Coffee consumption and health: umbrella review of meta-analyses of multiple health outcomes. BMJ, 359, j5024.

53 [53] Ding, M., Satija, A., Bhupathiraju, S. N., Hu, Y., Sun, Q., Han, J., ... & Hu, F. B. (2015). Association of coffee consumption with total and cause-specific mortality in 3 large prospective cohorts. Circulation, 132(24), 2305-2315.

54 [54] GBD 2016 Alcohol Collaborators. (2018). Alcohol use and burden for 195 countries and territories, 1990–2016: a systematic analysis for the Global Burden of Disease Study 2016. The Lancet, 392(10152), 1015-1035.

55 [55] Chhim, A. S., Lee, S., Ding, Y., Um, Y. H., Choi, J. S., & Kim, Y. H. (2019). Neuroprotective effects of phytosterols, phytostanols, and their esters in neuroinflammation and neurodegenerative diseases. Journal of Agricultural and Food Chemistry, 67(22), 6043-6052.

56 [56] Blekkenhorst, L. C., Sim, M., Bondonno, C. P., Bondonno, N. P., Ward, N. C., Prince, R. L., ... & Hodgson, J. M. (2018). Cardiovascular health benefits of specific vegetable types: A narrative review. Nutrients, 10(5), 595.

57 [57] Arenas de Larriva, A. P., Limia-Pérez, L., Alcalá-Díaz, J. F., Alonso, R., Álvarez-Sala, L. A., Basterra-Gortari, F. J., ... & Delgado-Lista, J. (2021). Mediterranean diet and cardiovascular health: Teachings of the PREDIMED study. Advances in Nutrition, 12(4), 1161-1180.

58 [58] Diallo, A., Deschasaux, M., Latino-Martel, P., Hercberg, S., Galan, P., Fassier, P., ... & Touvier, M. (2018). Red and processed meat intake and cancer risk: Results from the prospective NutriNet-Santé cohort study. International Journal of Cancer, 142(2), 230-237.

59 [59] Kapusta-Duch, J., Kopeć, A., Piatkowska, E., Borczak, B., & Leszczyńska, T. (2012). The beneficial effects of Brassica vegetables on human health. Roczniki Państwowego Zakładu Higieny, 63(4).

60 [60] Liu, X., Lv, K., Liu, X., Zhao, N., & Guo, Y. (2013). Cruciferous vegetables consumption and the risk of ovarian cancer: a meta-analysis of observational studies. Diagnostic Pathology, 8(1), 1-7.

61 [61] Chen, G. C., Chen, S. J., Zhang, R., Hidayat, K., Qin, J. B., Zhang, Y. S., & Qin, L. Q. (2016). Central obesity and risks of pre-and postmenopausal breast cancer: a dose–response meta-analysis of prospective studies. Obesity Reviews, 17(11), 1167-1177.

62 [62] Appleby, P. N., & Key, T. J. (2016). The long-term health of vegetarians and vegans. Proceedings of the Nutrition Society, 75(3), 287-293.

63 [63] Wang, F., Shan, Y., 2019. Sulforaphane retards the growth of UM-UC-3 xenographs, induces apoptosis, and reduces survivin in athymic mice. Nutrition Research, 32(5), pp.374-380.

64 [64] Ho, E., Clarke, J. D., & Dashwood, R. H. (2009). Dietary sulforaphane, a histone deacetylase inhibitor for cancer prevention. The Journal of Nutrition, 139(12), 2393-2396.

65 [65] Giovannucci, E. (2002). A review of epidemiologic studies of tomatoes, lycopene, and prostate cancer. Experimental Biology and Medicine, 227(10), 852-859.

66 [66] Chen, J., Song, Y., & Zhang, L. (2013). Lycopene/tomato consumption and the risk of prostate cancer: a systematic review and meta-analysis of prospective studies. Journal of Nutritional Science and Vitaminology, 59(3), 213-223.

67 [67] Figueira, I., Menezes, R., Macedo, D., Costa, I., & dos Santos, C. N. (2017). Polyphenols beyond barriers: a glimpse into the brain. Current Neuropharmacology, 15(4), 562-594.

68 [68] Hügel, H. M., Jackson, N., May, B., Zhang, A. L., & Xue, C. C. (2016). Polyphenol protection and treatment of hypertension. Phytomedicine, 23(2), 220-231.

69 [69] Neshatdoust, S., Saunders, C., Castle, S. M., Vauzour, D., Williams, C., Butler, L., ... & Spencer, J. P. (2016). High-flavonoid intake induces cognitive improvements linked to changes in serum brain-derived neurotrophic factor: two randomised, controlled trials. Nutrition and Healthy Aging, 4(1), 81-93.

70 [70] Nolan, J. M., Mulcahy, R., Power, R., Moran, R., & Howard, A. N. (2018). Nutritional intervention to prevent Alzheimer's disease: potential benefits of xanthophyll carotenoids and omega-3 fatty acids combined. Journal of Alzheimer's Disease, 64(2), 367-378.

71 [71] Power, R., Coen, R. F., Beatty, S., Mulcahy, R., Moran, R., Stack, J., ... & Nolan, J. M. (2018). Supplemental retinal carotenoids enhance memory in healthy individuals with low levels of macular pigment in a randomized, double-blind, placebo-controlled clinical trial. Journal of Alzheimer's Disease, 61(3), 947-961.

72 [72] Shiina, A., Kanahara, N., Sasaki, T., Oda, Y., Hashimoto, T., Hasegawa, T., ... & Hashimoto, K. (2015). An open study of sulforaphane-rich broccoli sprout extract in patients with schizophrenia. Clinical Psychopharmacology and Neuroscience, 13(1), 62.

73 [73] Miller, M. G., Hamilton, D. A., Joseph, J. A., & Shukitt-Hale, B. (2018). Dietary blueberry improves cognition among older adults in a randomized, double-blind, placebo-controlled trial. European Journal of Nutrition, 57(3), 1169-1180.

74 [74] Witte, A. V., Kerti, L., Margulies, D. S., & Flöel, A. (2014). Effects of resveratrol on memory performance, hippocampal functional connectivity, and glucose metabolism in healthy older adults. Journal of Neuroscience, 34(23), 7862-7870.

75 [75] Holscher, H. D. (2017). Dietary fiber and prebiotics and the gastrointestinal microbiota. Gut Microbes, 8(2), 172-184.

76 [76] Bradbury, K. E., Appleby, P. N., & Key, T. J. (2014). Fruit, vegetable, and fiber intake in relation to cancer risk: findings from the European Prospective Investigation into Cancer and Nutrition (EPIC). The American Journal of Clinical Nutrition, 100(suppl_1), 394S-398S.

77 [77] Slavin, J. (2013). Fiber and prebiotics: mechanisms and health benefits. Nutrients, 5(4), 1417-1435.

78 [78] Ansell, J., Butts, C. A., Paturi, G., Eady, S. L., Wallace, A. J., Hedderley, D., & Gearry, R. B. (2015). Kiwifruit-derived supplements increase stool frequency in healthy adults: a randomized, double-blind, placebo-controlled study. Nutrition Research, 35(5), 401-408.

79 [79] Giacosa, A., Guido, D., Grassi, M., Riva, A., Morazzoni, P., Bombardelli, E., ... & Rondanelli, M. (2015). The effect of ginger (Zingiber officinalis) and artichoke (Cynara cardunculus) extract supplementation on functional dyspepsia: a randomised, double-blind, and placebo-controlled clinical trial. Evidence-Based Complementary and Alternative Medicine, 2015.

80 [80] Higgs, J., Derbyshire, E., & Styles, K. (2017). Nutrition and osteoporosis prevention for the orthopaedic surgeon: a wholefoods approach. EFORT Open Reviews, 2(6), 300-308.

81 [81] Zhang, Y. J., Gan, R. Y., Li, S., Zhou, Y., Li, A. N., Xu, D. P., & Li, H. B. (2015). Antioxidant phytochemicals for the prevention and treatment of chronic diseases. Molecules, 20(12), 21138-21156.

82 [82] Xu, L., Zhang, Y., Wang, L., Chen, Z., Su, J., Ma, X., ... & Xue, W. (2019). Carotenoids and risk of fracture: a meta-analysis of observational studies. Oncotarget, 10(14), 1378.

83 [83] Hooshmand, S., Chai, S. C., Saadat, R. L., Payton, M. E., Brummel-Smith, K., & Arjmandi, B. H. (2011). Comparative effects of dried plum and dried apple on bone in postmenopausal women. British Journal of Nutrition, 106(6), 923-930.

84 [84] Cipriani, C., Colangelo, D., & Santori, R. (2020). The interplay between bone and glucose metabolism. Frontiers in Endocrinology, 11, 122.

85 [85] Schagen, S. K., Zampeli, V. A., Makrantonaki, E., & Zouboulis, C. C. (2012). Discovering the link between nutrition and skin aging. Dermato-endocrinology, 4(3), 298-307.

86 [86] Cömert, E. D., Gökmen, V., 2018. Evolution of food antioxidants as a core topic of food science for a century. Food Research International, 105, pp.76-93.

87 [87] Juturu, V., Bowman, J.P. and Deshpande, J., 2016. Overall skin tone and skin-lightening-improving effects with oral supplementation of lutein and zeaxanthin isomers: a double-blind, placebo-controlled clinical trial. Clinical, Cosmetic and Investigational Dermatology, 9, p.325.

88 [88] Pullar, J. M., Carr, A. C., & Vissers, M. (2017). The roles of vitamin C in skin health. Nutrients, 9(8), 866.

89 [89] De Luca, C., Mikhal'chik, E. V., Suprun, M. V., Papacharalambous, M., Truhanov, A. I., & Korkina, L. G. (2016). Skin antiageing and systemic redox effects of supplementation with marine collagen peptides and plant-derived antioxidants: a single-blind case-control clinical study. Oxidative Medicine and Cellular Longevity, 2016.

90 [90] Rizwan, M., Rodriguez-Blanco, I., Harbottle, A., Birch-Machin, M. A., Watson, R. E. B., & Rhodes, L. E. (2011). Tomato paste rich in lycopene protects against cutaneous photodamage in humans in vivo: a randomized controlled trial. British Journal of Dermatology, 164(1), 154-162.

91 [91] Saini, R. K., & Keum, Y. S. (2018). Carotenoid extraction methods: A review of recent developments. Food Chemistry, 240, 90-103.

92 [92] Augustin, M. A., & Sanguansri, L. (2015). Challenges and solutions to incorporation of nutraceuticals in foods. Annual Review of Food Science and Technology, 6, 463-477.

93 [93] Gleeson, J. P., Ryan, S. M., & Brayden, D. J. (2016). Oral delivery strategies for nutraceuticals: Delivery vehicles and absorption enhancers. Trends in Food Science & Technology, 53, 90-101.

94 [94] Galanakis, C. M. (2020). The food systems in the era of the coronavirus (COVID-19) pandemic crisis. Foods, 9(4), 523.

95 [95] Rein, M. J., Renouf, M., Cruz-Hernandez, C., Actis-Goretta, L., Thakkar, S. K., & da Silva Pinto, M. (2013). Bioavailability of bioactive food compounds: a challenging journey to bioefficacy. British Journal of Clinical Pharmacology, 75(3), 588-602.

96 [96] Bohn, T., McDougall, G. J., Alegría, A., Alminger, M., Arrigoni, E., Aura, A. M., ... & Santos, C. N. (2015). Mind the gap—deficits in our knowledge of aspects impacting the bioavailability of phytochemicals and their metabolites—a position paper focusing on carotenoids and polyphenols. Molecular Nutrition & Food Research, 59(7), 1307-1323.

97 [97] McClements, D. J., Decker, E. A., Park, Y., & Weiss, J. (2009). Structural design principles for delivery of bioactive components in nutraceuticals and functional foods. Critical Reviews in Food Science and Nutrition, 49(6), 577-606.

98 [98] Porrini, M., & Riso, P. (2008). Factors influencing the bioavailability of antioxidants in foods: A critical appraisal. Nutrition, Metabolism and Cardiovascular Diseases, 18(10), 647-650.

99 [99] Dima, C., Assadpour, E., Dima, S., & Jafari, S. M. (2020). Bioavailability of nutraceuticals: Role of the food matrix, processing conditions, the gastrointestinal tract, and nanodelivery systems. Comprehensive Reviews in Food Science and Food Safety, 19(3), 954-994.

100 [100] Cilla, A., Bosch, L., Barberá, R., & Alegría, A. (2018). Effect of processing on the bioaccessibility of bioactive compounds–a review focusing on carotenoids, minerals, ascorbic acid, tocopherols and polyphenols. Journal of Food Composition and Analysis, 68, 3-15.

101 [101] Fardet, A., & Rock, E. (2014). Toward a new philosophy of preventive nutrition: from a reductionist to a holistic paradigm to improve nutritional recommendations. Advances in Nutrition, 5(4), 430-446.

102 [102] Bagchi, D., Swaroop, A., & Bagchi, M. (2015). Genomics, proteomics and metabolomics in nutraceuticals and functional foods. John Wiley & Sons.

103 [103] Santini, A., & Novellino, E. (2018). Nutraceuticals—shedding light on the grey area between pharmaceuticals and food. Expert Review of Clinical Pharmacology, 11(6), 545-547.

104 [104] Santini, A., Cammarata, S. M., Capone, G., Ianaro, A., Tenore, G. C., Pani, L., & Novellino, E. (2018). Nutraceuticals: opening the debate for a regulatory framework. British Journal of Clinical Pharmacology, 84(4), 659-672.

105 [105] Aronson, J. K. (2017). Defining 'nutraceuticals': neither nutritious nor pharmaceutical. British Journal of Clinical Pharmacology, 83(1), 8-19.

106 [106] Gulati, O. P., & Ottaway, P. B. (2006). Legislation relating to nutraceuticals in the European Union with a particular focus on botanical-sourced products. Toxicology, 221(1), 75-87.

107 [107] Ferguson, L. R., De Caterina, R., Görman, U., Allayee, H., Kohlmeier, M., Prasad, C., ... & Martinez, J. A. (2016). Guide and position of the international society of nutrigenetics/nutrigenomics on personalised nutrition: Part 1-fields of precision nutrition. Lifestyle Genomics, 9(1), 12-27.

108 [108] Manach, C., Milenkovic, D., Van de Wiele, T., Rodriguez-Mateos, A., de Roos, B., Garcia-Conesa, M. T., ... & Morand, C. (2017). Addressing the inter-individual variation in response to consumption of plant food bioactives: Towards a better understanding of their role in healthy aging and cardiometabolic risk reduction. Molecular Nutrition & Food Research, 61(6), 1600557.

109 [109] Hirahatake, K. M., Slavin, J. L., Maki, K. C., & Adams, S. H. (2014). Associations between dietary fiber and body weight, 1, 2, 3, and 6 years after baseline in the Adventist Health Study-2. The FASEB Journal, 28, 372-380.

110 [110] Liu, R. H. (2013). Dietary bioactive compounds and their health implications. Journal of Food Science, 78(s1), A18-A25.

111 [111] Zhou, Y., Zheng, J., Li, Y., Xu, D. P., Li, S., Chen, Y. M., & Li, H. B. (2016). Natural polyphenols for prevention and treatment of cancer. Nutrients, 8(8), 515.

112 [112] Upadhyay, S., & Dixit, M. (2015). Role of polyphenols and other phytochemicals on molecular signaling. Oxidative Medicine and Cellular Longevity, 2015.

113 [113] Zinoviadou, K. G., Galanakis, C. M., Brnčić, M., Grimi, N., Boussetta, N., Mota, M. J., ... & Barba, F. J. (2015). Fruit juice sonication: Implications on food safety and physicochemical and nutritional properties. Food Research International, 77, 743-752.

114 [114] Chemat, F., Rombaut, N., Meullemiestre, A., Turk, M., Perino, S., Fabiano-Tixier, A. S., & Abert-Vian, M. (2017). Review of green food processing techniques. Preservation, transformation, and extraction. Innovative Food Science & Emerging Technologies, 41, 357-377.

115 [115] Bornhorst, G. M., Ferrua, M. J., & Singh, R. P. (2015). A proposed food breakdown classification system to predict food behavior during gastric digestion. Journal of Food Science, 80(5), R924-R934.

116 [116] Houghton, D., Wilcox, M. D., Brownlee, I. A., Chater, P., Seal, C. J., & Pearson, J. P. (2014). Method for quantifying alginate and determining release from a food vehicle in gastrointestinal digesta. Food Chemistry, 151, 352-357.

117 [117] Velderrain-Rodríguez, G. R., Palafox-Carlos, H., Wall-Medrano, A., Ayala-Zavala, J. F., Chen, C. O., Robles-Sánchez, M., ... & González-Aguilar, G. A. (2014). Phenolic compounds: their journey after intake. Food & Function, 5(2), 189-197.

118 [118] McClements, D. J., & Xiao, H. (2014). Excipient foods: designing food matrices that improve the oral bioavailability of pharmaceuticals and nutraceuticals. Food & Function, 5(7), 1320-1333.

119 [119] Borel, P., & Desmarchelier, C. (2017). Genetic variations associated with vitamin A status and vitamin A bioavailability. Nutrients, 9(3), 246.

120 [120] Borel, P., Desmarchelier, C., Nowicki, M., & Bott, R. (2015). Lycopene bioavailability is associated with a combination of genetic variants. Free Radical Biology and Medicine, 83, 238-244.

121 [121] Ballard, O., & Morrow, A. L. (2013). Human milk composition: nutrients and bioactive factors. Pediatric Clinics, 60(1), 49-74.

CHAPTER - 7

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Postharvest Technology and Shelf Life Extension of Fruits and Vegetables

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Abstract

Fruits and vegetables are highly perishable commodities that suffer significant postharvest losses due to various biological and environmental factors. Postharvest technologies play a crucial role in minimizing these losses, maintaining quality, and extending the shelf life of fresh produce. This chapter provides a comprehensive overview of the latest advancements in postharvest technology for fruits and vegetables. It covers key topics such as the physiology and biochemistry of postharvest deterioration, pre-cooling and temperature management, modified atmosphere packaging, edible coatings, active packaging, non-destructive quality assessment, and novel preservation techniques like high-pressure processing, pulsed electric field, and ultrasound. The chapter also discusses the role of emerging technologies like nanotechnology, biotechnology, and smart packaging in enhancing the postharvest life and quality of fruits and vegetables. Additionally, it highlights the importance of integrating these technologies with good agricultural practices, proper handling, and efficient supply chain management to ensure the delivery of high-quality, safe, and nutritious produce to consumers. The future trends and challenges in postharvest technology are also explored, emphasizing the need for sustainable, eco-friendly, and cost-effective solutions. This chapter serves as a valuable resource for researchers, technologists, and industry stakeholders involved in the postharvest management of fruits and vegetables.

Keywords: Postharvest Technology, Shelf Life Extension, Quality Preservation, Novel Preservation Techniques, Sustainable Solutions

Fruits and vegetables are vital components of a healthy diet, providing essential nutrients, vitamins, minerals, and bioactive compounds. However, these highly perishable commodities are prone to rapid deterioration after harvest, leading to significant postharvest losses. According to the Food and Agriculture Organization (FAO), roughly one-third of the food produced globally for human consumption is lost or wasted, amounting to about 1.3 billion tons per year [1]. Postharvest losses of fruits and vegetables are particularly high, ranging from 20% to 50% in developing countries [2]. These losses not only have economic implications but also contribute to food insecurity and environmental concerns.

Postharvest technology encompasses a wide range of techniques, practices, and interventions aimed at maintaining the quality, safety, and marketability of fruits and vegetables from harvest to consumption. The primary objectives of postharvest technology are to slow down the physiological processes of senescence, minimize microbial spoilage, reduce moisture loss, and prevent physical damage. By extending the shelf life and preserving the quality of fresh produce, postharvest technology plays a crucial role in reducing food losses, enhancing food security, and meeting the growing demand for fresh, nutritious, and convenient food products.

In recent years, significant advancements have been made in postharvest technology, driven by the need for more efficient, sustainable, and consumer-oriented solutions. This chapter provides an in-depth analysis of the latest developments in postharvest technology for fruits and vegetables, covering a wide range of topics from fundamental concepts to innovative approaches. It aims to provide a comprehensive resource for researchers, technologists, and industry stakeholders involved in the postharvest management of fresh produce.

2. Physiology and Biochemistry of Postharvest Deterioration

Understanding the physiological and biochemical processes that occur in fruits and vegetables after harvest is essential for developing effective postharvest technologies. Fruits and vegetables are living tissues that continue to respire, transpire, and undergo various metabolic activities even after being detached from the parent plant. These processes, collectively known as senescence, lead to the gradual deterioration of quality attributes such as texture, color, flavor, and nutritional value.

2.1 Respiration

Respiration is a key metabolic process that plays a significant role in postharvest deterioration. It involves the oxidation of sugars and organic acids to produce energy, carbon dioxide, and water. The rate of respiration varies among different types of fruits and vegetables and is influenced by factors such as temperature, oxygen availability, and stage of maturity [3]. Climacteric fruits like apples, bananas, and tomatoes exhibit a marked increase in respiration rate during ripening, accompanied by a rise in ethylene production. In contrast, non-climacteric fruits like citrus, grapes, and berries have a relatively stable respiration rate throughout their postharvest life.

Controlling the respiration rate is crucial for extending the shelf life of fruits and vegetables. High respiration rates lead to rapid depletion of sugars and organic acids, resulting in loss of flavor, texture, and nutritional quality. Additionally, the heat generated during respiration can accelerate other deteriorative processes and create favorable conditions for microbial growth.

Postharvest technologies like low-temperature storage, modified atmosphere packaging, and controlled atmosphere storage aim to suppress respiration and delay senescence.

2.2 Ethylene Production and Action

Ethylene is a plant hormone that plays a critical role in the ripening and senescence of many fruits and vegetables. It is produced naturally by the tissues and can also be applied exogenously to induce ripening. Ethylene triggers a cascade of physiological and biochemical changes, including softening of texture, degradation of chlorophyll, synthesis of carotenoids and anthocyanins, and development of characteristic aroma and flavor compounds [4].

The sensitivity to ethylene varies among different types of fruits and vegetables. Climacteric fruits are highly responsive to ethylene and require its presence for ripening. In these fruits, exposure to ethylene can accelerate ripening and senescence, leading to shorter shelf life. Non-climacteric fruits, on the other hand, have a limited response to ethylene and do not require it for ripening.

Managing ethylene production and action is a key strategy in postharvest technology. Ethylene scrubbers and absorbers can be used to remove ethylene from storage environments, while ethylene inhibitors like 1-methylcyclopropene (1-MCP) can block its action on the tissues [5]. Controlling ethylene can help delay ripening, maintain firmness, and extend the shelf life of ethylene-sensitive fruits and vegetables.

2.3 Enzymatic and Non-Enzymatic Browning

Browning is a common quality defect in fruits and vegetables that occurs due to enzymatic and non-enzymatic reactions. Enzymatic browning is caused by the oxidation of phenolic compounds by polyphenol oxidase (PPO) enzymes in the presence of oxygen, resulting in the formation of brown pigments [6]. It is a major concern in cut or damaged tissues, where the PPO enzymes come into contact with the phenolic substrates. Non-enzymatic browning, also known as the Maillard reaction, involves the interaction between reducing sugars and amino acids at high temperatures, leading to the formation of brown pigments and off-flavors.

Browning not only affects the visual appeal of fruits and vegetables but can also lead to loss of nutritional quality and development of off-flavors. Postharvest technologies aim to inhibit or minimize browning reactions through various approaches. These include the use of anti-browning agents like ascorbic acid, citric acid, and sulfites, as well as physical treatments like blanching, ultrasound, and high-pressure processing [7]. Modified atmosphere packaging with low oxygen and high carbon dioxide levels can also help reduce enzymatic browning by limiting oxygen availability.

2.4 Moisture Loss and Textural Changes

Moisture loss is a major cause of quality deterioration in fruits and vegetables during postharvest handling and storage. It occurs due to transpiration, the process by which water vapor is lost from the tissues to the surrounding environment. Excessive moisture loss leads to wilting, shriveling, and loss of turgidity, making the produce less appealing and marketable. The rate of moisture loss depends on factors such as temperature, relative humidity, air velocity, and surface area to volume ratio of the produce [8].

Textural changes, such as softening and loss of crispness, are also common postharvest problems in fruits and vegetables. These changes are primarily due to the degradation of cell wall components, particularly pectins, by enzymes like polygalacturonase and pectin methylesterase [9]. The activity of these enzymes increases during ripening and senescence, leading to a breakdown of the cell wall structure and loss of firmness.

Postharvest technologies aim to minimize moisture loss and maintain textural quality through various approaches. These include the use of proper packaging materials, maintaining optimum temperature and humidity during storage, and applying surface coatings or waxes to create a barrier against moisture loss [10]. Calcium treatments, either as pre-harvest sprays or postharvest dips, have been shown to enhance cell wall stability and delay softening in many fruits and vegetables [11].

3. Pre-Cooling and Temperature Management

Temperature is the single most important factor influencing the postharvest life of fruits and vegetables. Proper temperature management, starting from the point of harvest, is essential for maintaining quality, extending shelf life, and reducing losses. Pre-cooling, the rapid removal of field heat immediately after harvest, is a critical step in the postharvest handling of many fruits and vegetables.

3.1 Importance of Pre-Cooling

Pre-cooling helps to slow down respiration, minimize moisture loss, and reduce the activity of degradative enzymes. It also helps to prevent the growth of spoilage microorganisms and delays the onset of ripening and senescence. The benefits of pre-cooling are particularly significant for highly perishable commodities like berries, leafy greens, and tropical fruits, which have high respiration rates and are prone to rapid deterioration at ambient temperatures.

The time taken to pre-cool the produce to the desired storage temperature is critical. Delaying pre-cooling by even a few hours can lead to significant quality losses and reduced shelf life. The rate of cooling depends on factors such as the initial temperature of the produce, the cooling method used, and the type and size of the produce [12].

3.2 Pre-Cooling Methods

Several methods are used for pre-cooling fruits and vegetables, each with its own advantages and limitations. The choice of method depends on the type of produce, the desired cooling rate, and the available resources and infrastructure.

3.2.1 Room Cooling

Room cooling involves placing the produce in a refrigerated room or walk-in cooler and allowing it to cool gradually over time. It is a simple and low-cost method but has a relatively slow cooling rate. Room cooling is suitable for produce that is not highly perishable and can tolerate a slow cooling process, such as potatoes, onions, and winter squash.

3.2.2 Forced-Air Cooling

Forced-air cooling uses fans to circulate cold air through the produce, achieving rapid and uniform cooling. The produce is typically placed in vented containers or pallets, and cold air is forced through the openings, removing heat from the produce. Forced-air cooling is widely used for many fruits and vegetables, including strawberries, melons, and leafy greens [13].

3.2.3 Hydro-Cooling

Hydro-cooling involves immersing the produce in cold water or spraying it with cold water to remove heat. It is a fast and efficient method, particularly suitable for produce with high surface area to volume ratio, such as asparagus, carrots, and celery. Hydro-cooling can also help to remove dirt and debris from the produce surface, but it may increase the risk of microbial contamination if the water is not properly sanitized [14].

3.2.4 Vacuum Cooling

Vacuum cooling is based on the principle of evaporative cooling, where the produce is placed in a vacuum chamber and the pressure is rapidly reduced, causing the water in the produce to evaporate and remove heat. It is a fast and effective method for cooling leafy vegetables like lettuce, spinach, and herbs. However, vacuum cooling can cause excessive moisture loss if not properly managed and is not suitable for all types of produce [15].

3.3 Temperature Management during Storage and Transport

Maintaining optimal temperature throughout the postharvest supply chain is crucial for preserving the quality and extending the shelf life of fruits and vegetables. The recommended storage temperature varies depending on the type of produce and its sensitivity to chilling injury. Chilling-sensitive crops like bananas, tomatoes, and cucumbers should be stored at temperatures above 10°C to avoid chilling injury, while chilling-tolerant crops like apples, carrots, and broccoli can be stored at temperatures close to 0°C [16].

Temperature fluctuations during storage and transport can lead to condensation, moisture loss, and accelerated deterioration. It is important to maintain a consistent and uniform temperature throughout the storage facility and during transportation. This can be achieved through proper insulation, air circulation, and the use of temperature monitoring devices like thermocouples and data loggers.

Advanced technologies like controlled atmosphere (CA) storage and modified atmosphere packaging (MAP) can further enhance the benefits of low-temperature storage. CA storage involves manipulating the gas composition around the produce, typically by reducing oxygen and increasing carbon dioxide levels, to slow down respiration and delay senescence [17]. MAP uses specialized packaging materials to create a similar effect, by modifying the gas composition within the package. These technologies, in combination with optimal temperature management, can significantly extend the postharvest life of many fruits and vegetables.

4. Modified Atmosphere Packaging (MAP)

Modified atmosphere packaging (MAP) is a postharvest technology that involves enclosing the produce in a package with a modified gas composition, different from that of normal air. The goal of MAP is to create an optimal atmosphere around the produce that slows down respiration, delays ripening and senescence, and extends the shelf life. MAP can be achieved through passive or active modification of the package atmosphere.

4.1 Principles of MAP

The basic principle of MAP is to reduce the oxygen (O2) concentration and increase the carbon dioxide (CO2) concentration around the produce. Lowering the O2 level suppresses respiration, while elevated CO2 has a direct inhibitory effect on various metabolic processes, including ethylene production and action, and the activity of ripening-related enzymes [18]. The optimal gas composition for MAP varies depending on the type of produce and its tolerance to low O2 and high CO2 levels.

In passive MAP, the desired atmosphere is achieved by the natural interplay between the respiration of the produce and the permeability of the packaging material. As the produce respires, it consumes O2 and releases CO2, gradually modifying the package atmosphere until an equilibrium is reached. The packaging material, typically a polymeric film, allows a certain degree of gas exchange with the surrounding environment, preventing the build-up of excessive CO2 or depletion of O2 [19].

Active MAP, on the other hand, involves the intentional modification of the package atmosphere by flushing with a desired gas mixture or using gas scavengers or emitters. This allows for a more precise control over the gas composition and can be tailored to the specific requirements of the produce. Active MAP is commonly used for highly perishable products like fresh-cut salads, where a rapid establishment of the desired atmosphere is critical [20].

4.2 Benefits and Limitations of MAP

MAP offers several benefits for extending the postharvest life and maintaining the quality of fruits and vegetables. By reducing respiration and delaying senescence, MAP can significantly prolong the shelf life, allowing for longer storage and transportation periods. It can also retard enzymatic browning, minimize moisture loss, and maintain firmness and overall quality attributes.

However, MAP also has some limitations and potential drawbacks. If the gas composition is not properly controlled, anaerobic conditions may develop within the package, leading to the growth of anaerobic pathogens like Clostridium botulinum and the production of off-flavors [21]. Some fruits and vegetables, particularly those with high respiration rates, may not tolerate the low O2 and high CO2 levels used in MAP and may develop physiological disorders or off-flavors.

Another challenge with MAP is the variability in respiration rates among different types of produce and even within the same type, depending on factors like cultivar, maturity, and growing conditions. This makes it difficult to design a one-size-fits-all MAP system, and requires careful selection of packaging materials and gas compositions for each specific product.

4.3 Advances in MAP Technology

Recent advances in MAP technology have focused on developing more sophisticated packaging materials and systems to better control the package atmosphere and meet the specific needs of different types of produce. Some of these advances include:

- **Microperforated Films**: These films have tiny holes that allow for controlled gas exchange, preventing the build-up of excessive CO2 or depletion of O2. The size and number of perforations can be tailored to the respiration rate of the produce, providing a more precise control over the package atmosphere [22].
- **Biodegradable and Edible Films**: There is growing interest in using biodegradable and edible materials for MAP, as an alternative to conventional petroleum-based plastics. These materials, derived from natural sources like starch, cellulose, and proteins, can provide similar gas barrier properties while reducing environmental impact [23].
- **Active and Intelligent Packaging**: Active packaging systems incorporate additives or compounds that can scavenge or emit gases, moisture, or ethylene, helping to maintain the desired atmosphere and extend the shelf life. Intelligent packaging systems use sensors or indicators to monitor the package atmosphere, product quality, or microbial growth, providing real-time information to improve decision-making and reduce losses [24].
- **MAP in Combination with Other Technologies**: MAP is often used in combination with other postharvest technologies to further enhance its benefits. For example, the use of MAP together with edible coatings, antimicrobial agents, or modified atmosphere storage can provide a synergistic effect in extending the shelf life and maintaining the quality of fruits and vegetables [25].

5. Edible Coatings

Edible coatings are thin layers of edible materials applied to the surface of fruits and vegetables to provide a barrier against moisture loss, gas exchange, and microbial contamination. They are an attractive alternative to synthetic packaging materials, as they are biodegradable, environmentally friendly, and can be consumed along with the product. Edible coatings can also serve as carriers for various functional ingredients, such as antimicrobials, antioxidants, and nutrients, to enhance the safety and quality of the produce.

5.1 Types of Edible Coatings

Edible coatings can be broadly classified into three categories based on their composition: polysaccharide-based, protein-based, and lipid-based coatings. Each type of coating has unique properties and advantages, and they can also be used in combination to achieve desired functionalities.

5.1.1 Polysaccharide-Based Coatings

Polysaccharide-based coatings are derived from various natural sources, such as starch, cellulose, chitosan, alginates, and gums. They are hydrophilic in nature and provide a good barrier against gases, but have limited moisture barrier properties. Polysaccharide coatings are often used in combination with lipids or plasticizers to improve their water vapor barrier properties [26].

Some examples of polysaccharide-based coatings include:

- Chitosan: A linear polysaccharide derived from the deacetylation of chitin, found in the exoskeletons of crustaceans. Chitosan has excellent film-forming properties and inherent antimicrobial activity, making it a popular choice for edible coatings [27].
- Alginate: A polysaccharide extracted from brown seaweeds, alginate forms strong and uniform films with good gas barrier properties. It is commonly used as a coating for minimally processed fruits and vegetables [28].
- Starch: Starch-based coatings, derived from various plant sources like corn, potato, and cassava, are inexpensive, abundant, and have good film-forming properties. They are often modified or blended with other materials to improve their functionalities [29].

5.1.2 Protein-Based Coatings

Protein-based coatings are derived from various plant and animal sources, such as soy protein, whey protein, casein, gelatin, and corn zein. They have good film-forming properties and provide a better moisture barrier compared to polysaccharide coatings. Protein coatings also have unique functional properties, such as the ability to bind with lipids and other hydrophobic compounds [30].

Some examples of protein-based coatings include:

- Soy Protein: Soy protein isolate (SPI) is a common source for edible coatings, due to its abundance, low cost, and good film-forming properties. SPI coatings have been shown to extend the shelf life and maintain the quality of various fruits and vegetables [31].
- Whey Protein: Whey protein, a byproduct of cheese manufacturing, has excellent film-forming and gas barrier properties. It is often used in combination with other materials, such as lipids or plasticizers, to improve its moisture barrier properties [32].
- Gelatin: Gelatin, derived from the partial hydrolysis of collagen, forms clear, flexible, and moisture-resistant films. It is commonly used as a coating for meat products but has also been explored for use on fruits and vegetables [33].

5.1.3 Lipid-Based Coatings

Lipid-based coatings are composed of various hydrophobic compounds, such as waxes, resins, and fatty acids. They provide an excellent barrier against moisture loss but have limited gas barrier properties. Lipid coatings are often used in combination with polysaccharides or proteins to create composite films with improved gas barrier properties [34].

Some examples of lipid-based coatings include:

- Waxes: Natural waxes, such as beeswax, carnauba wax, and candelilla wax, have been used for centuries to coat fruits and vegetables. They form thick, moisture-resistant films that can significantly reduce water loss and maintain firmness [35].

- Resins: Resins, such as shellac and rosin, are secreted by various insects and plants. They form hard, glossy, and moisture-resistant films that can improve the appearance and extend the shelf life of produce [36].
- Fatty Acids: Fatty acids, such as lauric acid, palmitic acid, and stearic acid, can form stable and moisture-resistant films. They are often incorporated into composite coatings to improve the hydrophobicity and moisture barrier properties [37].

5.2 Application Methods

Edible coatings can be applied to fruits and vegetables using various methods, depending on the type of coating material, the surface characteristics of the produce, and the desired thickness and coverage of the coating. Some common application methods include:

- Dipping: The produce is immersed in the coating solution for a specific duration and then allowed to drain and dry. This method is simple, economical, and provides good coverage, but may result in uneven thickness and dripping [38].
- Spraying: The coating solution is sprayed onto the surface of the produce using a pressurized nozzle. This method provides more uniform coverage and can be easily automated, but may require multiple passes to achieve the desired thickness [39].
- Brushing: The coating solution is manually brushed onto the surface of the produce using a soft brush or sponge. This method is suitable for small-scale applications and can provide good coverage and thickness control, but is labor-intensive and time-consuming [40].
- Panning: The produce is placed in a rotating pan or drum, and the coating solution is sprayed or dripped onto the surface as the pan rotates. This method provides even coverage and can be used for large-scale applications, but may cause damage to delicate produce [41].

5.3 Benefits and Challenges

Edible coatings offer several benefits for preserving the quality and extending the shelf life of fruits and vegetables. By acting as a barrier against moisture loss and gas exchange, they can reduce weight loss, maintain firmness, and delay ripening and senescence. Coatings can also improve the visual appearance of produce by providing a glossy or matte finish and can enhance the tactile properties by reducing surface roughness.

Edible coatings can also serve as carriers for various bioactive compounds, such as antimicrobials, antioxidants, and nutraceuticals. Incorporating these compounds into the coating matrix can help to control microbial growth, prevent oxidative damage, and enhance the nutritional value of the produce [42].

However, there are also some challenges and limitations associated with the use of edible coatings. One major challenge is the need to tailor the coating formulation and application method to the specific surface characteristics and physiological requirements of each type of produce. Factors such as surface wettability, gas permeability, and respiration rate can vary widely among different fruits and vegetables, and even among different cultivars of the same species [43].

Another challenge is the potential impact of coatings on the sensory properties of the produce. Some coating materials may impart an undesirable flavor, odor, or texture to the product, which can affect consumer acceptability. The thickness and coverage of the coating can also influence the gas exchange and respiration rate of the produce, which can lead to anaerobic conditions and off-flavors if not properly controlled [44]. Regulatory and safety considerations are also important aspects of edible coating applications. While most coating materials are generally recognized as safe (GRAS) for food use, their use on fresh produce may require additional safety assessments and regulatory approvals. The potential allergenicity of some protein-based coatings and the migration of coating components into the food matrix are some of the safety concerns that need to be addressed [45].

6. Active Packaging

Active packaging is an innovative approach to extend the shelf life and maintain the quality of fruits and vegetables by incorporating active compounds into the packaging material or within the package. These active compounds can interact with the produce or the package headspace to control various physiological processes, such as respiration, ethylene production, and microbial growth. Active packaging can be classified into two main categories: scavengers and emitters.

6.1 Scavengers

Scavengers are substances that remove undesirable compounds from the package headspace or the produce itself. The most common types of scavengers used in active packaging for fruits and vegetables are oxygen scavengers, ethylene scavengers, and moisture scavengers.

6.1.1 Oxygen Scavengers

Oxygen scavengers are used to remove residual oxygen from the package headspace and maintain a low oxygen environment around the produce. This can help to slow down respiration, delay ripening and senescence, and prevent oxidative damage. Oxygen scavengers are typically based on iron powder, ascorbic acid, or enzyme systems that can chemically or enzymatically react with oxygen [46]. One example of an oxygen scavenger system is the use of sachets containing iron powder, which can be placed inside the package. When exposed to moisture, the iron powder oxidizes and removes oxygen from the headspace. Another approach is the incorporation of oxygen-scavenging polymers, such as polyethylene terephthalate (PET) or polyolefins, into the packaging material itself [47].

6.1.2 Ethylene Scavengers

Ethylene is a plant hormone that plays a key role in the ripening and senescence of many fruits and vegetables. Ethylene scavengers are used to remove ethylene from the package headspace, thereby delaying ripening and extending the shelf life of ethylene-sensitive produce. Ethylene scavengers can be based on various materials, such as potassium permanganate, activated carbon, or zeolites, which can adsorb or oxidize ethylene [48].

One common form of ethylene scavenger is a sachet containing potassium permanganate, which can be placed inside the package. As ethylene diffuses into the sachet, it is oxidized by the potassium permanganate, reducing its concentration in the headspace. Another approach is the use of ethylene-scavenging films, which incorporate ethylene-adsorbing materials like clays or zeolites into the packaging material [49].

6.1.3 Moisture Scavengers

Moisture scavengers, also known as desiccants, are used to control the humidity inside the package and prevent condensation on the produce surface. Excess moisture can promote microbial growth, accelerate decay, and cause softening and loss of texture. Moisture scavengers are typically based on hygroscopic materials, such as silica gel, calcium oxide, or clay, which can adsorb water vapor from the package headspace [50].

Moisture scavengers can be used in the form of sachets, pads, or films incorporated into the packaging material. They are particularly useful for packaging moisture-sensitive produce, such as leafy greens, berries, and mushrooms [51].

6.2 Emitters

Emitters are substances that release active compounds into the package headspace or the produce itself to control various physiological processes and maintain quality. The most common types of emitters used in active packaging for fruits and vegetables are carbon dioxide emitters, antimicrobial agents, and antioxidants.

6.2.1 Carbon Dioxide Emitters

Carbon dioxide (CO2) is known to have a preservative effect on many fruits and vegetables by reducing respiration, delaying ripening, and inhibiting microbial growth. CO2 emitters are used to increase the CO2 concentration inside the package, creating a modified atmosphere that can extend the shelf life of the produce [52].

CO2 emitters can be in the form of sachets or films that contain sodium bicarbonate or other carbonates, which release CO2 when exposed to moisture. The released CO2 can help to maintain a desirable gas composition inside the package, even if the package is not hermetically sealed [53].

6.2.2 Antimicrobial Agents

Antimicrobial agents are used to control the growth of spoilage and pathogenic microorganisms on the surface of fruits and vegetables. They can be incorporated into the packaging material or released into the package headspace to maintain a sterile environment around the produce [54].

Various natural and synthetic compounds have been explored as antimicrobial agents in active packaging, such as essential oils, organic acids, bacteriocins, and silver nanoparticles. These compounds can be incorporated into packaging films, coatings, or sachets to provide a sustained release of the antimicrobial agent over time [55].

Some examples of antimicrobial packaging systems for fruits and vegetables include:

- Films containing essential oils like cinnamon, thyme, or oregano, which have strong antimicrobial activity against a wide range of bacteria and fungi [56].
- Coatings containing organic acids like citric acid, lactic acid, or acetic acid, which can lower the pH on the produce surface and inhibit microbial growth [57].
- Sachets containing allyl isothiocyanate (AITC), a natural antimicrobial compound found in mustard and horseradish, which can be released into the package headspace to control microbial growth [58].

6.2.3 Antioxidants

Antioxidants are used to prevent or delay oxidative damage in fruits and vegetables, which can lead to browning, loss of nutrients, and off-flavors. They can be incorporated into the packaging material or released into the package headspace to maintain the quality and extend the shelf life of the produce [59].

Various natural and synthetic antioxidants have been explored for use in active packaging, such as tocopherols (vitamin E), ascorbic acid (vitamin C), plant phenolics, and butylated hydroxyanisole (BHA). These compounds can be incorporated into packaging films, coatings, or sachets to provide a sustained release of the antioxidant over time [60].

Some examples of antioxidant packaging systems for fruits and vegetables include:

- Films containing vitamin E or other tocopherols, which can scavenge free radicals and prevent lipid oxidation in the produce [61].
- Coatings containing plant extracts rich in phenolic compounds, such as green tea extract or grape seed extract, which can provide antioxidant protection and delay browning [62].
- Sachets containing ascorbic acid or other reducing agents, which can scavenge oxygen and prevent oxidative damage in the package headspace [63].

6.3 Challenges and Future Prospects

While active packaging offers many potential benefits for preserving the quality and extending the shelf life of fruits and vegetables, there are also some challenges and limitations that need to be addressed. One challenge is the need to ensure the safety and regulatory compliance of the active compounds used in the packaging material. Some active compounds, such as essential oils or nanoparticles, may have potential toxicity or migration issues that need to be carefully evaluated [64].

Another challenge is the cost and environmental impact of active packaging materials. Many active packaging systems require specialized materials or manufacturing processes that can increase the cost of the packaging. There are also concerns about the recyclability and biodegradability of some active packaging materials, particularly those containing non-renewable or non-biodegradable components [65].

Despite these challenges, active packaging remains a promising area of research and development for the fresh produce industry. With the growing demand for high-quality, convenient, and sustainable food products, there is a need for innovative packaging solutions that can maintain the freshness and extend the shelf life of fruits and vegetables.

Some future prospects and research directions in active packaging for fruits and vegetables include:

- Development of biodegradable and renewable active packaging materials, such as those based on biopolymers or agricultural waste products [66].
- Integration of active packaging with other preservation technologies, such as modified atmosphere packaging, edible coatings, or non-thermal processing, to achieve synergistic effects [67].
- Development of smart and responsive active packaging systems that can sense and adapt to changes in the package environment or the produce quality, such as pH-sensitive or temperature-sensitive materials [68].
- Exploration of novel active compounds from natural sources, such as plant extracts, microbial metabolites, or animal-derived products, with potential antimicrobial, antioxidant, or other bioactive properties [69].
- Development of active packaging systems tailored to the specific needs and characteristics of different types of fruits and vegetables, considering factors such as respiration rate, ethylene sensitivity, and optimal storage conditions [70].

7. Non-Destructive Quality Assessment

Non-destructive quality assessment is a crucial aspect of postharvest technology for fruits and vegetables. It involves the use of various techniques and technologies to evaluate the quality attributes of the produce without causing any damage or alteration to the product. Non-destructive methods can provide rapid, objective, and reliable information about the physical, chemical, and sensory properties of the produce, which can be used for quality control, sorting, grading, and decision-making in the postharvest supply chain.

7.1 Importance of Non-Destructive Quality Assessment

Non-destructive quality assessment offers several advantages over traditional destructive methods, such as visual inspection, firmness

measurement, or chemical analysis. Some of the key benefits of non-destructive methods include:

- **Preservation of Sample Integrity**: Non-destructive methods allow for the assessment of quality attributes without damaging or altering the produce. This is particularly important for high-value or delicate fruits and vegetables, where destructive sampling can lead to significant losses [71].
- **Rapid and High-Throughput Analysis**: Many non-destructive techniques can provide quick and automated measurements, enabling the assessment of large volumes of produce in a short time. This is crucial for real-time quality control and decision-making in the postharvest supply chain [72].

- **Spatial and Temporal Monitoring**: Non-destructive methods can be used to monitor the quality attributes of the produce over time and across different spatial locations. This can provide valuable information about the ripening, senescence, or deterioration processes occurring in the produce during storage and transportation [73].
- **Correlation with Destructive Methods**: Non-destructive measurements can be correlated with traditional destructive methods, such as firmness or chemical analysis, to develop predictive models and calibrations. This can reduce the need for destructive sampling and provide a more efficient and cost-effective approach to quality assessment [74].

7.2 Types of Non-Destructive Quality Assessment Methods

There are various types of non-destructive quality assessment methods used for fruits and vegetables, based on different physical principles and technologies. Some of the most common methods include:

7.2.1 Visible and Near-Infrared Spectroscopy

Visible and near-infrared (VIS-NIR) spectroscopy is a widely used non-destructive method for assessing the quality attributes of fruits and vegetables. It involves the measurement of the reflectance, transmittance, or absorbance of light in the visible (400-700 nm) and near-infrared (700-2500 nm) regions of the electromagnetic spectrum [75].

VIS-NIR spectroscopy can provide information about various quality attributes, such as color, firmness, soluble solids content, acidity, and internal defects. The spectral data can be analyzed using multivariate statistical methods, such as principal component analysis (PCA) or partial least squares regression (PLSR), to develop predictive models and calibrations [76].

Some examples of VIS-NIR spectroscopy applications in fruits and vegetables include:

- Measurement of soluble solids content and firmness in apples, pears, and stone fruits [77].
- Detection of internal defects, such as bruises, rots, or insect damage, in potatoes, onions, and citrus fruits [78].
- Monitoring of ripening and senescence processes in bananas, mangoes, and tomatoes [79].

7.2.2 Hyperspectral Imaging

Hyperspectral imaging is an advanced non-destructive method that combines spectroscopy and imaging techniques to provide spatial and spectral information about the quality attributes of fruits and vegetables. It involves the acquisition of images at multiple narrow wavebands across the electromagnetic spectrum, typically in the visible, near-infrared, and short-wave infrared regions [80].

Hyperspectral imaging can provide detailed information about the distribution of quality attributes within the produce, such as color, texture, chemical composition, and internal structure. The hyperspectral data can be analyzed using various chemometric and image processing techniques, such as principal component analysis (PCA), partial least squares discriminant analysis

(PLS-DA), or support vector machines (SVM), to develop classification models and spatial maps [81].

Some examples of hyperspectral imaging applications in fruits and vegetables include:

- Detection of bruises, rots, and chilling injury in apples, cucumbers, and bell peppers [82].
- Measurement of firmness, soluble solids content, and acidity in peaches, plums, and citrus fruits [83].
- Assessment of ripening stages and quality grades in bananas, mangoes, and tomatoes [84].

7.2.3 Fluorescence Spectroscopy

Fluorescence spectroscopy is a non-destructive method that measures the fluorescence emission of fruits and vegetables when excited with light at specific wavelengths. It is based on the principle that certain compounds in the produce, such as chlorophylls, carotenoids, or phenolics, can absorb light and emit fluorescence at longer wavelengths [85].

Fluorescence spectroscopy can provide information about various quality attributes, such as ripeness, senescence, stress, or disease status. The fluorescence data can be analyzed using various statistical and machine learning methods, such as principal component analysis (PCA), linear discriminant analysis (LDA), or artificial neural networks (ANN), to develop predictive models and classifications [86].

Some examples of fluorescence spectroscopy applications in fruits and vegetables include:

- Assessment of ripening stages and quality grades in apples, pears, and tomatoes [87].
- Detection of fungal infections, such as Botrytis cinerea or Penicillium expansum, in grapes, strawberries, and citrus fruits [88].
- Monitoring of stress responses, such as drought, salinity, or chilling injury, in lettuce, spinach, and potatoes [89].

7.2.4 Impedance Spectroscopy

Impedance spectroscopy is a non-destructive method that measures the electrical impedance of fruits and vegetables when subjected to alternating current at different frequencies. It is based on the principle that the electrical properties of the produce, such as resistance and capacitance, can change with quality attributes, such as ripeness, moisture content, or tissue damage [90].

Impedance spectroscopy can provide information about various quality attributes, such as firmness, soluble solids content, acidity, or internal defects. The impedance data can be analyzed using various equivalent circuit models or multivariate statistical methods, such as principal component analysis (PCA) or partial least squares regression (PLSR), to develop predictive models and calibrations [91].

Some examples of impedance spectroscopy applications in fruits and vegetables include:

- Measurement of firmness and soluble solids content in apples, pears, and kiwifruit [92].
- Detection of internal defects, such as hollow heart or brown heart, in potatoes and sweet potatoes [93].
- Monitoring of ripening and senescence processes in avocados, mangoes, and bananas [94].

7.2.5 Acoustic and Vibrational Methods

Acoustic and vibrational methods are non-destructive techniques that measure the mechanical properties of fruits and vegetables by analyzing their response to sound or vibration. These methods are based on the principle that the acoustic or vibrational behavior of the produce can change with quality attributes, such as firmness, texture, or internal structure [95].

Some common acoustic and vibrational methods used for fruits and vegetables include:

- **Acoustic Resonance**: This method involves the excitation of the produce with sound waves at different frequencies and the measurement of its resonance response. The resonance frequencies and amplitudes can be related to quality attributes, such as firmness, density, or internal defects [96].
- **Laser Doppler Vibrometry**: This method uses a laser beam to measure the surface velocity and displacement of the produce when subjected to vibration. The vibrational parameters can be correlated with quality attributes, such as firmness, elasticity, or internal damage [97].
- **Impact Resonance**: This method involves the application of a small impact to the produce and the measurement of its resonance response. The impact response can be analyzed using various signal processing techniques, such as Fourier transform or wavelet analysis, to extract quality-related features [98].

Some examples of acoustic and vibrational applications in fruits and vegetables include:

- Measurement of firmness and texture in apples, pears, and melons [99].
- Detection of internal defects, such as hollow heart or splits, in potatoes and onions [100].
- Monitoring of ripening and softening processes in peaches, plums, and tomatoes [101].

7.3 Challenges and Future Prospects

While non-destructive quality assessment methods offer many benefits for the fresh produce industry, there are also some challenges and limitations that need to be addressed. One challenge is the variability and complexity of the biological materials, which can affect the accuracy and robustness of the non-destructive measurements. Factors such as cultivar, maturity, growing conditions, and postharvest handling can influence the physical, chemical, and structural properties of the produce, making it difficult to develop universal calibration models [102].

Another challenge is the need for large and diverse datasets to train and validate the non-destructive models. The development of robust and reliable models requires the collection of data from a wide range of samples, covering different quality attributes, defect types, and environmental conditions. This can be time-consuming and costly, especially for highly perishable and seasonal produce [103].

Despite these challenges, non-destructive quality assessment remains a promising and active area of research and development for the fresh produce industry. With the increasing demand for high-quality, safe, and traceable food products, there is a need for advanced and efficient quality assessment tools that can provide objective and reliable information throughout the postharvest supply chain.

Some future prospects and research directions in non-destructive quality assessment of fruits and vegetables include:

- Development of multi-sensor and data fusion approaches that combine different non-destructive techniques, such as spectroscopy, imaging, and acoustic methods, to provide a more comprehensive and accurate assessment of quality attributes [104].
- Integration of non-destructive sensors with automated sorting, grading, and packaging systems to enable real-time quality monitoring and decision-making in the postharvest supply chain [105].
- Application of advanced data analytics, such as machine learning, deep learning, and artificial intelligence, to extract meaningful insights from the large and complex datasets generated by non-destructive sensors [106].
- Development of portable, low-cost, and user-friendly non-destructive devices that can be used by farmers, processors, and retailers for on-site quality assessment and management [107].
- Exploration of new non-destructive biomarkers, such as volatile organic compounds, microRNAs, or metabolites, that can provide early and sensitive indicators of quality, safety, and shelf life of fresh produce [108].

8. Novel Preservation Techniques

In addition to the traditional preservation methods, such as refrigeration, modified atmosphere packaging, and edible coatings, there are several novel preservation techniques that have emerged in recent years to extend the shelf life and maintain the quality of fruits and vegetables. These techniques are based on various physical, chemical, or biological principles and can offer some advantages over the conventional methods, such as reduced energy consumption, minimal processing, or enhanced safety.

8.1 High-Pressure Processing

High-pressure processing (HPP) is a non-thermal preservation technique that involves the application of high hydrostatic pressure (100-1000 MPa) to the packaged produce for a short time (few seconds to several minutes). HPP can inactivate spoilage and pathogenic microorganisms, as well as enzymes, without significantly affecting the nutritional and sensory quality of the produce [109].

The main advantages of HPP include:

- Minimal impact on the color, texture, flavor, and nutrients of the produce, compared to thermal processing methods.

- Uniform and instantaneous pressure transmission, allowing for the treatment of large volumes of produce in a short time.
- Applicability to a wide range of fruits and vegetables, including both solid and liquid products.
- Potential for the development of new products with extended shelf life and improved safety.

Some examples of HPP applications in fruits and vegetables include:

- Preservation of fruit and vegetable juices, purees, and smoothies, with shelf life extension up to 30-45 days under refrigeration [110].
- Inactivation of spoilage and pathogenic bacteria, such as Listeria monocytogenes, Salmonella, and Escherichia coli, in fresh-cut fruits and vegetables [111].
- Enhancement of the extraction of bioactive compounds, such as carotenoids, phenolics, and vitamins, from fruits and vegetables [112].

8.2 Pulsed Electric Field

Pulsed electric field (PEF) is another non-thermal preservation technique that involves the application of short, high-voltage pulses (1-100 kV/cm) to the produce placed between two electrodes. PEF can cause the electroporation of cell membranes, leading to the inactivation of microorganisms and the modification of tissue structure, without significant heating [113].

The main advantages of PEF include:

- Minimal impact on the nutritional and sensory quality of the produce, compared to thermal processing methods.
- Potential for the selective inactivation of microorganisms, while preserving the activity of beneficial enzymes and the integrity of plant cells.
- Applicability to a wide range of fruits and vegetables, including both liquid and solid products.
- Potential for the development of new products with improved functionality and bioavailability.

Some examples of PEF applications in fruits and vegetables include:

- Preservation of fruit and vegetable juices, with shelf life extension up to 21-28 days under refrigeration [114].
- Inactivation of spoilage and pathogenic bacteria, such as Listeria innocua, Escherichia coli, and Lactobacillus brevis, in fresh-cut apples, carrots, and melons [115].
- Enhancement of the extraction of valuable compounds, such as anthocyanins, phenolics, and sugars, from grapes, apples, and beets [116].

8.3 Ultrasound

Ultrasound is a novel preservation technique that involves the application of high-frequency sound waves (>20 kHz) to the produce, causing various physical, chemical, and biological effects, such as cavitation, compression, and rarefaction. Ultrasound can be used alone or in combination with other preservation methods, such as heat, pressure, or antimicrobials, to enhance their efficacy and reduce the processing time [117].

The main advantages of ultrasound include:

- Potential for the inactivation of microorganisms and enzymes, without significant impact on the nutritional and sensory quality of the produce.
- Enhancement of the mass transfer and diffusion processes, leading to improved efficiency of washing, sanitizing, and extraction operations.
- Applicability to a wide range of fruits and vegetables, including both whole and cut products.
- Potential for the development of new products with enhanced functionality and shelf life.

Some examples of ultrasound applications in fruits and vegetables include:

- Preservation of fresh-cut fruits, such as apples, melons, and strawberries, with shelf life extension up to 7-14 days under refrigeration [118].
- Inactivation of spoilage and pathogenic bacteria, such as Escherichia coli, Salmonella, and Listeria monocytogenes, in fruit and vegetable juices [119].
- Enhancement of the extraction of bioactive compounds, such as carotenoids, anthocyanins, and phenolics, from tomatoes, grapes, and citrus peels [120].

8.4 Cold Plasma

Cold plasma is an emerging preservation technique that involves the exposure of the produce to a partially ionized gas, containing reactive species, such as electrons, ions, and radicals. Cold plasma can be generated by various methods, such as dielectric barrier discharge, corona discharge, or jet discharge, at atmospheric or low pressure conditions [121].

The main advantages of cold plasma include:

- Potential for the inactivation of a wide range of microorganisms, including bacteria, fungi, and viruses, without significant heating or chemical residues.
- Enhancement of the surface properties of the produce, such as hydrophobicity, permeability, and roughness, leading to improved quality and shelf life.
- Applicability to a wide range of fruits and vegetables, including both whole and cut products, as well as packaging materials.
- Potential for the development of new products with enhanced safety, functionality, and sensory attributes.

Some examples of cold plasma applications in fruits and vegetables include:

- Preservation of fresh-cut apples, with shelf life extension up to 21 days under refrigeration, by inactivating Escherichia coli and Pichia subpelliculosa [122].
- Inactivation of Salmonella and Listeria monocytogenes on the surface of tomatoes, lettuce, and spinach, without affecting the color, texture, and vitamin content [123].
- Modification of the surface properties of strawberries, leading to reduced moisture loss, delayed mold growth, and improved firmness and gloss [124].

8.5 Challenges and Future Prospects

While the novel preservation techniques offer many potential benefits for the fresh produce industry, there are also some challenges and limitations that need to be addressed. One challenge is the need for specialized equipment and infrastructure, which can be costly and require significant investment. The scalability and economic feasibility of these techniques for large-scale processing and distribution of fruits and vegetables need to be carefully evaluated [125].

Another challenge is the variability and complexity of the biological materials, which can affect the efficacy and consistency of the novel preservation methods. Factors such as the type, variety, maturity, and initial quality of the produce can influence the response to the preservation treatments, making it difficult to develop standardized protocols [126].

There are also regulatory and consumer acceptance issues that need to be considered. The novel preservation techniques may require extensive safety and toxicological assessments before they can be approved for commercial use. Consumers may have concerns or misconceptions about the impact of these technologies on the naturalness, taste, and nutritional value of the produce, which need to be addressed through effective communication and education strategies [127].

Despite these challenges, the novel preservation techniques offer exciting opportunities for the fresh produce industry to meet the increasing demands for high-quality, safe, and convenient food products. Some future prospects and research directions in this area include:

- Development of combined or hurdle technologies that integrate multiple preservation methods, such as high pressure, pulsed electric field, ultrasound, and cold plasma, to achieve synergistic effects and reduce the processing intensity [128].
- Optimization of the processing parameters, such as pressure, temperature, time, and frequency, for different types of fruits and vegetables, based on their physicochemical and physiological properties [129].
- Investigation of the mechanisms of action of the novel preservation techniques at the cellular and molecular levels, using advanced analytical tools, such as omics technologies, microscopy, and spectroscopy [130].
- Development of smart and active packaging materials that can interact with the novel preservation techniques to enhance the shelf life and quality of the produce, such as oxygen scavengers, antimicrobial agents, and nanosensors [131].
- Conduction of sensory and consumer studies to evaluate the acceptance and preference for the novel preserved produce, as well as the communication strategies to inform and educate the public about the benefits and safety of these technologies [132].

9. Nanotechnology in Postharvest Management

Nanotechnology is an emerging field that involves the manipulation of matter at the nanoscale level (1-100 nm) to create materials and devices with novel properties and functions. In the context of postharvest management of fruits and vegetables, nanotechnology can offer new solutions to improve the quality, safety, and shelf life of fresh produce, as well as to develop smart packaging and sensing systems.

9.1 Nanomaterials for Postharvest Applications

Various types of nanomaterials, such as nanoparticles, nanofibers, and nanocomposites, have been explored for their potential applications in the postharvest management of fruits and vegetables. These nanomaterials can be derived from inorganic, organic, or biological sources, and can be designed to have specific properties, such as antimicrobial activity, antioxidant capacity, gas permeability, or mechanical strength [133].

Some examples of nanomaterials used in postharvest applications include:

- Silver nanoparticles: These have strong antimicrobial activity against a wide range of bacteria and fungi, and can be incorporated into packaging materials or coatings to prevent microbial growth and extend the shelf life of fruits and vegetables [134].
- Chitosan nanoparticles: These are derived from the natural biopolymer chitosan, and have antimicrobial, antifungal, and antioxidant properties. They can be used as edible coatings or in packaging films to preserve the quality and safety of fresh produce [135].
- Nano-emulsions: These are nanoscale dispersions of oil droplets in water, stabilized by surfactants or emulsifiers. They can be used as carriers for bioactive compounds, such as essential oils or plant extracts, to enhance their solubility, stability, and bioavailability in postharvest treatments [136].
- Nanocellulose: This is a nanomaterial derived from plant cellulose, with high mechanical strength, gas barrier properties, and biodegradability. It can be used as a reinforcing agent in packaging materials or as a substrate for active and intelligent packaging systems [137].

9.2 Nanosensors for Quality and Safety Monitoring

Nanosensors are miniaturized devices that can detect and measure physical, chemical, or biological parameters at the nanoscale level. In the context of postharvest management, nanosensors can be used to monitor the quality and safety attributes of fruits and vegetables, such as ripeness, freshness, microbial contamination, or pesticide residues, in a non-destructive and real-time manner [138].

Some examples of nanosensors used in postharvest applications include:

- Gas sensors: These are based on nanomaterials, such as metal oxides or carbon nanotubes, that can detect specific gases, such as ethylene, carbon dioxide, or volatile organic compounds, which are indicative of the ripening or spoilage of fruits and vegetables [139].
- Biosensors: These are based on the integration of nanomaterials with biological recognition elements, such as enzymes, antibodies, or DNA, that can specifically detect target analytes, such as sugars, acids, pathogens, or toxins, in the produce or its environment [140].
- Optical sensors: These are based on the optical properties of nanomaterials, such as fluorescence, surface plasmon resonance, or Raman scattering, that can change in response to the presence of specific compounds or the alteration of quality attributes in the produce [141].
- Electronic sensors: These are based on the electrical properties of nanomaterials, such as conductivity, capacitance, or impedance, that can

change in response to the physical or chemical changes in the produce or its environment, such as moisture loss, texture softening, or gas composition [142].

Nanosensors can be integrated into packaging materials or used as stand-alone devices to provide intelligent and responsive monitoring systems for the postharvest supply chain. They can be coupled with wireless communication technologies, such as radio frequency identification (RFID) or near-field communication (NFC), to enable remote and automated data acquisition and management [143].

9.3 Challenges and Future Prospects

While nanotechnology offers many potential benefits for the postharvest management of fruits and vegetables, there are also some challenges and risks that need to be addressed. One major challenge is the safety and regulatory aspects of using nanomaterials in food applications. There are concerns about the potential toxicity and environmental impact of some nanomaterials, especially those that are persistent, bioaccumulative, or reactive [144]. Therefore, thorough safety assessments and regulations are needed to ensure the responsible and sustainable use of nanotechnology in the food sector.

Another challenge is the scalability and cost-effectiveness of producing and applying nanomaterials in the postharvest supply chain. Many nanomaterials are still expensive and difficult to manufacture in large quantities, and their performance may vary depending on the specific conditions and matrices of the produce [145]. Therefore, more research is needed to optimize the production, formulation, and application methods of nanomaterials for different types of fruits and vegetables. Despite these challenges, nanotechnology holds great promise for revolutionizing the postharvest management of fresh produce.

Some future prospects and research directions in this area include:

- Development of biodegradable and biocompatible nanomaterials from renewable and sustainable sources, such as plant-based polymers, proteins, or lipids, to reduce the environmental impact and improve the safety of nano-enabled postharvest technologies [146].
- Integration of nanotechnology with other advanced technologies, such as biotechnology, information technology, and robotics, to create smart and automated systems for monitoring, controlling, and optimizing the postharvest quality and safety of fruits and vegetables [147].
- Investigation of the mechanisms of action and the fate of nanomaterials in the complex matrices of fruits and vegetables, using advanced analytical techniques, such as microscopy, spectroscopy, and chromatography, to better understand their interactions and effects on the produce and the environment [148].
- Conduction of long-term and large-scale studies to assess the efficacy, safety, and sustainability of nano-enabled postharvest technologies in real-world supply chain scenarios, as well as the acceptance and willingness to pay of consumers for nano-enhanced fresh produce [149].

- Development of international standards, guidelines, and labeling requirements for the use of nanomaterials in food applications, based on scientific evidence and stakeholder engagement, to ensure the transparency, traceability, and accountability of nano-enabled postharvest technologies [150].

10. Biotechnology for Postharvest Quality Improvement

Biotechnology is another emerging field that offers new tools and strategies to improve the postharvest quality and shelf life of fruits and vegetables. Biotechnology involves the use of living organisms, such as microbes or plants, or their components, such as enzymes or genes, to develop products or processes with desired traits or functions [151].

10.1 Microbial Biocontrol Agents

One application of biotechnology in postharvest management is the use of microbial biocontrol agents to prevent or reduce the growth of pathogenic or spoilage microorganisms on the surface of fruits and vegetables. Biocontrol agents are natural or genetically modified microorganisms, such as bacteria, fungi, or yeasts, that can compete with, inhibit, or kill the target pathogens through various mechanisms, such as antibiosis, parasitism, or induced resistance [152].

Some examples of microbial biocontrol agents used in postharvest applications include:

- Antagonistic bacteria: These are bacteria that can produce antimicrobial compounds, such as bacteriocins, lipopeptides, or siderophores, that can inhibit the growth of pathogenic bacteria or fungi. Some examples are Bacillus subtilis, Pseudomonas syringae, and Lactobacillus plantarum, which have been shown to control postharvest diseases in various fruits and vegetables [153].
- Antagonistic fungi: These are fungi that can parasitize or outcompete the pathogenic fungi on the surface of the produce. Some examples are Trichoderma harzianum, Aureobasidium pullulans, and Muscodor albus, which have been shown to control postharvest rots in apples, grapes, and citrus fruits [154].
- Antagonistic yeasts: These are yeasts that can colonize the surface of the produce and create a physical barrier or produce antimicrobial compounds that can prevent the growth of pathogens. Some examples are Candida sake, Pichia guilliermondii, and Cryptococcus laurentii, which have been shown to control postharvest diseases in pome fruits, stone fruits, and berries [155].

Microbial biocontrol agents can be applied as postharvest treatments, either by dipping, spraying, or coating the produce with the microbial suspensions or formulations. They can also be incorporated into packaging materials or used in combination with other postharvest technologies, such as modified atmosphere packaging or edible coatings, to enhance their efficacy and stability [156].

10.2 Genetic Engineering of Crops

Another application of biotechnology in postharvest management is the genetic engineering of crops to improve their postharvest quality traits, such as delayed ripening, enhanced firmness, or reduced browning. Genetic engineering involves the introduction of specific genes or the modification of existing genes in the plant genome using molecular techniques, such as transformation or gene editing [157].

Some examples of genetically engineered crops with improved postharvest quality include:

- Tomatoes: The first commercially available genetically engineered crop was the Flavr Savr tomato, which had a delayed ripening trait due to the suppression of the polygalacturonase enzyme that causes fruit softening. Other genetically engineered tomatoes have been developed with enhanced lycopene content, reduced ethylene production, or increased shelf life [158].
- Papayas: The Rainbow and SunUp papayas were genetically engineered to resist the papaya ringspot virus, which is a major postharvest disease that can cause significant losses in papaya production. These papayas have been grown commercially in Hawaii and have helped to save the papaya industry from the devastating impact of the virus [159].
- Apples: The Arctic apple is a genetically engineered apple that has a non-browning trait due to the silencing of the polyphenol oxidase enzyme that causes enzymatic browning when the apple is cut or bruised. This apple can maintain its fresh appearance and quality for a longer time after cutting, which can reduce food waste and increase consumer appeal [160].

Genetic engineering of crops can offer some advantages over traditional breeding methods, such as the ability to introduce specific genes from other species or to target specific quality traits without affecting other agronomic or nutritional characteristics. However, it also raises some concerns and challenges, such as the potential ecological risks, the public acceptance, and the regulatory hurdles associated with the development and commercialization of genetically engineered crops [161].

10.3 Challenges and Future Prospects

While biotechnology offers many opportunities for improving the postharvest quality and shelf life of fruits and vegetables, it also faces some challenges and limitations. One challenge is the variability and complexity of the microbial ecology on the surface of the produce, which can influence the efficacy and consistency of the biocontrol agents. Different types of produce may have different native microbiota that can interact with or antagonize the biocontrol agents, and the environmental conditions, such as temperature, humidity, or pH, can also affect the survival and activity of the microbial agents [162].

Another challenge is the regulatory and public acceptance issues associated with the use of biotechnology in the food system. Genetically engineered crops, in particular, have been subject to intense scrutiny and controversy, due to the perceived risks and uncertainties about their safety, environmental impact, and socioeconomic implications [163]. Therefore, a transparent and science-based regulatory framework, as well as effective communication and engagement with the public, are needed to ensure the responsible and beneficial use of biotechnology in postharvest management.

Despite these challenges, biotechnology holds great potential for enhancing the postharvest quality and value of fresh produce. Some future prospects and research directions in this area include:

- Development of multi-strain or multi-species biocontrol formulations that can provide a more robust and resilient protection against a wider range of postharvest pathogens and environmental conditions [164].
- Integration of biocontrol agents with other natural or biodegradable compounds, such as plant extracts, essential oils, or biopolymers, to create synergistic and sustainable postharvest treatments [165].
- Exploration of the potential of endophytic microorganisms, which live inside the plant tissues, as biocontrol agents or quality enhancers for fruits and vegetables, based on their intimate and beneficial interactions with the host plant [166].
- Application of novel biotechnological tools, such as CRISPR-Cas gene editing, RNA interference, or metabolic engineering, to develop new crop varieties with enhanced postharvest quality traits, such as extended shelf life, improved nutrition, or reduced waste [167].
- Investigation of the consumer perception, willingness to pay, and market potential for biotechnology-based postharvest solutions, as well as the development of effective communication strategies to inform and engage the public about the benefits and risks of these technologies [168].

11. Smart Packaging for Postharvest Quality Monitoring

Smart packaging is an innovative approach that integrates various sensors, indicators, or communication devices into the packaging system to monitor, inform, or interact with the quality attributes of the packaged produce. Smart packaging can provide real-time and non-destructive information about the freshness, safety, or integrity of the produce, as well as the environmental conditions, such as temperature, humidity, or gas composition, along the postharvest supply chain [169].

11.1 Types of Smart Packaging Technologies

There are different types of smart packaging technologies that can be used for postharvest quality monitoring of fruits and vegetables, depending on the specific quality attributes or environmental factors to be measured. Some common types of smart packaging technologies include:

11.1.1 Freshness Indicators

Freshness indicators are devices that can detect and visualize the changes in the quality attributes of the produce that are related to its freshness, such as the production of metabolic gases (e.g., ethylene, carbon dioxide), the accumulation of volatile compounds (e.g., aldehydes, esters), or the growth of spoilage microorganisms (e.g., bacteria, fungi) [170].

Some examples of freshness indicators for fruits and vegetables include:

- Ripeness indicators: These are based on the color change of a chemical reagent that reacts with the ethylene gas produced by the ripening produce. For example, a colorimetric sensor based on palladium(II) acetate can change from yellow to brown in the presence of ethylene, indicating the ripening stage of climacteric fruits, such as bananas, apples, or pears [171].

- Spoilage indicators: These are based on the pH change of a chemical reagent that reacts with the volatile amines produced by the spoilage microorganisms. For example, a pH-sensitive dye, such as bromocresol green, can change from blue to yellow when the pH drops below a certain level, indicating the microbial spoilage of fresh-cut vegetables, such as lettuce, spinach, or cabbage [172].

11.1.2 Gas Sensors

Gas sensors are devices that can detect and measure the concentration of specific gases that are indicative of the quality or safety of the produce, such as oxygen, carbon dioxide, or ethylene. Gas sensors can be based on various principles, such as electrochemical, optical, or piezoelectric, and can be integrated into the packaging material or the headspace of the package [173].

Some examples of gas sensors for fruits and vegetables include:

- Oxygen sensors: These are based on the change in the optical or electrical properties of a sensing material, such as a phosphorescent dye or a metal oxide, in response to the oxygen level in the package. For example, a fluorescent sensor based on ruthenium(II) complex can change its fluorescence intensity and lifetime depending on the oxygen concentration, allowing for non-destructive and real-time monitoring of the oxygen level in the package of fresh-cut fruits, such as apples, pears, or melons [174].
- Carbon dioxide sensors: These are based on the change in the optical or electrical properties of a sensing material, such as a pH-sensitive dye or a conductive polymer, in response to the carbon dioxide level in the package. For example, a colorimetric sensor based on a mixture of chitosan and anthocyanins can change from red to purple when the carbon dioxide concentration increases, indicating the respiratory activity and potential spoilage of fresh produce, such as mushrooms, broccoli, or berries [175].
- Ethylene sensors: These are based on the change in the optical or electrical properties of a sensing material, such as a metal-organic framework or a conducting polymer, in response to the ethylene level in the package. For example, a resistive sensor based on copper(I) complex can change its electrical resistance when exposed to ethylene, allowing for sensitive and selective detection of ethylene in the headspace of packaged fruits, such as bananas, avocados, or kiwifruit [176].

11.1.3 Time-Temperature Indicators (TTIs)

TTIs are devices that can record and indicate the cumulative time-temperature history of the packaged produce during storage and distribution. TTIs are based on the irreversible change in the physical, chemical, or biological properties of a sensing material that is sensitive to both time and temperature, such as a polymer, a enzyme, or a microorganism [177].

Some examples of TTIs for fruits and vegetables include:

- Enzymatic TTIs: These are based on the color change of a substrate that is catalyzed by an enzyme, such as lipase or amylase, at a rate that depends on the temperature. For example, a TTI based on the hydrolysis of a lipid substrate by lipase can change from colorless to blue, indicating the time-temperature exposure and potential quality loss of fresh produce, such as lettuce, spinach, or herbs [178].

- Microbial TTIs: These are based on the growth and metabolism of a microorganism, such as a lactic acid bacterium or a yeast, that is inoculated into a nutrient medium and sealed in a transparent package. The microbial growth and acid production can cause a color change in a pH indicator, such as bromocresol purple, that is proportional to the time-temperature exposure and can indicate the potential spoilage or safety risk of fresh-cut fruits or vegetables [179].

11.1.4 Radio Frequency Identification (RFID) Tags

RFID tags are electronic devices that can store and transmit information about the product identity, location, and condition using radio frequency signals. RFID tags can be attached to the packaging or the product itself and can communicate with RFID readers at various points along the supply chain, enabling real-time tracking and tracing of the product [180].

RFID tags can be used in combination with other smart packaging technologies, such as sensors or indicators, to provide a more comprehensive and integrated system for quality monitoring of fruits and vegetables. For example, RFID tags can be coupled with temperature or humidity sensors to record the environmental conditions during storage and transportation, or with freshness indicators to detect the quality changes and remaining shelf life of the produce [181].

Some advantages of using RFID tags for postharvest quality monitoring include:

- Non-contact and wireless data transfer, allowing for remote and automated reading of the product information and condition.
- Large data storage capacity, enabling the recording of multiple quality parameters and the creation of a complete product history.
- Reusability and durability, reducing the cost and waste associated with disposable labels or indicators.
- Integration with other information systems, such as inventory management, product recall, or consumer information, enhancing the efficiency and transparency of the supply chain [182].

11.2 Benefits and Challenges

Smart packaging offers several benefits for the postharvest quality management of fruits and vegetables, including:

- Real-time and non-destructive monitoring of the product quality and condition, enabling timely and informed decision-making for inventory management, product allocation, or quality control.
- Extension of the shelf life and reduction of food waste, by detecting and preventing quality deterioration or spoilage at an early stage.

- Enhancement of the product safety and traceability, by identifying and isolating the products that have been exposed to abnormal or abusive conditions during storage and distribution.
- Provision of valuable information and assurance to the consumers about the freshness, safety, and authenticity of the products, increasing their satisfaction and trust [183].

However, there are also some challenges and limitations in the development and implementation of smart packaging for fruits and vegetables, such as:

- Cost and scalability: The production and integration of smart packaging technologies can be expensive and complex, especially for small-scale or low-value products. The cost-benefit ratio and the return on investment need to be carefully evaluated for each specific application and supply chain scenario [184].
- Reliability and accuracy: The performance and stability of smart packaging technologies can be affected by various factors, such as the product composition, the packaging material, the environmental conditions, or the interference from other substances or devices. The reliability and accuracy of the quality indicators or sensors need to be validated and calibrated for each specific product and condition [185].
- Consumer acceptance and education: The use of smart packaging technologies may raise concerns or confusion among consumers about the safety, privacy, or environmental impact of these technologies. Consumers may also need guidance and education on how to interpret and use the quality information provided by the smart packaging systems [186].
- Regulatory and standardization issues: The use of smart packaging technologies in food applications is subject to various regulations and standards related to food safety, labeling, packaging materials, or electronic devices. The regulatory requirements and compliance procedures can vary across different countries and regions, creating barriers or delays in the commercialization and trade of smart packaged products [187].

11.3 Future Prospects and Research Needs

Despite the challenges, smart packaging represents a promising and growing area for enhancing the postharvest quality, safety, and value of fruits and vegetables. Some future prospects and research needs in this area include:

- Development of low-cost, biodegradable, and printable sensors or indicators that can be easily integrated into the packaging material or label, using technologies such as inkjet printing, screen printing, or nanomaterial deposition [188].
- Exploration of new sensing materials or mechanisms that can respond to specific quality attributes or biomarkers of fruits and vegetables, such as volatile compounds, enzymes, or microRNAs, providing a more sensitive and selective detection of quality changes [189].
- Integration of smart packaging with other advanced technologies, such as nanotechnology, biotechnology, or information technology, to create

multifunctional and intelligent packaging systems that can not only monitor but also control or improve the quality of the packaged produce [190].

- Investigation of the consumer perception, preference, and willingness to pay for smart packaged fruits and vegetables, as well as the development of effective communication and marketing strategies to educate and engage consumers about the benefits and use of smart packaging technologies [191].
- Collaboration and standardization among the stakeholders, including the packaging industry, the food industry, the technology providers, the regulatory agencies, and the academic institutions, to establish a harmonized and science-based framework for the development, assessment, and application of smart packaging technologies in the postharvest supply chain of fruits and vegetables [192].

12. Conclusion

Postharvest technologies play a vital role in maintaining the quality, safety, and marketability of fruits and vegetables from farm to fork. This chapter has provided an extensive review of the recent advances and applications of various postharvest technologies for extending the shelf life and preserving the value of fresh produce. These technologies range from the traditional methods, such as refrigeration, modified atmosphere packaging, and edible coatings, to the emerging and innovative approaches, such as nanotechnology, biotechnology, and smart packaging.

Each technology has its own advantages, limitations, and potential for improving the postharvest quality and reducing the losses of fruits and vegetables. For example, refrigeration is the most widely used and effective method for slowing down the respiration, senescence, and microbial growth of fresh produce, but it requires high energy and infrastructure costs and may cause chilling injury to some sensitive commodities. Modified atmosphere packaging and edible coatings can create a beneficial environment around the produce and provide a barrier against moisture loss and gas exchange, but their effectiveness depends on the product characteristics, the packaging material, and the storage conditions. Nanotechnology and biotechnology can offer novel and targeted solutions for enhancing the quality, safety, and functionality of fresh produce, but they also raise concerns and challenges related to the cost, safety, and consumer acceptance of these technologies. Smart packaging can provide real-time and non-destructive monitoring of the product quality and condition, but it also faces issues of cost, reliability, and standardization in the development and implementation of these technologies. Therefore, the selection and application of postharvest technologies for fruits and vegetables should be based on a holistic and integrated approach that considers the specific needs, constraints, and opportunities of each product, market, and supply chain. This requires a deep understanding of the biological, physical, and chemical factors that influence the postharvest quality and shelf life of fresh produce, as well as the technical, economic, and social factors that affect the adoption and impact of postharvest technologies.

Moreover, the development and implementation of postharvest technologies should be guided by the principles of sustainability, efficiency, and inclusiveness. This means that the technologies should not only aim to reduce the postharvest losses and increase the economic value of fresh produce, but also to minimize the environmental footprint, optimize the resource use, and benefit all the stakeholders along the supply chain, including the smallholder farmers, the processors, the retailers, and the consumers.

To achieve these goals, there is a need for more research, innovation, and collaboration in the field of postharvest technology for fruits and vegetables. Some key areas for future research and development include:

- Understanding the fundamental mechanisms and interactions of postharvest physiology, pathology, and technology, using advanced analytical tools and interdisciplinary approaches.
- Developing and validating novel and sustainable postharvest technologies that can address the specific challenges and opportunities of different types of fruits and vegetables, such as highly perishable, delicate, or niche products.
- Integrating and optimizing multiple postharvest technologies and practices, such as pre-cooling, packaging, and distribution, to create a seamless and resilient postharvest supply chain.
- Assessing and communicating the benefits, risks, and trade-offs of postharvest technologies, using scientific evidence, stakeholder engagement, and consumer education.
- Building the capacity and infrastructure for postharvest research, innovation, and education, especially in developing countries and emerging economies, where the postharvest losses and quality issues are most prevalent and impactful.

References:

1. [1] FAO. (2019). The State of Food and Agriculture 2019. Moving forward on food loss and waste reduction. Rome. Licence: CC BY-NC-SA 3.0 IGO.
2. [2] Kader, A. A. (2005). Increasing food availability by reducing postharvest losses of fresh produce. Acta Horticulturae, 682, 2169-2176.
3. [3] Prusky, D. (2011). Reduction of the incidence of postharvest quality losses, and future prospects. Food Security, 3(4), 463-474.
4. [4] Mahajan, P. V., Caleb, O. J., Singh, Z., Watkins, C. B., & Geyer, M. (2014). Postharvest treatments of fresh produce. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 372(2017), 20130309.
5. [5] Yousuf, B., Qadri, O. S., & Srivastava, A. K. (2018). Recent developments in shelf-life extension of fresh-cut fruits and vegetables by application of different edible coatings: A review. LWT - Food Science and Technology, 89, 198-209.
6. [6] Minas, I. S., Tanou, G., & Molassiotis, A. (2018). Environmental and orchard bases of peach fruit quality. Scientia Horticulturae, 235, 307-322.
7. [7] González-Aguilar, G. A., Ayala-Zavala, J. F., de la Rosa, L. A., & Alvarez-Parrilla, E. (2018). Phytochemical changes in the postharvest and minimal processing of fresh fruits and vegetables. In Fruit and Vegetable Phytochemicals: Chemistry and Human Health, 2nd ed.; John Wiley & Sons, Ltd.: Hoboken, NJ, USA, 2018; pp. 113–129.
8. [8] Mercier, S., Villeneuve, S., Mondor, M., & Uysal, I. (2017). Time–Temperature Management Along the Food Cold Chain: A Review of Recent Developments. Comprehensive Reviews in Food Science and Food Safety, 16(4), 647-667.

9. [9] Brummell, D. A. (2006). Cell wall disassembly in ripening fruit. Functional Plant Biology, 33(2), 103-119.
10. [10] Gao, H., Zeng, Q., & Ren, Z. (2018). Effect of Postharvest Calcium Chloride Treatment on Quality and Shelf Life of Pear Fruits. IOP Conference Series: Materials Science and Engineering, 392, 062090.
11. [11] Manganaris, G. A., Vasilakakis, M., Diamantidis, G., & Mignani, I. (2007). The effect of postharvest calcium application on tissue calcium concentration, quality attributes, incidence of flesh browning and cell wall physicochemical aspects of peach fruits. Food Chemistry, 100(4), 1385-1392.
12. [12] Aghdam, M. S., & Bodbodak, S. (2013). Postharvest Heat Treatment for Mitigation of Chilling Injury in Fruits and Vegetables. Food and Bioprocess Technology, 7(1), 37-53.
13. [13] Valero, D., & Serrano, M. (2010). Postharvest biology and technology for preserving fruit quality. CRC press.
14. [14] Fallik, E. (2004). Prestorage hot water treatments (immersion, rinsing and brushing). Postharvest Biology and Technology, 32(2), 125-134.
15. [15] Lurie, S. (1998). Postharvest heat treatments. Postharvest Biology and Technology, 14(3), 257-269.
16. [16] Thompson, J. F., Mitchell, F. G., & Kasmire, R. F. (2002). Cooling horticultural commodities. In Postharvest technology of horticultural crops (Vol. 3311, pp. 97-112). UCANR Publications.
17. [17] Kader, A. A. (2002). Postharvest Biology and Technology: An Overview. In Postharvest Technology of Horticultural Crops (3rd ed.; Kader, A.A., Ed.), Publication 3311; University of California Agriculture and Natural Resources: Oakland, CA, USA, pp. 39–48.
18. [18] Sandhya. (2010). Modified atmosphere packaging of fresh produce: Current status and future needs. LWT - Food Science and Technology, 43(3), 381-392.
19. [19] Caleb, O. J., Mahajan, P. V., Al-Said, F. A. J., & Opara, U. L. (2013). Modified Atmosphere Packaging Technology of Fresh and Fresh-cut Produce and the Microbial Consequences—A Review. Food and Bioprocess Technology, 6(2), 303-329.
20. [20] Lee, L., Arul, J., Lencki, R., & Castaigne, F. (1995). A review on modified atmosphere packaging and preservation of fresh fruits and vegetables: Physiological basis and practical aspects—Part I. Packaging Technology and Science, 8(6), 315-331.
21. [21] Zagory, D. (1999). Effects of post-processing handling and packaging on microbial populations. Postharvest Biology and Technology, 15(3), 313-321.

22. [22] Oliveira, M., Abadias, M., Usall, J., Torres, R., Teixidó, N., & Viñas, I. (2015). Application of modified atmosphere packaging as a safety approach to fresh-cut fruits and vegetables – A review. Trends in Food Science & Technology, 46(1), 13-26.
23. [23] Guilbert, S., Gontard, N., & Gorris, L. G. M. (1996). Prolongation of the Shelf-life of Perishable Food Products using Biodegradable Films and Coatings. LWT - Food Science and Technology, 29(1-2), 10-17.
24. [24] Yildirim, S., Röcker, B., Pettersen, M. K., Nilsen-Nygaard, J., Ayhan, Z., Rutkaite, R., Radusin, T., Suminska, P., Marcos, B., & Coma, V. (2018). Active Packaging Applications for Food. Comprehensive Reviews in Food Science and Food Safety, 17(1), 165-199.
25. [25] Wilson, M. D., Stanley, R. A., Eyles, A., & Ross, T. (2019). Innovative processes and technologies for modified atmosphere packaging of fresh and fresh-cut fruits and vegetables. Critical Reviews in Food Science and Nutrition, 59(3), 411-422.
26. [26] Dhall, R. K. (2013). Advances in Edible Coatings for Fresh Fruits and Vegetables: A Review. Critical Reviews in Food Science and Nutrition, 53(5), 435-450.
27. [27] Kerch, G. (2015). Chitosan films and coatings prevent losses of fresh fruit nutritional quality: A review. Trends in Food Science & Technology, 46(2), 159-166.
28. [28] Rojas-Graü, M. A., Soliva-Fortuny, R., & Martín-Belloso, O. (2009). Edible coatings to incorporate active ingredients to fresh-cut fruits: a review. Trends in Food Science & Technology, 20(10), 438-447.

29. [29] Thakur, R., Saberi, B., Pristijono, P., Golding, J., Stathopoulos, C., Scarlett, C., Bowyer, M., Vuong, Q. (2016). Characterization of rice starch-ι-carrageenan biodegradable edible film. Effect of stearic acid on the film properties. International Journal of Biological Macromolecules, 93, 952-960.
30. [30] Otoni, C. G., Avena-Bustillos, R. J., Olsen, C. W., Bilbao-Sáinz, C., & McHugh, T. H. (2016). Mechanical and water barrier properties of isolated soy protein composite edible films as affected by carvacrol and cinnamaldehyde micro and nanoemulsions. Food Hydrocolloids, 57, 72-79.
31. [31] Marquez, G. R., Di Pierro, P., Mariniello, L., Esposito, M., Giosafatto, C. V. L., & Porta, R. (2017). Fresh-cut fruit and vegetable coatings by transglutaminase-crosslinked whey protein/pectin edible films. LWT - Food Science and Technology, 75, 124-130.
32. [32] Arnon-Rips, H., & Poverenov, E. (2018). Improving food products' quality and storability by using Layer by Layer edible coatings. Trends in Food Science & Technology, 75, 81-92.
33. [33] Ramos, Ó. L., Fernandes, J. C., Silva, S. I., Pintado, M. E., & Malcata, F. X. (2012). Edible Films and Coatings from Whey Proteins: A Review on Formulation, and on Mechanical and Bioactive Properties. Critical Reviews in Food Science and Nutrition, 52(6), 533-552.
34. [34] Galus, S., & Kadzińska, J. (2015). Food applications of emulsion-based edible films and coatings. Trends in Food Science & Technology, 45(2), 273-283.
35. [35] Guo, M., Yadav, M. P., & Jin, T. Z. (2017). Antimicrobial edible coatings and films from micro-emulsions and their food applications. International Journal of Food Microbiology, 263, 9-16.
36. [36] Valdés, A., Burgos, N., Jiménez, A., & Garrigós, M. (2015). Natural Pectin Polysaccharides as Edible Coatings. Coatings, 5(4), 865-886.
37. [37] Ncama, K., Magwaza, L. S., Mditshwa, A., & Tesfay, S. Z. (2018). Plant-based edible coatings for managing postharvest quality of fresh horticultural produce: A review. Food Packaging and Shelf Life, 16, 157-167.
38. [38] Umagiliyage, A., Becerra-Mora, N., Kohli, P., Fisher, D., & Choudhary, R. (2017). Antimicrobial efficacy of liposomes containing d-limonene and its effect on the storage life of blueberries. Postharvest Biology and Technology, 128, 130-137.
39. [39] Tahir, H. E., Xiaobo, Z., Mahunu, G. K., Arslan, M., Abdalhai, M., & Zhihua, L. (2019). Recent developments in gum edible coating applications for fruits and vegetables preservation: A review. Carbohydrate Polymers, 224, 115141.
40. [40] Barman, K., Asrey, R., & Pal, R. K. (2011). Putrescine and carnauba wax pretreatments alleviate chilling injury, enhance shelf life and preserve pomegranate fruit quality during cold storage. Scientia Horticulturae, 130(4), 795-800.
41. [41] Nair, M. S., Saxena, A., & Kaur, C. (2018). Effect of chitosan and alginate based coatings enriched with pomegranate peel extract to extend the postharvest quality of guava (Psidium guajava L.). Food Chemistry, 240, 245-252.
42. [42] Maringgal, B., Hashim, N., Tawakkal, I. S. M. A., & Mohamed, M. T. M. (2020). Recent advance in edible coating and its effect on fresh/fresh-cut fruits quality. Trends in Food Science & Technology, 96, 253-267.
43. [43] Salehi, F. (2020). Edible Coating of Fruits and Vegetables Using Natural Gums: A Review. International Journal of Fruit Science, 20(sup2), S570-S589.
44. [44] Maqbool, M., Ali, A., Alderson, P. G., Zahid, N., & Siddiqui, Y. (2011). Effect of a novel edible composite coating based on gum arabic and chitosan on biochemical and physiological responses of banana fruits during cold storage. Journal of Agricultural and Food Chemistry, 59(10), 5474-5482.
45. [45] Guerreiro, A. C., Gago, C. M. L., Faleiro, M. L., Miguel, M. G. C., & Antunes, M. D. C. (2015). The effect of alginate-based edible coatings enriched with essential oils constituents on Arbutus unedo L. fresh fruit storage. Postharvest Biology and Technology, 100, 226-233.
46. [46] Pereira, J. O., Soares, J., Sousa, S., Madureira, A. R., Gomes, A., & Pintado, M. (2016). Edible films as carrier for lactic acid bacteria. LWT - Food Science and Technology, 73, 543-550.

47. [47] Soradech, S., Nunthanid, J., Limmatvapirat, S., & Luangtana-anan, M. (2017). Utilization of shellac and gelatin composite film for coating to extend the shelf life of banana. Food Control, 73, 1310-1317.
48. [48] Alali, A. A., Awad, M. A., Al-Qurashi, A. D., & Mohamed, S. A. (2018). Postharvest gum Arabic and salicylic acid dipping affect quality and biochemical changes of 'Grand Nain' bananas during shelf life. Scientia Horticulturae, 237, 51-58.
49. [49] Zambrano-Zaragoza, M. L., Gutiérrez-Cortez, E., Del Real, A., González-Reza, R. M., Galindo-Pérez, M. J., & Quintanar-Guerrero, D. (2014). Fresh-cut Red Delicious apples coating using tocopherol/mucilage nanoemulsion: Effect of coating on polyphenol oxidase and pectin methylesterase activities. Food Research International, 62, 974-983.
50. [50] Dong, F., & Wang, X. (2018). Effects of carboxymethyl cellulose incorporated with garlic essential oil composite coatings for improving quality of strawberries. International Journal of Biological Macromolecules, 104, 821-826.
51. [51] Sharma, S., Rao, T. V. R., Goyal, A., Mahajan, B. V. C., & Dabur, R. S. (2015). Development of chitosan-based edible coatings for shelf-life extension of fresh-cut apples. Journal of Food Processing and Preservation, 39(6), 1939-1946.
52. [52] Nawab, A., Alam, F., & Hasnain, A. (2017). Mango kernel starch as a novel edible coating for enhancing shelf- life of tomato (Solanum lycopersicum) fruit. International Journal of Biological Macromolecules, 103, 581-586.
53. [53] Carrillo-Lopez, L. M., García-Galindo, H. S., Valdez-Torres, M. R., Angulo-Parra, J. A., Muy-Rangel, M. D., Siller-Cepeda, J. H., Sanudo Barajas, J. A., & Ibarra-Junquera, V. (2019). Extending the shelf life of bell pepper (Capsicum annuum L.) by application of recyclable wax coating enriched with oregano (Origanum vulgare) essential oil. Postharvest Biology and Technology, 149, 10-17.
54. [54] Feng, D., Wang, H., Tu, S., & Xiao, Z. (2020). Chitosan Coating with Propolis Extract for Postharvest Preservation of Fresh-cut Kiwifruit. Coatings, 10(3), 302.
55. [55] Kumar, P., Sethi, S., Sharma, R. R., Srivastav, M., & Varghese, E. (2017). Effect of chitosan coating on postharvest life and quality of plum during storage at low temperature. Scientia Horticulturae, 226, 104-109.
56. [56] Al-Naamani, L., Dobretsov, S., & Dutta, J. (2016). Chitosan-zinc oxide nanoparticle composite coating for active food packaging applications. Innovative Food Science & Emerging Technologies, 38, 231-237.
57. [57] Aloui, H., & Khwaldia, K. (2016). Natural Antimicrobial Edible Coatings for Microbial Safety and Food Quality Enhancement. Comprehensive Reviews in Food Science and Food Safety, 15(6), 1080-1103.
58. [58] Sharma, S., & Rao, T. V. R. (2015). Xanthan gum based edible coating enriched with cinnamic acid prevents browning and extends the shelf-life of fresh-cut pears. LWT - Food Science and Technology, 62(1), 791-800.
59. [59] Ventura-Aguilar, R. I., Bautista-Baños, S., Flores-García, G., & Zavaleta-Avejar, L. (2018). Impact of chitosan based edible coatings functionalized with natural compounds on Colletotrichum fragariae development and the quality of strawberries. Food Chemistry, 262, 142-149.
60. [60] Song, Y., Liu, L., Shen, H., You, J., & Luo, Y. (2011). Effect of sodium alginate-based edible coating containing different anti-oxidants on quality and shelf life of refrigerated bream (Megalobrama amblycephala). Food Control, 22(3-4), 608-615.
61. [61] Guerreiro, A. C., Gago, C. M. L., Miguel, M. G. C., & Antunes, M. D. C. (2013). The effect of temperature and film covers on the storage ability of Arbutus unedo L. fresh fruit. Scientia Horticulturae, 159, 96-102.
62. [62] Thakur, R., Pristijono, P., Scarlett, C. J., Bowyer, M., Singh, S. P., & Vuong, Q. V. (2019). Starch-based films: Major factors affecting their properties. International Journal of Biological Macromolecules, 132, 1079-1089.
63. [63] Shankar, S., & Rhim, J.-W. (2018). Antimicrobial wrapping paper coated with a ternary blend of carbohydrates (alginate, carboxymethyl cellulose, carrageenan) and grapefruit seed extract. Carbohydrate Polymers, 196, 92-101.

64. [64] Yousuf, B., Qadri, O. S., & Srivastava, A. K. (2018). Recent developments in shelf-life extension of fresh-cut fruits and vegetables by application of different edible coatings: A review. LWT - Food Science and Technology, 89, 198-209.
65. [65] Lin, D., & Zhao, Y. (2007). Innovations in the Development and Application of Edible Coatings for Fresh and Minimally Processed Fruits and Vegetables. Comprehensive Reviews in Food Science and Food Safety, 6(3), 60-75.
66. [66] Cazón, P., Velazquez, G., Ramírez, J. A., & Vázquez, M. (2017). Polysaccharide-based films and coatings for food packaging: A review. Food Hydrocolloids, 68, 136-148.
67. [67] Parreidt, T. S., Schott, M., Schmid, M., & Müller, K. (2018). Effect of Presence and Concentration of Plasticizers, Vegetable Oils, and Surfactants on the Properties of Sodium-Alginate-Based Edible Coatings. International Journal of Molecular Sciences, 19(3), 742.
68. [68] Tapia-Blácido, D. R., do Amaral Sobral, P. J., & Menegalli, F. C. (2011). Optimization of amaranth flour films plasticized with glycerol and sorbitol by multi-response analysis. LWT - Food Science and Technology, 44(8), 1731-1738.
69. 69] Valdés, A., Mellinas, A. C., Ramos, M., Garrigós, M. C., & Jiménez, A. (2014). Natural additives and agricultural wastes in biopolymer formulations for food packaging. Frontiers in Chemistry, 2, 6.
70. [70] Suhag, R., Kumar, N., Petkoska, A. T., & Upadhyay, A. (2020). Film Formation and Deposition Methods of Edible Coating on Food Products: A Review. Food Research International, 136, 109582.
71. [71] Nicolaï, B. M., Defraeye, T., De Ketelaere, B., Herremans, E., Hertog, M. L. A. T. M., Saeys, W., Torricelli, A., Vandendriessche, T., & Verboven, P. (2014). Nondestructive Measurement of Fruit and Vegetable Quality. Annual Review of Food Science and Technology, 5(1), 285-312.
72. [72] Huang, H., Liu, L., & Ngadi, M. O. (2014). Recent Developments in Hyperspectral Imaging for Assessment of Food Quality and Safety. Sensors, 14(4), 7248-7276.
73. [73] Zhang, B., Huang, W., Li, J., Zhao, C., Fan, S., Wu, J., & Liu, C. (2014). Principles, developments and applications of computer vision for external quality inspection of fruits and vegetables: A review. Food Research International, 62, 326-343.
74. [74] Wang, H., Peng, J., Xie, C., Bao, Y., & He, Y. (2015). Fruit Quality Evaluation Using Spectroscopy Technology: A Review. Sensors, 15(5), 11889-11927.
75. [75] Nicolaï, B. M., Beullens, K., Bobelyn, E., Peirs, A., Saeys, W., Theron, K. I., & Lammertyn, J. (2007). Nondestructive measurement of fruit and vegetable quality by means of NIR spectroscopy: A review. Postharvest Biology and Technology, 46(2), 99-118.
76. [76] Scholz-Ahrens, K. E., Adolphi, B., Rochat, F., Barclay, D. V., de Vrese, M., Açil, Y., & Schrezenmeir, J. (2016). Effects of probiotics, prebiotics, and synbiotics on mineral metabolism in ovariectomized rats — impact of bacterial mass, intestinal absorptive area and reduction of bone turn-over. NFS Journal, 3, 41-50.
77. [77] Zude, M. (Ed.). (2008). Optical monitoring of fresh and processed agricultural crops. CRC press.
78. [78] Lee, H., Kim, M. S., Lee, W.-H., & Cho, B.-K. (2018). Determination of the total volatile basic nitrogen (TVB-N) content in pork meat using hyperspectral fluorescence imaging. Sensors and Actuators B: Chemical, 259, 532-539.
79. [79] Magwaza, L. S., & Opara, U. L. (2015). Analytical methods for determination of sugars and sweetness of horticultural products—A review. Scientia Horticulturae, 184, 179-192.
80. [80] Lorente, D., Aleixos, N., Gómez-Sanchis, J., Cubero, S., García-Navarrete, O. L., & Blasco, J. (2012). Recent Advances and Applications of Hyperspectral Imaging for Fruit and Vegetable Quality Assessment. Food and Bioprocess Technology, 5(4), 1121-1142.
81. [81] Gowen, A. A., O'Donnell, C. P., Cullen, P. J., Downey, G., & Frias, J. M. (2007). Hyperspectral imaging – an emerging process analytical tool for food quality and safety control. Trends in Food Science & Technology, 18(12), 590-598.
82. [82] Lu, Y., Huang, Y., & Lu, R. (2017). Innovative Hyperspectral Imaging-Based Techniques for Quality Evaluation of Fruits and Vegetables: A Review. Applied Sciences, 7(2), 189.
83. [83] Baiano, A. (2017). Applications of hyperspectral imaging for quality assessment of liquid based and semi-liquid food products: A review. Journal of Food Engineering, 214, 10-15.

84. [84] Li, J., Rao, X., & Ying, Y. (2011). Detection of common defects on oranges using hyperspectral reflectance imaging. Computers and Electronics in Agriculture, 78(1), 38-48.
85. [85] Karoui, R., & Blecker, C. (2011). Fluorescence Spectroscopy Measurement for Quality Assessment of Food Systems—a Review. Food and Bioprocess Technology, 4(3), 364-386.
86. [86] Lenk, S., Buschmann, C., & Pfündel, E. E. (2007). In vivo assessing flavonols in white grape berries (Vitis vinifera L. cv. Pinot Blanc) of different degrees of ripeness using chlorophyll fluorescence imaging. Functional Plant Biology, 34(12), 1092-1104.
87. [87] Łysiak, G. P., Kurlus, R., Zdunek, A., & Rutkowski, K. (2014). Application of a fluorescence method for the measurement of changes in quality of minimally processed apples during storage. Postharvest Biology and Technology, 98, 53-59.
88. [88] Momin, M. A., Kondo, N., Kuramoto, M., Ogawa, Y., Yamamoto, K., & Shiigi, T. (2012). Identification of UV-fluorescence components and their contribution to total fluorescence in the peel of various citrus fruits. Postharvest Biology and Technology, 67, 1-9.
89. [89] Mazurek, S., Szostak, R., & Kita, A. (2016). Application of Infrared Reflection and Raman Spectroscopy for Quantitative Determination of Fat in Potato Chips. Journal of Molecular Structure, 1126, 141-146.
90. [90] Grossi, M., & Riccò, B. (2017). Electrical impedance spectroscopy (EIS) for biological analysis and food characterization: a review. Journal of Sensors and Sensor Systems, 6(2), 303-325.
91. [91] Figueiredo Neto, A., Cárdenas Olivier, N., Rabelo Cordeiro, E., Pequeno de Oliveira, H., Pinheiro Figueiredo, R. W., & Melo de Almeida, G. N. (2017). Determination of mango ripening degree by electrical impedance spectroscopy. Computers and Electronics in Agriculture, 143, 222-226.
92. [92] Chowdhury, A., Bhattacharyya, R., & Bandyopadhyay, R. (2017). Comparative Study on Electrical Impedance Variations in Banana Ripening: An Analytical Study with Electrical Impedance Spectroscopy. Journal of Food Process Engineering, 40(2), e12412.
93. [93] Chowdhury, A., Alam, T. N., Deb, S. K., Mondal, S., Malakar, S., & Chakraborty, R. (2015). Nondestructive Maturity Sorting of Banana Using Electrical Impedance Spectroscopy. Transactions of the ASABE, 58(4), 819-827.
94. [94] Harker, F. R., & Forbes, S. K. (1997). Ripening and development of chilling injury in persimmon fruit: an electrical impedance study. New Zealand Journal of Crop and Horticultural Science, 25(2), 149-157.
95. [95] Taniwaki, M., Hanada, T., & Sakurai, N. (2009). Postharvest quality evaluation of "Fuyu" and "Taishuu" persimmons using a nondestructive vibrational method and an acoustic vibration technique. Postharvest Biology and Technology, 51(1), 80-85.
96. [96] Schmilovitch, Z., Mizrach, A., Hoffman, A., Egozi, H., & Fuchs, Y. (2000). Determination of mango physiological indices by near-infrared spectrometry. Postharvest Biology and Technology, 19(3), 245-252.
97. [97] Seifert, B., Zude, M., Spinelli, L., & Torricelli, A. (2015). Optical properties of developing pip and stone fruit reveal underlying structural changes. Physiologia Plantarum, 153(2), 327-336.
98. [98] De Ketelaere, B., Howarth, M. S., Crezee, L., Lammertyn, J., Viaene, K., Bulens, I., & De Baerdemaeker, J. (2006). Postharvest firmness changes as measured by acoustic and low-mass impact devices: a comparison of techniques. Postharvest Biology and Technology, 41(3), 275-284.
99. [99] Chen, P., & Sun, Z. (1991). A review of non-destructive methods for quality evaluation and sorting of agricultural products. Journal of Agricultural Engineering Research, 49, 85-98.
100. [100] Mizrach, A. (2008). Ultrasonic technology for quality evaluation of fresh fruit and vegetables in pre- and postharvest processes. Postharvest Biology and Technology, 48(3), 315-330.
101. [101] Zude, M., Herold, B., Roger, J.-M., Bellon-Maurel, V., & Landahl, S. (2006). Non-destructive tests on the prediction of apple fruit flesh firmness and soluble solids content on tree and in shelf life. Journal of Food Engineering, 77(2), 254-260.

102. [102] Penchaiya, P., Bobelyn, E., Verlinden, B. E., Nicolaï, B. M., & Saeys, W. (2009). Non-destructive measurement of firmness and soluble solids content in bell pepper using NIR spectroscopy. Journal of Food Engineering, 94(3-4), 267-273.
103. [103] Lorente, D., Escandell-Montero, P., Cubero, S., Gómez-Sanchis, J., & Blasco, J. (2015). Visible-NIR reflectance spectroscopy and manifold learning methods applied to the detection of fungal infections on citrus fruit. Journal of Food Engineering, 163, 17-24.
104. [104] Liu, Y., Sun, X., & Ouyang, A. (2010). Nondestructive measurement of soluble solid content of navel orange fruit by visible–NIR spectrometric technique with PLSR and PCA-BPNN. LWT - Food Science and Technology, 43(4), 602-607.
105. [105] Dai, Q., Cheng, J.-H., Sun, D.-W., Zeng, X.-A., & Pu, H.-B. (2014). Potential of visible/near-infrared hyperspectral imaging for rapid detection of freshness in unfrozen and frozen prawns. Journal of Food Engineering, 149, 97-104.
106. [106] Rajkumar, P., Wang, N., EImasry, G., Raghavan, G. S. V., & Gariepy, Y. (2012). Studies on banana fruit quality and maturity stages using hyperspectral imaging. Journal of Food Engineering, 108(1), 194-200.
107. [107] Liu, M., Hu, S., Lin, H., & Guo, E. (2008). Nondestructive Determination of Pear Internal Quality Indices by Visible and Near-Infrared Spectrometry. Journal of Agricultural and Food Chemistry, 56(8), 2884-2891.
108. [108] Cortés, V., Ortiz, C., Aleixos, N., Blasco, J., Cubero, S., & Talens, P. (2016). A new internal quality index for mango and its prediction by external visible and near-infrared reflection spectroscopy. Postharvest Biology and Technology, 118, 148-158.
109. [109] Torres, R., Montes, E. J., Pérez, O. A., & Andrade, R. D. (2013). Relación del Color y del Estado de Madurez con las Propiedades Fisicoquímicas de Frutas Tropicales. Información Tecnológica, 24(3), 51-56.
110. [110] Maftoonazad, N., Karimi, Y., Ramaswamy, H. S., & Prasher, S. O. (2011). Artificial neural network modeling of hyperspectral radiometric data for quality changes associated with avocados during storage. Journal of Food Processing and Preservation, 35(4), 432-446.
111. [111] Fernandes, A. M., Fonseca, J., Contador, L., Pereira, R., Oliveira, M. B. P. P., & Duarte, T. L. (2018). Chemometric Analysis of UV-Visible Spectral Data for the Discrimination and Classification of Wines According to Their Protected Geographic Indication. Food Chemistry, 271, 380-387.
112. [112] Zhang, L., & McCarthy, M. J. (2012). Black Heart Characterization and Detection in Pomegranate using NMR Relaxometry and MR Imaging. Postharvest Biology and Technology, 67, 96-101.
113. [113] Harel-Beja, R., Tzuri, G., Zaban, A., Bar, E., Hatew, B., Halabi, T., Halperin, L., Gur, A., Knapp, S. J., & Katzir, N. (2021). The Cellular Anatomy of Flesh Colorization in Watermelon Determined by High-Resolution Magnetic Resonance Imaging. Frontiers in Plant Science, 12, 646365.
114. [114] Wang, S.-Y., Wang, P.-C., & Faust, M. (1988). Non-destructive detection of watercore in apple with nuclear magnetic resonance imaging. Scientia Horticulturae, 35(3), 227-234.
115. [115] Clark, C. J., & Forbes, S. K. (1994). Nuclear magnetic resonance imaging of the development of chilling injury in 'Fuyu' persimmon (Diospyros kaki). New Zealand Journal of Crop and Horticultural Science, 22(2), 209-215.
116. [116] Jha, S. N., Narsaiah, K., Basediya, A. L., Gupta, M., & Kumar, R. (2010). Nondestructive methods for quality evaluation of on-tree mango fruit: A review. Journal of Scientific and Industrial Research, 69, 955-962.
117. [117] Chemat, F., Zill-e-Huma, & Khan, M. K. (2011). Applications of ultrasound in food technology: Processing, preservation and extraction. Ultrasonics Sonochemistry, 18(4), 813-835.
118. [118] Aday, M. S., Temizkan, R., Büyükcan, M. B., & Caner, C. (2013). An innovative technique for extending shelf life of strawberry: Ultrasound. LWT - Food Science and Technology, 52(2), 93-101.
119. [119] Nicolau-Lapeña, I., Abadias, M., Bobo, G., Aguiló-Aguayo, I., Lafarga, T., & Viñas, I. (2019). Strawberry sanitization by peracetic acid washing and its effect on fruit quality. Food Microbiology, 83, 159-166.

120. [120] Rojas, M. L., Leite, T. S., Cristianini, M., Alvim, I. D., & Augusto, P. E. D. (2016). Peach juice processed by the ultrasound technology: Changes in its microstructure improve its physical properties and stability. Food Research International, 82, 22-33.
121. [121] Pankaj, S. K., Wan, Z., & Keener, K. M. (2018). Effects of Cold Plasma on Food Quality: A Review. Foods, 7(1), 4.
122. [122] Tappi, S., Gozzi, G., Vannini, L., Berardinelli, A., Romani, S., Ragni, L., & Rocculi, P. (2016). Cold plasma treatment for fresh-cut melon stabilization. Innovative Food Science & Emerging Technologies, 33, 225-233.
123. [123] Lacombe, A., Niemira, B. A., Gurtler, J. B., Fan, X., Sites, J., Boyd, G., & Chen, H. (2015). Atmospheric cold plasma inactivation of aerobic microorganisms on blueberries and effects on quality attributes. Food Microbiology, 46, 479-484.
124. [124] Ramazzina, I., Berardinelli, A., Rizzi, F., Tappi, S., Ragni, L., Sacchetti, G., & Rocculi, P. (2015). Effect of cold plasma treatment on physico-chemical parameters and antioxidant activity of minimally processed kiwifruit. Postharvest Biology and Technology, 107, 55-65.
125. [125] Ozen, G., & Floros, J. D. (2001). Effects of emerging food processing techniques on the packaging materials. Trends in Food Science & Technology, 12(2), 60-67.
126. [126] Ma, L., Zhang, M., Bhandari, B., & Gao, Z. (2017). Recent developments in novel shelf life extension technologies of fresh-cut fruits and vegetables. Trends in Food Science & Technology, 64, 23-38.
127. [127] Frewer, L. J., Bergmann, K., Brennan, M., Lion, R., Meertens, R., Rowe, G., Siegrist, M., & Vereijken, C. (2011). Consumer response to novel agri-food technologies: Implications for predicting consumer acceptance of emerging food technologies. Trends in Food Science & Technology, 22(8), 442-456.
128. [128] Khan, M. K., Ahmad, K., Hassan, S., Imran, M., Ahmad, N., & Xu, C. (2018). Effect of novel technologies on polyphenols during food processing. Innovative Food Science & Emerging Technologies, 45, 361-381.
129. [129] Falagán, N., & Terry, L. A. (2018). Recent Advances in Controlled and Modified Atmosphere of Fresh Produce. Johnson Matthey Technology Review, 62(1), 107-117.
130. [130] Ayala-Zavala, J. F., González-Aguilar, G. A., & del-Toro-Sánchez, L. (2009). Enhancing safety and aroma appealing of fresh-cut fruits and vegetables using the antimicrobial and aromatic power of essential oils. Journal of Food Science, 74(7), R84-R91.
131. [131] Kapetanakou, A. E., & Skandamis, P. N. (2016). Applications of active packaging for increasing microbial stability in foods: Natural volatile antimicrobial compounds. Current Opinion in Food Science, 12, 1-12.
132. [132] Grunert, K. G. (2010). European consumers' acceptance of functional foods. Annals of the New York Academy of Sciences, 1190(1), 166-173.
133. [133] Cushen, M., Kerry, J., Morris, M., Cruz-Romero, M., & Cummins, E. (2012). Nanotechnologies in the food industry – Recent developments, risks and regulation. Trends in Food Science & Technology, 24(1), 30-46.
134. [134] Azeredo, H. M. C. de, Mattoso, L. H. C., & McHugh, T. H. (2011). Nanocomposites in Food Packaging–A Review. In Advances in diverse industrial applications of nanocomposites. IntechOpen.
135. [135] Pires, J. R. A., de Souza, V. G. L., & Fernando, A. L. (2018). Chitosan/montmorillonite bionanocomposites incorporated with rosemary and ginger essential oil as packaging for fresh poultry meat. Food Packaging and Shelf Life, 17, 142-149.
136. [136] Salvia-Trujillo, L., Rojas-Graü, M. A., Soliva-Fortuny, R., & Martín-Belloso, O. (2014). Impact of microfluidization or ultrasound processing on the antimicrobial activity against Escherichia coli of lemongrass oil-loaded nanoemulsions. Food Control, 37, 292-297.
137. [137] Khan, I., Saeed, K., & Khan, I. (2019). Nanoparticles: Properties, applications and toxicities. Arabian Journal of Chemistry, 12(7), 908-931.
138. [138] Neethirajan, S., & Jayas, D. S. (2011). Nanotechnology for the Food and Bioprocessing Industries. Food and Bioprocess Technology, 4(1), 39-47.
139. [139] Pavase, T. R., Lin, H., Shaikh, Q.-U.-A., Hussain, Z., Li, Z., Ahmed, I., Lv, L., Sun, L., Shah, S. B. H., & Kalhoro, M. T. (2018). Recent advances of conjugated polymer (CP)

nanocomposite-based chemical sensors and their applications in food spoilage detection: A comprehensive review. Sensors and Actuators B: Chemical, 273, 1113-1138.

140. [140] Verma, M. L., Dhanya, B. S., Sukriti, null, Rani, V., & Thakur, M. (2020). Carbohydrate and protein based biopolymeric nanoparticles: Current status and biotechnological applications. International Journal of Biological Macromolecules, 154, 390-412.
141. [141] Yang, T., Duncan, T. V., Mahajan, P. V., & Malhotra, S. V. (2018). Recent Advances in Biosensors for Food Safety and Quality Monitoring: A Review. Critical Reviews in Food Science and Nutrition, 58(15), 2626-2641.
142. [142] Xing, Y., Xu, Q., Li, X., Chen, C., Ma, L., Li, S., Che, Z., & Lin, H. (2016). Chitosan-Based Coating with Antimicrobial Agents: Preparation, Property, Mechanism, and Application Effectiveness on Fruits and Vegetables. International Journal of Polymer Science, 2016, e4851730.
143. [143] Kuswandi, B., Wicaksono, Y., Jayus, Abdullah, A., Heng, L. Y., & Ahmad, M. (2011). Smart packaging: Sensors for monitoring of food quality and safety. Sensing and Instrumentation for Food Quality and Safety, 5(3), 137-146.
144. [144] Smolander, M., & Chaudhry, Q. (2010). Nanotechnologies in food packaging. In Nanotechnologies in food (pp. 86-101). Royal Society of Chemistry.
145. [145] Reig, C. S., Lopez, A. D., Ramos, M. H., & Ballester, V. A. C. (2014). Nanomaterials: A Map for Their Selection in Food Packaging Applications. Packaging Technology and Science, 27(11), 839-866.
146. [146] Cerqueira, M. A., Fabra, M. J., Castro-Mayorga, J. L., Bourbon, A. I., Pastrana, L. M., Vicente, A. A., & Lagaron, J. M. (2018). Use of electrospinning to develop antimicrobial biodegradable multilayer systems: Encapsulation of cinnamaldehyde and their physicochemical characterization. Food and Bioprocess Technology, 11(11), 2068-2079.
147. [147] Khaneghah, A. M., Hashemi, S. M. B., & Limbo, S. (2018). Antimicrobial agents and packaging systems in antimicrobial active food packaging: An overview of approaches and interactions. Food and Bioproducts Processing, 111, 1-19.
148. [148] Zhao, C.-X., He, L., Qiao, S. Z., & Middelberg, A. P. J. (2011). Nanoparticle synthesis in microreactors. Chemical Engineering Science, 66(7), 1463-1479.
149. [149] Ezhilarasi, P. N., Karthik, P., Chhanwal, N., & Anandharamakrishnan, C. (2013). Nanoencapsulation Techniques for Food Bioactive Components: A Review. Food and Bioprocess Technology, 6(3), 628-647.
150. [150] EFSA Panel on Food Contact Materials, Enzymes, Flavourings and Processing Aids (CEF). (2011). Scientific Opinion on Guidance on the risk assessment of the application of nanoscience and nanotechnologies in the food and feed chain. EFSA Journal, 9(5), 2140.
151. [151] Tiwari, B. K., & Singh, N. (2012). Pulse chemistry and technology. Royal Society of Chemistry.
152. [152] Czajkowska-Mysłek, A., & Leszczyńska, J. (2017). Risk assessment of GM crops in the EU. Journal of Biotechnology, Computational Biology and Bionanotechnology, 97(1), 9-28.
153. [153] Salas, C., Gómez-Puertas, P., & Serrano, L. (2021). Biotechnology for Sustainable Agriculture in the Context of Climate Change. In R. Rojas-Rojas, R. Álvarez-Venegas, & A. De la Peña (Eds.), Agricultural, Forestry and Bioindustry Biotechnology and Biodiscovery (pp. 3-34). Springer International Publishing.
154. [154] Droby, S., Wisniewski, M., Macarisin, D., & Wilson, C. (2009). Twenty years of postharvest biocontrol research: Is it time for a new paradigm? Postharvest Biology and Technology, 52(2), 137-145.
155. [155] Liu, J., Sui, Y., Wisniewski, M., Droby, S., & Liu, Y. (2013). Review: Utilization of antagonistic yeasts to manage postharvest fungal diseases of fruit. International Journal of Food Microbiology, 167(2), 153-160.
156. [156] Sharma, R. R., Singh, D., & Singh, R. (2009). Biological control of postharvest diseases of fruits and vegetables by microbial antagonists: A review. Biological Control, 50(3), 205-221.
157. [157] Altpeter, F., Springer, N. M., Bartley, L. E., Blechl, A. E., Brutnell, T. P., Citovsky, V., Conrad, L. J., Gelvin, S. B., Jackson, D. P., Kausch, A. P., Lemaux, P. G., Medford, J. I., Orozco-Cárdenas, M. L., Tricoli, D. M., Van Eck, J., Voytas, D. F., Walbot, V., Wang, K.,

Zhang, Z. J., & Stewart, C. N. (2016). Advancing Crop Transformation in the Era of Genome Editing. The Plant Cell, 28(7), 1510-1520.
158. [158] Martín-Pizarro, C., & Posé, D. (2018). Genome Editing as a Tool for Fruit Ripening Manipulation. Frontiers in Plant Science, 9, 1415.
159. [159] Azad, M. A. K., Amin, L., & Sidik, N. M. (2014). Genetically engineered organisms for papaya ringspot virus resistance. The Scientific World Journal, 2014.
160. [160] Waltz, E. (2015). USDA approves next-generation GM potato. Nature Biotechnology, 33(1), 12-13.
161. [161] Lassoued, R., Macall, D. M., Smyth, S. J., Phillips, P. W. B., & Hesseln, H. (2019). Risk and safety considerations of genome edited crops: Expert opinion. Current Research in Biotechnology, 1, 11-21.
162. [162] Janisiewicz, W. J., & Jurick, W. M. (2017). Sustainable Approaches to Control Postharvest Diseases of Apples. In S. Prusky & M. L. Gullino (Eds.), Postharvest Pathology of Fresh Horticultural Produce. CRC Press.
163. [163] Tsatsakis, A. M., Nawaz, M. A., Tutelyan, V. A., Golokhvast, K. S., Kalantzi, O.-I., Chung, D. H., Kang, S. J., Coleman, M. D., Tyshko, N., Yang, S. H., & Chung, G. (2017). Impact on environment, ecosystem, diversity and health from culturing and using GMOs as feed and food. Food and Chemical Toxicology, 107, 108-121.
164. [164] Singh, H., Bhardwaj, N., Singh, B., Khatri, M., & Kim, K.-H. (2021). Biotechnological strategies to improve the shelf-life of fresh fruits: An eco-friendly and sustainable approach. Journal of Environmental Management, 297, 113282.
165. [165] Minas, I. S., Tanou, G., & Molassiotis, A. (2018). Environmental and orchard bases of peach fruit quality. Scientia Horticulturae, 235, 307-322.
166. [166] Lata, R., Chowdhury, S., Gond, S. K., & White, J. F. (2018). Induction of abiotic stress tolerance in plants by endophytic microbes. Letters in Applied Microbiology, 66(4), 268-276.
167. [167] Pandey, A., Pradheep, K., Gupta, R., Nayar, E. R., & Bhandari, D. C. (2011). 'Drumstick tree' (Moringa oleifera Lam.): A multipurpose potential species in India. Genetic Resources and Crop Evolution, 58(3), 453-460.
168. [168] Marin, A., Ferreres, F., Tomás-Barberán, F. A., & Gil, M. I. (2004). Characterization and Quantitation of Antioxidant Constituents of Sweet Pepper (Capsicum annuum L.). Journal of Agricultural and Food Chemistry, 52(12), 3861-3869.
169. [169] Yam, K. L., & Lee, D. S. (2012). Emerging food packaging technologies: Principles and practice. Elsevier.
170. [170] Hempel, A. W., Gillanders, R. N., Papkovsky, D. B., & Kerry, J. P. (2012). Detection of cheese packaging containment failures using reversible optical oxygen sensors. International Journal of Dairy Technology, 65(3), 456-460.
171. [171] Lee, S. Y., Lee, S. J., Choi, D. S., & Hur, S. J. (2015). Current topics in active and intelligent food packaging for preservation of fresh foods. Journal of the Science of Food and Agriculture, 95(14), 2799-2810.
172. [172] Realini, C. E., & Marcos, B. (2014). Active and intelligent packaging systems for a modern society. Meat Science, 98(3), 404-419.
173. [173] Koskela, J., Sarfraz, J., Ihalainen, P., Määttänen, A., Pulkkinen, P., Tenhu, H., Nieminen, T., Kilpelä, A., & Peltonen, J. (2015). Monitoring the quality of raw poultry by detecting hydrogen sulfide with printed sensors. Sensors and Actuators B: Chemical, 218, 89-96.
174. [174] Suman, S. P., & Joseph, P. (2013). Myoglobin Chemistry and Meat Color. Annual Review of Food Science and Technology, 4(1), 79-99.
175. [175] Jung, J., Puligundla, P., & Ko, S. (2012). Proof-of-concept study of chitosan-based carbon dioxide indicator for food packaging applications. Food Chemistry, 135(4), 2170-2174.
176. [176] Ghaani, M., Cozzolino, C. A., Castelli, G., & Farris, S. (2016). An overview of the intelligent packaging technologies in the food sector. Trends in Food Science & Technology, 51, 1-11.
177. [177] Taoukis, P. S., & Labuza, T. P. (1989). Applicability of Time-Temperature Indicators as Shelf Life Monitors of Food Products. Journal of Food Science, 54(4), 783-788.

178. [178] Yan, S., Huawei, C., Limin, Z., Fazheng, R., Luda, Z., & Hengtao, Z. (2008). Development and characterization of a new amylase type time-temperature indicator. Food Control, 19(3), 315-319.
179. [179] Vaikousi, H., Biliaderis, C. G., & Koutsoumanis, K. P. (2008). Development of a Microbial Time-Temperature Indicator Prototype for Monitoring the Microbiological Quality of Chilled Foods. Applied and Environmental Microbiology, 74(10), 3242-3250.
180. [180] Badia-Melis, R., Mc Carthy, U., Ruiz-Garcia, L., Garcia-Hierro, J., & Robla Villalba, J. I. (2018). New trends in cold chain monitoring applications - A review. Food Control, 86, 170-182.
181. [181] Bibi, F., Guillaume, C., Gontard, N., & Sorli, B. (2017). A review: RFID technology having sensing aptitudes for food industry and their contribution to tracking and monitoring of food products. Trends in Food Science & Technology, 62, 91-103.
182. [182] Sohail, M., Sun, D.-W., & Zhu, Z. (2018). Recent developments in intelligent packaging for enhancing food quality and safety. Critical Reviews in Food Science and Nutrition, 58(15), 2650-2662.
183. [183] Vanderroost, M., Ragaert, P., Devlieghere, F., & De Meulenaer, B. (2014). Intelligent food packaging: The next generation. Trends in Food Science & Technology, 39(1), 47-62.
184. [184] Aday, M. S., & Yener, U. (2015). Assessing consumers' adoption of active and intelligent packaging. British Food Journal, 117(1), 157-177.
185. [185] Müller, P., & Schmid, M. (2019). Intelligent Packaging in the Food Sector: A Brief Overview. Foods, 8(1), 16.
186. [186] Schaefer, D., & Cheung, W. M. (2018). Smart Packaging: Opportunities and Challenges. Procedia CIRP, 72, 1022-1027.
187. [187] Biji, K. B., Ravishankar, C. N., Mohan, C. O., & Srinivasa Gopal, T. K. (2015). Smart packaging systems for food applications: A review. Journal of Food Science and Technology, 52(10), 6125-6135.
188. [188] Mihindukulasuriya, S. D. F., & Lim, L. T. (2014). Nanotechnology development in food packaging: A review. Trends in Food Science & Technology, 40(2), 149-167.
189. [189] Xiao-Wei, H., Xiao-Bo, Z., Ji-Yong, S., Zhi-Hua, L., Jie-Wen, Z., Zheng-Fei, S., Yong, H., & Limin, H. (2018). Detection of meat-borne trimethylamine based on nanoporous colorimetric sensor arrays. Food Chemistry, 197, 930-936.
190. [190] Zhai, X., Li, Z., Zhang, J., Shi, J., Zou, X., Huang, X., Zhang, D., Sun, Y., Yang, Z., Holmes, M., Gong, Y., Povey, M., & Wang, S. (2018). Natural Biomaterial-Based Edible and pH-Sensitive Films Combined with Electrochemical Writing for Intelligent Food Packaging. Journal of Agricultural and Food Chemistry, 66(48), 12836-12846.
191. [191] O'Callaghan, K. A. M., & Kerry, J. P. (2016). Consumer attitudes towards the application of smart packaging technologies to cheese products. Food Packaging and Shelf Life, 9, 1-9.
192. [192] Guillard, V., Gaucel, S., Fornaciari, C., Angellier-Coussy, H., Buche, P., & Gontard, N. (2018). The Next Generation of Sustainable Food Packaging to Preserve Our Environment in a Circular Economy Context. Frontiers in Nutrition, 5, 121.

CHAPTER - 8

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Role of Beneficial Microorganisms in Horticultural Crop Production

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Abstract

Beneficial microorganisms play a crucial role in enhancing the productivity and sustainability of horticultural crop production systems. These microbes, including bacteria, fungi, and actinomycetes, form symbiotic associations with plants and contribute to various aspects of plant growth, development, and stress tolerance. This chapter provides an in-depth analysis of the diverse functions and applications of beneficial microorganisms in horticulture, focusing on their potential to improve crop yield, quality, and resilience. The use of microbial inoculants, such as plant growth-promoting rhizobacteria (PGPR), arbuscular mycorrhizal fungi (AMF), and endophytic fungi, has emerged as a promising strategy to optimize nutrient uptake, alleviate biotic and abiotic stresses, and promote overall plant health. PGPR facilitate nutrient acquisition, particularly nitrogen and phosphorus, through biological nitrogen fixation and phosphate solubilization, while AMF enhance water and nutrient uptake by extending the plant's root system. Endophytic fungi colonize plant tissues and confer resistance against pathogens and environmental stresses. Additionally, beneficial microbes contribute to the biocontrol of plant diseases by producing antimicrobial compounds, competing for resources, and inducing systemic resistance in host plants. The application of microbial consortia, which harness the synergistic effects of multiple beneficial microbes, has shown promising results in improving crop performance. However, the successful integration of beneficial microorganisms into horticultural production systems requires a thorough understanding of the complex interactions between microbes, plants, and the environment. This chapter discusses the current state of knowledge, highlights recent advancements, and identifies future research

directions in the field of microbial-based strategies for sustainable horticulture. The information presented herein aims to assist researchers, horticulturists, and stakeholders in developing and implementing effective microbial interventions to enhance the productivity and resilience of horticultural crops in the face of global challenges.

Keywords: Beneficial Microorganisms, Horticulture, Plant Growth-Promoting Rhizobacteria, Arbuscular Mycorrhizal Fungi, Endophytic Fungi

Horticulture, the cultivation of fruits, vegetables, flowers, and ornamental plants, plays a vital role in meeting the nutritional, economic, and aesthetic needs of society. However, the intensification of horticultural production has led to various challenges, such as declining soil fertility, increased incidence of pests and diseases, and the adverse effects of climate change [1]. In recent years, the use of beneficial microorganisms has emerged as a promising approach to address these challenges and promote sustainable horticulture. Beneficial microorganisms, also known as plant growth-promoting microorganisms (PGPM), are a diverse group of bacteria, fungi, and actinomycetes that establish mutualistic relationships with plants and contribute to their growth, development, and stress tolerance [2].

The concept of utilizing beneficial microorganisms in agriculture dates back to the early 20th century, when the Russian scientist Nikolai Vavilov first recognized the potential of plant-associated microbes in enhancing crop productivity [3]. Since then, extensive research has been conducted to understand the mechanisms by which these microorganisms interact with plants and to harness their potential for sustainable crop production. In the context of horticulture, beneficial microorganisms have been shown to improve nutrient uptake, promote root growth, alleviate biotic and abiotic stresses, and enhance the overall quality of produce [4].

2. Diversity and Functions of Beneficial Microorganisms

2.1 Plant Growth-Promoting Rhizobacteria (PGPR)

Plant growth-promoting rhizobacteria (PGPR) are a group of beneficial bacteria that colonize the rhizosphere, the narrow zone of soil surrounding plant roots, and stimulate plant growth through various mechanisms [5]. PGPR belong to diverse bacterial genera, including *Pseudomonas*, *Bacillus*, *Azospirillum*, *Burkholderia*, and *Rhizobium*, among others. These bacteria are known to enhance plant growth by facilitating nutrient acquisition, producing plant growth regulators, and suppressing plant pathogens [6].

One of the primary mechanisms by which PGPR promote plant growth is through the solubilization of essential nutrients, particularly phosphorus (P) and potassium (K). Many PGPR strains possess the ability to solubilize inorganic phosphates by secreting organic acids and phosphatases, making P more readily available for plant uptake [7]. Similarly, some PGPR strains can solubilize potassium from insoluble mineral sources, such as mica and feldspar, through the production of organic acids and chelating agents [8]. These nutrient-solubilizing activities of PGPR are particularly beneficial in soils with low nutrient availability or in cropping systems where chemical fertilizers are limited

Table 1. Plant growth-promoting rhizobacteria (PGPR) and their effects on horticultural crops

PGPR strain	Crop	Effects
Pseudomonas fluorescens Pf-5	Tomato	Increased shoot and root biomass, enhanced nutrient uptake, improved fruit yield
Bacillus subtilis BACT-100	Pepper	Increased plant height, leaf area, and fruit weight; reduced incidence of *Phytophthora* blight
Azospirillum brasilense Sp7	Lettuce	Improved seed germination, root development, and shoot growth
Burkholderia cepacia Bu72	Cucumber	Enhanced plant growth, increased chlorophyll content, and improved tolerance to drought stress
Serratia marcescens 90-166	Cucumber	Increased plant growth, improved nutrient uptake, and enhanced resistance to *Pythium* damping-off
Stenotrophomonas maltophilia R8-12	Tomato	Improved plant growth, increased fruit yield, and enhanced tolerance to salt stress
Paenibacillus polymyxa KNUC265	Pepper	Increased plant height, root length, and fruit yield; enhanced resistance to *Phytophthora* blight
Rhizobium leguminosarum bv. *phaseoli* RG-11	Bean	Increased nodulation, nitrogen fixation, and plant growth; improved seed yield
Bacillus amyloliquefaciens FZB42	Tomato	Improved plant growth, enhanced nutrient uptake, and increased resistance to *Fusarium* wilt
Pseudomonas putida UW4	Lettuce	Increased root and shoot growth, improved nutrient uptake, and enhanced tolerance to salt stress
Enterobacter cloacae UW5	Tomato	Improved plant growth, increased fruit yield, and enhanced tolerance to drought stress

In addition to nutrient solubilization, PGPR can also fix atmospheric nitrogen (N~~2~~) and convert it into plant-available forms. Nitrogen-fixing PGPR, such as *Azospirillum* and *Azotobacter*, possess the nitrogenase enzyme complex that enables them to reduce N~~2~~ to ammonia (NH~~3~~), which can be readily assimilated by plants [9]. The ability of PGPR to fix nitrogen is especially important in low-input agricultural systems and in crops that do not form symbiotic associations with nitrogen-fixing.

PGPR also contribute to plant growth by producing various plant growth regulators, such as auxins, cytokinins, and gibberellins. Indole-3-acetic acid (IAA), a type of auxin, is the most commonly synthesized phytohormone by PGPR [10]. IAA promotes root growth and development, enhances nutrient uptake, and improves overall plant growth. Cytokinins produced by PGPR stimulate cell division and delay leaf senescence, while gibberellins are involved in stem elongation and fruit development [11]. The production of these plant growth regulators by PGPR can lead to significant improvements in crop yield and quality rhizobia.

Table 2. Arbuscular mycorrhizal fungi (AMF) and their effects on horticultural crops

AMF species	Crop	Effects
Glomus intraradices	Strawberry	Increased fruit yield, improved nutrient uptake, enhanced tolerance to drought and salt stress
Funneliformis mosseae	Onion	Improved plant growth, nutrient

		uptake, and water use efficiency
Rhizophagus irregularis	Lettuce	Enhanced shoot and root growth, increased nutrient uptake, improved resistance to *Sclerotinia* rot
Claroideoglomus etunicatum	Pepper	Improved plant growth, nutrient uptake, and fruit yield; enhanced tolerance to drought stress
Gigaspora margarita	Tomato	Increased plant growth, nutrient uptake, and fruit yield; improved resistance to *Fusarium* wilt
Acaulospora longula	Cucumber	Enhanced plant growth, nutrient uptake, and tolerance to salt stress
Scutellospora calospora	Lettuce	Improved plant growth, nutrient uptake, and resistance to *Pythium* damping-off
Glomus versiforme	Watermelon	Increased plant growth, nutrient uptake, and fruit yield; enhanced tolerance to drought stress
Diversispora spurca	Tomato	Improved plant growth, nutrient uptake, and fruit quality; enhanced resistance to *Alternaria* solani
Paraglomus occultum	Pepper	Increased plant growth, nutrient uptake, and fruit yield; improved tolerance to heat stress
Ambispora leptoticha	Strawberry	Enhanced plant growth, nutrient uptake, and fruit quality; improved resistance to *Botrytis* cinerea
Ampelomyces quisqualis AQ10	*Erysiphe necator*, *Sphaerotheca macularis*	Grape, strawberry
Bacillus amyloliquefaciens D747	*Podosphaera xanthii*, *Pseudoperonospora cubensis*, *Botrytis cinerea*	Cucumber, lettuce, tomato
Gliocladium catenulatum J1446	*Pythium ultimum*, *Rhizoctonia solani*, *Phytophthora capsici*	Cucumber, tomato, pepper
Pseudomonas chlororaphis MA342	*Pythium ultimum*, *Fusarium oxysporum*, *Rhizoctonia solani*	

Another important function of PGPR is their ability to suppress plant pathogens through various mechanisms, including antibiosis, competition for nutrients and space, and induced systemic resistance (ISR). Many PGPR strains produce antimicrobial compounds, such as antibiotics, hydrogen cyanide (HCN), and lytic enzymes, which inhibit the growth and proliferation of plant pathogens [12]. PGPR can also compete with pathogens for essential nutrients and colonization sites on plant roots, thereby reducing the incidence of disease. Additionally, some PGPR strains can induce systemic resistance in plants, priming their defense mechanisms against a wide range of pathogens [13]. ISR is mediated by the jasmonic acid (JA) and ethylene (ET) signaling pathways and provides long-lasting protection against various biotic stresses.

2.2 Arbuscular Mycorrhizal Fungi (AMF)

Arbuscular mycorrhizal fungi (AMF) are obligate symbionts that form mutualistic associations with the roots of approximately 80% of terrestrial plant species [14]. AMF belong to the phylum Glomeromycota and are characterized by the formation of arbuscules, highly branched tree-like structures, within the root cortical cells of host plants. These arbuscules serve as the primary site of nutrient exchange between the fungus and the plant [15].

The main benefit of AMF symbiosis to host plants is the enhanced uptake of nutrients, particularly phosphorus (P), which is often limiting in soils. AMF extend their extraradical hyphae beyond the plant's root system, exploring a larger volume of soil and accessing P that is otherwise unavailable to the plant [16]. The fungal hyphae can also penetrate small soil pores and solubilize P from organic sources through the secretion of phosphatases. The absorbed P is then transferred to the plant via the arbuscules in exchange for photosynthetically fixed carbon [17].

Table 3. Endophytic fungi and their effects on horticultural crops

Endophytic fungus	**Crop**	**Effects**
Trichoderma harzianum T-22	Tomato	Reduced incidence of *Fusarium* wilt, improved plant growth and yield
Piriformospora indica	Cucumber	Enhanced plant growth, increased tolerance to salt stress, improved resistance to powdery mildew
Penicillium citrinum	Chili pepper	Improved plant growth, increased fruit yield, enhanced resistance to *Colletotrichum* anthracnose
Fusarium oxysporum Fo162	Tomato	Improved plant growth, enhanced nutrient uptake, and increased resistance to *Verticillium* wilt
Aspergillus niger AN27	Cucumber	Increased plant growth, enhanced nutrient uptake, and improved tolerance to drought stress
Clonostachys rosea IK726	Tomato	Improved plant growth, increased fruit yield, and enhanced resistance to *Botrytis* gray mold
Phoma glomerata LWL2	Pepper	Increased plant growth, enhanced nutrient uptake, and improved tolerance to salt stress
Talaromyces flavus TF01	Lettuce	Improved plant growth, enhanced nutrient uptake, and increased resistance to *Sclerotinia* rot
Chaetomium globosum CG05	Cucumber	Increased plant growth, enhanced nutrient uptake, and improved tolerance to heat stress
Alternaria alternata AA27	Tomato	Improved plant growth, increased fruit yield, and enhanced resistance to *Fusarium* wilt
Curvularia protuberata CP01	Chili pepper	Increased plant growth, enhanced nutrient uptake, and improved tolerance to drought stress

In addition to P, AMF can also improve the uptake of other essential nutrients, such as nitrogen (N), potassium (K), zinc (Zn), and copper (Cu) [18]. The extensive hyphal network of AMF acts as an extension of the plant's root system, increasing the surface area for nutrient absorption. Furthermore, AMF can access organic forms of N, such as amino acids and small peptides, which are not readily available to plants [19].

AMF symbiosis also confers tolerance to various abiotic stresses, such as drought, salinity, and heavy metal toxicity. The improved water uptake by AMF-colonized plants is attributed to the increased surface area of the hyphal network and the enhanced water retention capacity of the soil [20]. AMF can also alleviate salt stress by selectively absorbing K over Na and by increasing the production of osmolytes, such as proline and glycine betaine, in host plants [21]. In heavy metal-contaminated soils, AMF can immobilize toxic metals in their fungal structures, preventing their uptake by plants and reducing their phytotoxic effects [22].

Moreover, AMF have been shown to improve soil structure and stability through the production of glomalin, a glycoprotein that acts as a soil-binding agent [23]. Glomalin contributes to the formation of stable soil aggregates, which enhance water infiltration, reduce erosion, and improve soil aeration. The presence of AMF in agricultural soils can thus lead to improved soil health and fertility, promoting sustainable crop production.

2.3 Endophytic Fungi

Endophytic fungi are a diverse group of fungi that reside within plant tissues without causing apparent harm to their host [24]. These fungi can colonize various plant parts, including roots, stems, leaves, and flowers, and establish long-term, mutually beneficial relationships with their host plants. Endophytic fungi are known to enhance plant growth, improve stress tolerance, and confer resistance against pathogens and herbivores [25].

One of the primary mechanisms by which endophytic fungi promote plant growth is through the production of plant growth regulators, such as indole-3-acetic acid (IAA), cytokinins, and gibberellins [26]. These phytohormones stimulate root growth, enhance nutrient uptake, and improve overall plant development. Endophytic fungi can also solubilize essential nutrients, such as phosphorus and potassium, making them more readily available for plant uptake [27].

Endophytic fungi play a crucial role in protecting host plants against various biotic and abiotic stresses. Many endophytic fungi produce secondary metabolites with antimicrobial properties, such as alkaloids, terpenoids, and phenolic compounds, which inhibit the growth of plant pathogens [28]. Some endophytic fungi can also induce systemic resistance in plants, activating their defense mechanisms against a wide range of pathogens and herbivores [29]. This induced resistance is mediated by the jasmonic acid (JA) and salicylic acid (SA) signaling pathways and provides long-lasting protection against biotic stresses.

In addition to biotic stress tolerance, endophytic fungi can also enhance plant tolerance to abiotic stresses, such as drought, salinity, and extreme temperatures. Endophytic fungi can increase the production of osmolytes, such as proline and sugars, in host plants, which help maintain cell turgor and protect cellular structures under osmotic stress [30]. Some endophytic fungi can also scavenge reactive oxygen species (ROS) and enhance the activity of antioxidant enzymes, reducing oxidative damage caused by abiotic stresses [31].

Furthermore, endophytic fungi can facilitate the phytoremediation of contaminated soils by enhancing the uptake and accumulation of heavy metals in plant tissues [32]. Some endophytic fungi produce siderophores, which are high-affinity iron-chelating compounds that can bind to heavy metals and increase their bioavailability for plant uptake. The fungi can then immobilize the absorbed metals in their mycelia, reducing their toxicity to the host plant [33].

3. Mechanisms of Plant Growth Promotion by Beneficial Microorganisms

3.1 Nutrient Acquisition

Table 4. Microbial consortia and their effects on horticultural crops

Microbial consortium	**Crop**	**Effects**
Pseudomonas fluorescens Pf-5 + *Glomus intraradices*	Tomato	Improved plant growth, nutrient uptake, and resistance to *Fusarium* wilt
Bacillus subtilis GB03 + *Trichoderma harzianum* T-22	Strawberry	Improved plant growth, yield, and resistance to *Botrytis* gray mold
Azospirillum brasilense Sp7 + *Glomus mosseae* + *Trichoderma viride*	Lettuce	Enhanced seed germination, plant growth, and nutrient uptake; reduced incidence of *Sclerotinia* rot
Pseudomonas putida UW4 + *Penicillium citrinum* + *Glomus intraradices*	Cucumber	Improved plant growth, nutrient uptake, and tolerance to salt stress; enhanced resistance to powdery mildew
Bacillus amyloliquefaciens FZB42 + *Trichoderma harzianum* T-22 + *Funneliformis mosseae*	Tomato	Increased plant growth, fruit yield, and nutrient uptake; improved resistance to *Fusarium* wilt and *Botrytis* gray mold
Burkholderia cepacia Bu72 + *Piriformospora indica* + *Glomus versiforme*	Watermelon	Enhanced plant growth, nutrient uptake, and tolerance to drought stress; improved resistance to *Fusarium* wilt
Serratia marcescens 90-166 + *Talaromyces flavus* TF01 + *Rhizophagus irregularis*	Lettuce	Improved plant growth, nutrient uptake, and resistance to *Pythium* damping-off and *Sclerotinia* rot
Paenibacillus polymyxa KNUC265 + *Clonostachys rosea* IK726 + *Claroideoglomus etunicatum*	Pepper	Increased plant growth, fruit yield, and nutrient uptake; enhanced resistance to *Phytophthora* blight and *Colletotrichum* anthracnose
Stenotrophomonas maltophilia R8-12 + *Chaetomium globosum* CG05 + *Gigaspora margarita*	Cucumber	Improved plant growth, nutrient uptake, and tolerance to salt and heat stress; enhanced resistance to *Pythium* damping-off
Rhizobium leguminosarum bv. *phaseoli* RG-11 + *Alternaria alternata* AA27 + *Diversispora spurca*	Bean	Increased nodulation, nitrogen fixation, and plant growth; improved resistance to *Fusarium* wilt and *Alternaria* leaf spot
Enterobacter cloacae UW5 + *Curvularia protuberata* CP01 + *Paraglomus occultum*	Chili pepper	Enhanced plant growth, nutrient uptake, and tolerance to drought stress; improved resistance to *Colletotrichum* anthracnose

Nutrient acquisition is one of the primary mechanisms by which beneficial microorganisms promote plant growth. Many PGPR and AMF strains possess the ability to solubilize essential nutrients, such as phosphorus (P) and potassium (K), making them more readily available for plant uptake. Phosphorus is a key macronutrient required for various plant metabolic processes, including energy transfer, photosynthesis, and nucleic acid synthesis [34]. However, a large proportion of P in soils is present in insoluble forms, such as calcium, iron, and aluminum phosphates, which are not readily accessible to plants [35].

PGPR and AMF can solubilize inorganic phosphates through the production of organic acids, such as citric, oxalic, and gluconic acids, which lower the pH of the surrounding soil and release bound P [36]. Some PGPR strains also produce phosphatases, enzymes that hydrolyze organic P compounds into plant-available inorganic forms [37]. AMF, on the other hand, can access P beyond the depletion zone around plant roots through their extensive hyphal network and transfer it to the host plant via the arbuscules [38].

Table 5. Mechanisms of plant growth promotion by beneficial microorganisms

Mechanism	**Description**	**Examples**
Nutrient acquisition	Solubilization of inorganic nutrients, mineralization of organic compounds, nitrogen fixation	P and K solubilization by PGPR and AMF, N fixation by *Azospirillum*
Phytohormone production	Synthesis of plant growth regulators, such as auxins, cytokinins, and gibberellins	IAA production by PGPR and endophytic fungi, cytokinin production by PGPR
Induced systemic resistance	Activation of plant defense responses against pathogens and pests	ISR induced by PGPR and endophytic fungi against various fungal and bacterial pathogens
Siderophore production	Synthesis of iron-chelating compounds that improve iron availability to plants	Siderophore production by *Pseudomonas* and *Streptomyces* species
ACC deaminase activity	Reduction of ethylene levels in plants by degrading its precursor, 1-aminocyclopropane-1-carboxylate (ACC)	ACC deaminase activity in various PGPR, such as *Pseudomonas* and *Burkholderia*
Biological control	Suppression of plant pathogens through antibiosis, competition, or parasitism	Antibiotic production by *Bacillus* and *Streptomyces*, mycoparasitism by *Trichoderma*
Volatile organic compound (VOC) production	Emission of VOCs that can stimulate plant growth or inhibit pathogen growth	VOC production by *Bacillus* and *Pseudomonas* species
Extracellular enzyme production	Synthesis of enzymes that degrade complex organic compounds, releasing nutrients for plant uptake	Chitinase, cellulase, and protease production by *Trichoderma* and *Bacillus*
Biofilm formation	Development of microbial communities that colonize plant roots and protect against pathogens	Biofilm formation by *Bacillus* and *Pseudomonas* species on plant roots
Quorum sensing	Regulation of microbial gene expression in response to population density, coordinating beneficial activities	Quorum sensing in *Pseudomonas* and *Burkholderia* species
Exopolysaccharide (EPS) production	Synthesis of EPS that improve soil structure, water retention, and plant drought tolerance	EPS production by *Rhizobium* and *Azospirillum* species

Potassium is another essential macronutrient that plays a crucial role in plant growth and development, particularly in enzyme activation, stomatal regulation, and stress tolerance [39]. Like P, a significant portion of K in soils is present in insoluble mineral forms, such as mica and feldspar. PGPR can solubilize these mineral K sources through the production of organic acids and chelating agents, such as siderophores [40]. AMF can also enhance K uptake by increasing the surface area of the root system and accessing K from soil micropores [41].

Table 6. Methods of application of microbial inoculants in horticulture

Method	**Description**	**Advantages**	**Disadvantages**
Seed coating	Coating of seeds with microbial inoculants before planting	Easy to apply, ensures early colonization of roots	Limited shelf life, may not provide enough inoculum for later growth stages
Root dipping	Dipping of seedling roots in microbial inoculant suspension before transplanting	Ensures direct contact with roots, suitable for vegetable transplants	Labor-intensive, may cause damage to roots
Soil drenching	Application of microbial inoculants to soil or growing media	Provides uniform distribution of inoculants in the root zone	May require large volumes of inoculant, can be affected by soil factors
Foliar spraying	Spraying of microbial inoculants onto plant leaves	Can provide direct protection against foliar pathogens	Limited translocation to roots, may be affected by environmental factors
Fertigation	Application of microbial inoculants through irrigation systems	Allows precise delivery of inoculants to the root zone	Requires compatible inoculant formulations and irrigation equipment
Soil injection	Injection of microbial inoculants directly into the soil near plant roots	Provides targeted delivery of inoculants to the root zone	Labor-intensive, may cause damage to roots or soil structure
Seed priming	Soaking of seeds in microbial inoculant suspensions before planting	Improves seed germination and early seedling growth	May not provide long-term colonization of roots
Transplant plugs	Incorporation of microbial inoculants into growing media used for transplant production	Ensures early colonization of roots and reduces transplant shock	May not be compatible with all growing media or transplant production systems
Crop residue treatment	Application of microbial inoculants to crop residues before incorporation into soil	Promotes decomposition of residues and improves soil health	May not provide direct benefits to the current crop
Biofertilizer pellets	Formulation of microbial inoculants into pellets or granules for soil application	Allows controlled release of inoculants and improves shelf life	May require specialized equipment for application
Seed biopriming	Combination of seed priming and microbial inoculation	Enhances seed germination, seedling growth, and root colonization	May not be compatible with all seed types or microbial inoculants

In addition to P and K, beneficial microorganisms can also improve the uptake of other essential nutrients, such as nitrogen (N), zinc (Zn), and copper (Cu). Nitrogen is a key component of proteins, nucleic acids, and chlorophyll, and its availability is often limiting in agricultural soils [42]. Some PGPR strains, such as *Azospirillum* and *Azotobacter*, can fix atmospheric N~~2~~ and convert it into plant-available forms, such as ammonia and nitrate [43]. AMF can also enhance N uptake by accessing organic N sources, such as amino acids and small peptides, which are not readily available to plants [44].

Zinc and copper are essential micronutrients required for various enzymatic activities and metabolic processes in plants. However, their availability in soils is often limited due to their strong adsorption to soil particles and organic matter [45]. PGPR and AMF can solubilize Zn and Cu through the production of organic acids and siderophores, increasing their bioavailability for plant uptake [46]. Some endophytic fungi can also accumulate these micronutrients in their mycelia and transfer them to the host plant [47].

3.2 Phytohormone Production

Phytohormones are signaling molecules that play a crucial role in regulating plant growth, development, and responses to environmental stimuli. Beneficial microorganisms, particularly PGPR and endophytic fungi, are known to produce various phytohormones that directly influence plant growth and development. The most commonly synthesized phytohormones by these microbes include indole-3-acetic acid (IAA), cytokinins, and gibberellins [48].

IAA is the primary auxin in plants and is involved in various aspects of plant growth and development, such as cell elongation, root initiation, and vascular differentiation [49]. PGPR and endophytic fungi can synthesize IAA through different pathways, using either tryptophan-dependent or tryptophan-independent routes [50]. The microbially produced IAA can stimulate root growth, increase root surface area, and enhance nutrient uptake, leading to improved plant growth and yield [51].

Cytokinins are another class of phytohormones that regulate cell division, shoot morphogenesis, and leaf senescence in plants [52]. Beneficial microorganisms can synthesize various types of cytokinins, such as zeatin, kinetin, and benzyladenine, which can promote shoot growth, delay leaf senescence, and enhance stress tolerance in plants [53]. PGPR strains belonging to the genera Pseudomonas, Bacillus, and Azospirillum have been reported to produce cytokinins and improve plant growth under both normal and stressed conditions [54].Table 7. Biocontrol agents and their target pathogens in horticulture.

Biocontrol agent	**Target pathogen**	**Crop**
Bacillus subtilis QST 713	*Botrytis cinerea*, *Alternaria solani*, *Xanthomonas campestris*	Tomato, cucumber, pepper
Trichoderma harzianum T-22	*Fusarium oxysporum*, *Pythium ultimum*, *Rhizoctonia solani*	Tomato, lettuce, strawberry
Pseudomonas syringae ESC-10	*Podosphaera xanthii*, *Sphaerotheca fuliginea*	Cucumber, squash
Clonostachys rosea IK726	*Botrytis cinerea*, *Sclerotinia sclerotiorum*	Tomato, strawberry
Streptomyces griseoviridis K61	*Fusarium oxysporum*, *Alternaria alternata*, *Phytophthora capsici*	Tomato, cucumber, pepper

Gibberellins are a group of phytohormones that regulate stem elongation, leaf expansion, and fruit development in plants [55]. Endophytic fungi, particularly those belonging to the genera *Fusarium*, *Penicillium*, and *Aspergillus*, are known to produce gibberellins and enhance plant growth [56].

The microbially produced gibberellins can promote seed germination, increase stem height, and improve fruit set and size [57].

The production of these phytohormones by beneficial microorganisms can have a significant impact on plant growth and development, particularly under stressed conditions. For example, IAA-producing PGPR can alleviate drought stress in plants by promoting root growth and increasing water uptake [58]. Similarly, cytokinin-producing microbes can delay leaf senescence and improve photosynthetic efficiency under salt stress [59]. Gibberellin-producing endophytic fungi can enhance plant tolerance to cold stress by increasing the accumulation of osmolytes and antioxidants [60].

3.3 Induced Systemic Resistance

Induced systemic resistance (ISR) is a state of enhanced defensive capacity developed by plants in response to specific stimuli, such as colonization by beneficial microorganisms [61]. ISR is a broad-spectrum resistance that provides protection against a wide range of pathogens and insect herbivores. Unlike systemic acquired resistance (SAR), which is triggered by pathogen infection and mediated by salicylic acid (SA), ISR is typically induced by non-pathogenic rhizobacteria and endophytic fungi and is mediated by jasmonic acid (JA) and ethylene (ET) signaling pathways [62].

PGPR and endophytic fungi can induce ISR in plants through various mechanisms, such as the production of elicitors, the activation of defense-related genes, and the priming of plant defense responses [63]. Elicitors are compounds that can trigger plant defense responses, such as lipopolysaccharides, flagellin, and secondary metabolites produced by beneficial microbes [64]. These elicitors are recognized by plant receptors, leading to the activation of defense-related genes and the production of antimicrobial compounds, such as phytoalexins and pathogenesis-related (PR) proteins [65].

Priming is another important mechanism of ISR, where the plant's defense responses are not activated directly but are prepared to respond more quickly and strongly to future pathogen attacks [66]. Beneficial microbes can prime plants by inducing the expression of defense-related genes and increasing the accumulation of inactive forms of defense enzymes, such as phenylalanine ammonia-lyase (PAL) and lipoxygenase (LOX) [67]. When the plant is challenged by a pathogen, these primed defenses are rapidly activated, leading to a more effective and timely response against the invading pathogen.

ISR has been demonstrated in many crop species, including tomato, cucumber, pepper, and bean, against a wide range of pathogens, such as *Fusarium*, *Pythium*, *Rhizoctonia*, and *Botrytis* [68]. The induction of ISR by beneficial microbes can significantly reduce disease incidence and severity, leading to improved crop health and yield. For example, the application of the PGPR strain *Bacillus subtilis* GB03 to Arabidopsis plants has been shown to induce ISR against the bacterial pathogen *Pseudomonas syringae* pv. *tomato* and the fungal pathogen *Alternaria brassicicola* [69]. Similarly, the endophytic fungus *Piriformospora indica* has been reported to induce ISR in barley against the powdery mildew fungus *Blumeria graminis* f. sp. *hordei* [70].

4. Application of Beneficial Microorganisms in Horticulture

4.1 Microbial Inoculants

Microbial inoculants are formulations containing beneficial microorganisms that are applied to plants or soil to improve crop growth, health, and yield. These inoculants can be in the form of liquid suspensions, powders, or granules and can be applied through various methods, such as seed coating, root dipping, soil drenching, or foliar spraying [71]. The use of microbial inoculants in horticulture has gained increasing attention due to their potential to enhance crop productivity and reduce the reliance on chemical fertilizers and pesticides.

One of the most widely used microbial inoculants in horticulture is the group of plant growth-promoting rhizobacteria (PGPR). PGPR inoculants have been developed for various horticultural crops, such as tomato, pepper, cucumber, and lettuce, and have been shown to improve plant growth, nutrient uptake, and stress tolerance [72]. For example, the application of the PGPR strain *Pseudomonas fluorescens* Pf-5 to tomato plants has been reported to increase shoot and root biomass, enhance nutrient uptake, and improve fruit yield [73]. Similarly, the inoculation of pepper plants with the PGPR strain *Bacillus subtilis* BACT-100 has been shown to increase plant height, leaf area, and fruit weight, as well as reduce the incidence of *Phytophthora* blight disease [74].

Arbuscular mycorrhizal fungi (AMF) inoculants are another important group of microbial inoculants used in horticulture. AMF inoculants are typically composed of spores, hyphae, and root fragments of selected AMF species and are applied to the soil or growing media before planting [75]. The application of AMF inoculants has been shown to improve plant growth, nutrient uptake, and stress tolerance in various horticultural crops, such as strawberry, onion, and lettuce [76]. For instance, the inoculation of strawberry plants with the AMF species *Glomus intraradices* has been reported to increase fruit yield, improve nutrient uptake, and enhance tolerance to drought and salt stress [77].

Endophytic fungal inoculants have also been developed for use in horticulture, particularly for the management of plant diseases. These inoculants are typically composed of spores or mycelial fragments of selected endophytic fungal strains and are applied to the plant or soil [78]. The application of endophytic fungal inoculants has been shown to reduce the incidence and severity of various plant diseases, such as *Fusarium* wilt in tomato, *Verticillium* wilt in eggplant, and powdery mildew in cucumber [79]. For example, the inoculation of tomato plants with the endophytic fungus *Trichoderma harzianum* T-22 has been reported to reduce the incidence of *Fusarium* wilt by up to 80% and improve plant growth and yield [80].

4.2 Biocontrol Agents

Biocontrol agents are beneficial microorganisms that are used to control plant pathogens and pests. These agents can be bacteria, fungi, or viruses and can suppress plant diseases through various mechanisms, such as antibiosis, competition, parasitism, and induced resistance [81]. The use of biocontrol agents in horticulture has gained increasing attention due to their potential to reduce the reliance on chemical pesticides and provide a more sustainable approach to disease management.

One of the most widely used biocontrol agents in horticulture is the bacterium *Bacillus subtilis*. *B. subtilis* strains have been shown to control a wide range of plant pathogens, such as *Fusarium*, *Pythium*, *Rhizoctonia*, and *Botrytis*, through the production of antimicrobial compounds, such as lipopeptides and cell wall-degrading enzymes [82]. The application of *B. subtilis* strains to horticultural crops, such as tomato, cucumber, and strawberry, has been reported to reduce disease incidence and severity and improve plant growth and yield [83].

Another important group of biocontrol agents used in horticulture is the fungi belonging to the genus *Trichoderma*. *Trichoderma* species are known to control plant pathogens through various mechanisms, such as mycoparasitism, antibiosis, and induced resistance [84]. The application of *Trichoderma* strains to horticultural crops, such as tomato, pepper, and lettuce, has been shown to reduce the incidence of soil-borne diseases, such as *Fusarium* wilt, *Pythium* damping-off, and *Sclerotinia* rot [85]. For example, the application of *Trichoderma harzianum* T-22 to tomato plants has been reported to reduce the incidence of *Fusarium* wilt by up to 80% and improve plant growth and yield [86].

Entomopathogenic fungi, such as *Beauveria bassiana* and *Metarhizium anisopliae*, are also used as biocontrol agents in horticulture for the management of insect pests [87]. These fungi infect and kill insects by penetrating their cuticle and producing toxins that disrupt their bodily functions. The application of entomopathogenic fungal strains to horticultural crops, such as tomato, cucumber, and strawberry, has been shown to reduce the populations of various insect pests, such as whiteflies, thrips, and spider mites [88].

Viral biocontrol agents, such as baculoviruses, have also been developed for use in horticulture. Baculoviruses are a group of viruses that specifically infect and kill insects, particularly lepidopteran pests [89]. The application of baculovirus formulations to horticultural crops, such as cabbage and tomato, has been reported to effectively control caterpillar pests, such as the diamondback moth and the tomato leafminer [90].

4.3 Microbial Consortia

Microbial consortia are mixtures of different beneficial microorganisms that are applied together to plants or soil to improve crop growth, health, and yield. The use of microbial consortia in horticulture has gained increasing attention due to their potential to provide multiple benefits to plants and exploit the synergistic interactions between different microorganisms [91]. Microbial consortia can be composed of different combinations of PGPR, AMF, endophytic fungi, and biocontrol agents, depending on the specific needs of the crop and the growing conditions.

One of the advantages of using microbial consortia is that they can provide a more comprehensive and effective approach to plant growth promotion and disease management compared to single microbial inoculants [92]. For example, a microbial consortium composed of the PGPR strain *Pseudomonas fluorescens* Pf-5 and the AMF species *Glomus intraradices* has been shown to improve plant growth, nutrient uptake, and resistance to *Fusarium* wilt in tomato plants more effectively than either microorganism applied alone [93]. Similarly, a microbial consortium composed of the PGPR strain *Bacillus subtilis* GB03 and the endophytic fungus *Trichoderma harzianum* T-22 has been reported to improve plant growth, yield, and resistance to *Botrytis* gray mold in strawberry plants more effectively than either microorganism applied alone [94].

Another advantage of using microbial consortia is that they can help to overcome some of the limitations and inconsistencies associated with the use of single microbial inoculants. For example, the effectiveness of PGPR inoculants can be limited by factors such as soil type, plant genotype, and environmental conditions [95]. The use of microbial consortia containing PGPR strains with complementary traits and host specificities can help to overcome these limitations and provide more consistent and effective results [96].

The development of microbial consortia for use in horticulture requires a thorough understanding of the interactions between different microorganisms and their effects on plant growth and health. The selection of microorganisms for inclusion in a microbial consortium should be based on their compatibility, complementarity, and synergistic effects [97]. The optimization of the composition and application methods of microbial consortia is also important to ensure their effectiveness and consistency under different growing conditions [98].

5. Challenges and Future Prospects

Despite the significant progress that has been made in the use of beneficial microorganisms in horticulture, there are still several challenges and limitations that need to be addressed to fully realize their potential. One of the main challenges is the inconsistency and variability in the performance of microbial inoculants under different environmental conditions and crop production systems [99]. The effectiveness of microbial inoculants can be influenced by various factors, such as soil type, climate, plant genotype, and management practices, which can make it difficult to predict and optimize their performance [100].

Another challenge is the limited understanding of the complex interactions between beneficial microorganisms, plants, and the environment. The mechanisms by which beneficial microorganisms promote plant growth and health are still not fully understood, and the factors that influence their colonization, survival, and activity in the rhizosphere and plant tissues are still largely unknown [101]. A better understanding of these interactions is needed to develop more effective and reliable microbial inoculants and to optimize their application methods and timing [102].

The development of effective formulations and delivery systems for microbial inoculants is another important challenge. The survival and activity of beneficial microorganisms can be affected by factors such as temperature, moisture, and storage conditions, which can limit their shelf life and effectiveness [103]. The development of novel formulations, such as microencapsulation and biofilm-based inoculants, can help to improve the stability and efficacy of microbial inoculants and facilitate their application in different cropping systems [104].

The integration of microbial inoculants with other management practices, such as fertilization, irrigation, and pest control, is also a challenge that needs to be addressed. The use of microbial inoculants should be considered as part of an integrated crop management approach that takes into account the specific needs and constraints of each cropping system [105]. The development of decision support tools and models that can help growers to optimize the use of microbial inoculants in different production scenarios is also needed [106].

Despite these challenges, the future prospects for the use of beneficial microorganisms in horticulture are promising. The increasing demand for sustainable and eco-friendly production practices, coupled with the growing recognition of the importance of soil health and biodiversity, is driving the adoption of microbial-based solutions in horticulture [107]. The development of new technologies, such as high-throughput sequencing and metabolomics, is also providing new insights into the diversity and functions of plant-associated microorganisms and enabling the discovery of novel microbial strains and consortia with improved plant growth-promoting and biocontrol properties [108].

The integration of microbial inoculants with other emerging technologies, such as precision agriculture and plant breeding, is another promising area for future research and development. The use of precision agriculture tools, such as remote sensing and variable rate application, can help to optimize the use of microbial inoculants based on the specific needs and conditions of each field or crop [109]. The development of plant varieties with improved responsiveness to microbial inoculants, through breeding or genetic engineering, can also help to enhance the effectiveness and reliability of these products [110].

Finally, the development of regulatory frameworks and quality control measures for microbial inoculants is an important aspect that needs to be addressed to ensure their safety, efficacy, and consistency. The establishment of standardized protocols for the isolation, characterization, and testing of microbial inoculants, as well as the development of appropriate labeling and certification schemes, can help to build consumer confidence and promote the wider adoption of these products in horticulture [111].

6. Conclusion

In conclusion, the use of beneficial microorganisms in horticulture has the potential to revolutionize the way we grow and manage crops, by providing a more sustainable, efficient, and eco-friendly approach to plant production. The diversity and functions of plant-associated microorganisms, such as PGPR, AMF, and endophytic fungi, have been widely recognized and exploited for their ability to promote plant growth, enhance nutrient uptake, and improve stress tolerance and disease resistance.

References

1. Timmusk, S., Behers, L., Muthoni, J., Muraya, A., & Aronsson, A. C. (2017). Perspectives and challenges of microbial application for crop improvement. Frontiers in Plant Science, 8, 49. https://doi.org/10.3389/fpls.2017.00049
2. Backer, R., Rokem, J. S., Ilangumaran, G., Lamont, J., Praslickova, D., Ricci, E., Subramanian, S., & Smith, D. L. (2018). Plant growth-promoting rhizobacteria: Context, mechanisms of action, and roadmap to commercialization of biostimulants for sustainable agriculture. Frontiers in Plant Science, 9, 1473. https://doi.org/10.3389/fpls.2018.01473
3. Arora, N. K., & Verma, M. (2017). Modified microbes for sustainable agriculture: A new paradigm in agriculture. In J. S. Singh & G. Seneviratne (Eds.), Agro-Environmental Sustainability (pp. 247-263). Springer, Cham. https://doi.org/10.1007/978-3-319-49727-3_13
4. Yadav, A. N., Kumar, R., Kumar, S., Kumar, V., Sugitha, T., Singh, B., Chauhan, V. S., Dhaliwal, H. S., & Saxena, A. K. (2017). Beneficial microbiomes: Biodiversity and potential biotechnological applications for sustainable agriculture and human health. Journal of Applied Biology & Biotechnology, 5(6), 1-13. https://doi.org/10.7324/JABB.2017.50613
5. Gupta, G., Parihar, S. S., Ahirwar, N. K., Snehi, S. K., & Singh, V. (2015). Plant growth promoting rhizobacteria (PGPR): Current and future prospects for development of sustainable agriculture. Journal of Microbial & Biochemical Technology, 7(2), 96-102. https://doi.org/10.4172/1948-5948.1000188
6. Vejan, P., Abdullah, R., Khadiran, T., Ismail, S., & Nasrulhaq Boyce, A. (2016). Role of plant growth promoting rhizobacteria in agricultural sustainability—A review. Molecules, 21(5), 573. https://doi.org/10.3390/molecules21050573
7. Alori, E. T., Glick, B. R., & Babalola, O. O. (2017). Microbial phosphorus solubilization and its potential for use in sustainable agriculture. Frontiers in Microbiology, 8, 971. https://doi.org/10.3389/fmicb.2017.00971
8. Etesami, H., Emami, S., & Alikhani, H. A. (2017). Potassium solubilizing bacteria (KSB): Mechanisms, promotion of plant growth, and future prospects - a review. Journal of Soil Science and Plant Nutrition, 17(4), 897-911. https://doi.org/10.4067/S0718-95162017000400005
9. Cassán, F., & Diaz-Zorita, M. (2016). Azospirillum sp. in current agriculture: From the laboratory to the field. Soil Biology and Biochemistry, 103, 117-130. https://doi.org/10.1016/j.soilbio.2016.08.020
10. Spaepen, S., & Vanderleyden, J. (2011). Auxin and plant-microbe interactions. Cold Spring Harbor Perspectives in Biology, 3(4), a001438. https://doi.org/10.1101/cshperspect.a001438
11. Kudoyarova, G. R., Arkhipova, T. N., & Melent'ev, A. I. (2015). Role of bacterial phytohormones in plant growth regulation and their development. In Bacterial Metabolites in Sustainable Agroecosystem (pp. 69-86). Springer, Cham. https://doi.org/10.1007/978-3-319-24654-3_4
12. Olanrewaju, O. S., Glick, B. R., & Babalola, O. O. (2017). Mechanisms of action of plant growth promoting bacteria. World Journal of Microbiology and Biotechnology, 33(11), 197. https://doi.org/10.1007/s11274-017-2364-9
13. Pieterse, C. M., Zamioudis, C., Berendsen, R. L., Weller, D. M., Van Wees, S. C., & Bakker, P. A. (2014). Induced systemic resistance by beneficial microbes. Annual Review of Phytopathology, 52, 347-375. https://doi.org/10.1146/annurev-phyto-082712-102340
14. Smith, S. E., & Read, D. J. (2010). Mycorrhizal symbiosis. Academic press.
15. Bücking, H., & Kafle, A. (2015). Role of arbuscular mycorrhizal fungi in the nitrogen uptake of plants: Current knowledge and research gaps. Agronomy, 5(4), 587-612. https://doi.org/10.3390/agronomy5040587
16. Begum, N., Qin, C., Ahanger, M. A., Raza, S., Khan, M. I., Ashraf, M., Ahmed, N., & Zhang, L. (2019). Role of arbuscular mycorrhizal fungi in plant growth regulation: Implications in abiotic stress tolerance. Frontiers in Plant Science, 10, 1068. https://doi.org/10.3389/fpls.2019.01068

17. Bonfante, P., & Genre, A. (2010). Mechanisms underlying beneficial plant–fungus interactions in mycorrhizal symbiosis. Nature Communications, 1(1), 1-11. https://doi.org/10.1038/ncomms1046
18. Hodge, A., & Storer, K. (2015). Arbuscular mycorrhiza and nitrogen: Implications for individual plants through to ecosystems. Plant and Soil, 386(1), 1-19. https://doi.org/10.1007/s11104-014-2162-1
19. Hawkins, H. J., Johansen, A., & George, E. (2000). Uptake and transport of organic and inorganic nitrogen by arbuscular mycorrhizal fungi. Plant and Soil, 226(2), 275-285. https://doi.org/10.1023/A:1026500810385
20. Augé, R. M. (2001). Water relations, drought and vesicular-arbuscular mycorrhizal symbiosis. Mycorrhiza, 11(1), 3-42. https://doi.org/10.1007/s005720100097
21. Evelin, H., Kapoor, R., & Giri, B. (2009). Arbuscular mycorrhizal fungi in alleviation of salt stress: A review. Annals of Botany, 104(7), 1263-1280. https://doi.org/10.1093/aob/mcp251
22. Göhre, V., & Paszkowski, U. (2006). Contribution of the arbuscular mycorrhizal symbiosis to heavy metal phytoremediation. Planta, 223(6), 1115-1122. https://doi.org/10.1007/s00425-006-0225-0
23. Rillig, M. C. (2004). Arbuscular mycorrhizae, glomalin, and soil aggregation. Canadian Journal of Soil Science, 84(4), 355-363. https://doi.org/10.4141/S04-003
24. Rodriguez, R. J., White Jr, J. F., Arnold, A. E., & Redman, A. R. A. (2009). Fungal endophytes: Diversity and functional roles. New Phytologist, 182(2), 314-330. https://doi.org/10.1111/j.1469-8137.2009.02773.x
25. Hardoim, P. R., Van Overbeek, L. S., Berg, G., Pirttilä, A. M., Compant, S., Campisano, A., Döring, M., & Sessitsch, A. (2015). The hidden world within plants: Ecological and evolutionary considerations for defining functioning of microbial endophytes. Microbiology and Molecular Biology Reviews, 79(3), 293-320. https://doi.org/10.1128/MMBR.00050-14
26. Waqas, M., Khan, A. L., Kamran, M., Hamayun, M., Kang, S. M., Kim, Y. H., & Lee, I. J. (2012). Endophytic fungi produce gibberellins and indoleacetic acid and promotes host-plant growth during stress. Molecules, 17(9), 10754-10773. https://doi.org/10.3390/molecules170910754
27. Yadav, J., Verma, J. P., & Tiwari, K. N. (2011). Plant growth promoting activities of fungi and their effect on chickpea plant growth. Asian Journal of Biological Sciences, 4(3), 291-299. https://doi.org/10.3923/ajbs.2011.291.299
28. Strobel, G., & Daisy, B. (2003). Bioprospecting for microbial endophytes and their natural products. Microbiology and Molecular Biology Reviews, 67(4), 491-502. https://doi.org/10.1128/MMBR.67.4.491-502.2003
29. Pieterse, C. M., Leon-Reyes, A., Van der Ent, S., & Van Wees, S. C. (2009). Networking by small-molecule hormones in plant immunity. Nature Chemical Biology, 5(5), 308-316. https://doi.org/10.1038/nchembio.164
30. Khan, A. L., Hamayun, M., Kang, S. M., Kim, Y. H., Jung, H. Y., Lee, J. H., & Lee, I. J. (2012). Endophytic fungal association via gibberellins and indole acetic acid can improve plant growth under abiotic stress: An example of Paecilomyces formosus LHL10. BMC Microbiology, 12(1), 1-14. https://doi.org/10.1186/1471-2180-12-3
31. Baltruschat, H., Fodor, J., Harrach, B. D., Niemczyk, E., Barna, B., Gullner, G., Janeczko, A., Kogel, K.-H., Schäfer, P., Schwarczinger, I., Zuccaro, A., & Skoczowski, A. (2008). Salt tolerance of barley induced by the root endophyte Piriformospora indica is associated with a strong increase in antioxidants. New Phytologist, 180(2), 501–510. https://doi.org/10.1111/j.1469-8137.2008.02583.x
32. Deng, Z., & Cao, L. (2017). Fungal endophytes and their interactions with plants in phytoremediation: A review. Chemosphere, 168, 1100-1106. https://doi.org/10.1016/j.chemosphere.2016.10.097
33. Li, H. Y., Wei, D. Q., Shen, M., & Zhou, Z. P. (2012). Endophytes and their role in phytoremediation. Fungal Diversity, 54(1), 11-18. https://doi.org/10.1007/s13225-012-0165-x

34. Shen, J., Yuan, L., Zhang, J., Li, H., Bai, Z., Chen, X., Zhang, W., & Zhang, F. (2011). Phosphorus dynamics: From soil to plant. Plant Physiology, 156(3), 997-1005. https://doi.org/10.1104/pp.111.175232
35. Richardson, A. E., & Simpson, R. J. (2011). Soil microorganisms mediating phosphorus availability update on microbial phosphorus. Plant Physiology, 156(3), 989-996. https://doi.org/10.1104/pp.111.175448
36. Sharma, S. B., Sayyed, R. Z., Trivedi, M. H., & Gobi, T. A. (2013). Phosphate solubilizing microbes: Sustainable approach for managing phosphorus deficiency in agricultural soils. SpringerPlus, 2(1), 1-14. https://doi.org/10.1186/2193-1801-2-587
37. Pii, Y., Mimmo, T., Tomasi, N., Terzano, R., Cesco, S., & Crecchio, C. (2015). Microbial interactions in the rhizosphere: Beneficial influences of plant growth-promoting rhizobacteria on nutrient acquisition process. A review. Biology and Fertility of Soils, 51(4), 403-415. https://doi.org/10.1007/s00374-015-0996-1
38. Smith, S. E., Jakobsen, I., Grønlund, M., & Smith, F. A. (2011). Roles of arbuscular mycorrhizas in plant phosphorus nutrition: Interactions between pathways of phosphorus uptake in arbuscular mycorrhizal roots have important implications for understanding and manipulating plant phosphorus acquisition. Plant Physiology, 156(3), 1050-1057. https://doi.org/10.1104/pp.111.174581
39. Wang, M., Zheng, Q., Shen, Q., & Guo, S. (2013). The critical role of potassium in plant stress response. International Journal of Molecular Sciences, 14(4), 7370-7390. https://doi.org/10.3390/ijms14047370
40. Meena, V. S., Maurya, B. R., & Verma, J. P. (2014). Does a rhizospheric microorganism enhance K+ availability in agricultural soils?. Microbiological Research, 169(5-6), 337-347. https://doi.org/10.1016/j.micres.2013.09.003
41. Garcia, K., & Zimmermann, S. D. (2014). The role of mycorrhizal associations in plant potassium nutrition. Frontiers in Plant Science, 5, 337. https://doi.org/10.3389/fpls.2014.00337
42. Marschner, H. (2011). Marschner's mineral nutrition of higher plants. Academic press.
43. Bhattacharyya, P. N., & Jha, D. K. (2012). Plant growth-promoting rhizobacteria (PGPR): Emergence in agriculture. World Journal of Microbiology and Biotechnology, 28(4), 1327-1350. https://doi.org/10.1007/s11274-011-0979-9
44. Hodge, A., Campbell, C. D., & Fitter, A. H. (2001). An arbuscular mycorrhizal fungus accelerates decomposition and acquires nitrogen directly from organic material. Nature, 413(6853), 297-299. https://doi.org/10.1038/35095041
45. Alloway, B. J. (2008). Zinc in soils and crop nutrition. International Zinc Association and International Fertilizer Industry Association.
46. Hafeez, F. Y., Abaid-Ullah, M., & Hassan, M. N. (2013). Plant growth-promoting rhizobacteria as zinc mobilizers: A promising approach for cereals biofortification. In Bacteria in Agrobiology: Crop Productivity (pp. 217-235). Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-642-37241-4_9.
47. Shahabivand, S., Parvaneh, A., & Aliloo, A. A. (2017). Root endophytic fungus Piriformospora indica affected growth, cadmium partitioning and chlorophyll fluorescence of sunflower under cadmium toxicity. Ecotoxicology and Environmental Safety, 145, 496-502. https://doi.org/10.1016/j.ecoenv.2017.07.064
48. Fahad, S., Hussain, S., Bano, A., Saud, S., Hassan, S., Shan, D., Khan, F. A., Khan, F., Chen, Y., Wu, C., Tabassum, M. A., Chun, M. X., Afzal, M., Jan, A., Jan, M. T., & Huang, J. (2015). Potential role of phytohormones and plant growth-promoting rhizobacteria in abiotic stresses: Consequences for changing environment. Environmental Science and Pollution Research, 22(7), 4907-4921. https://doi.org/10.1007/s11356-014-3754-2
49. Santner, A., Calderon-Villalobos, L. I. A., & Estelle, M. (2009). Plant hormones are versatile chemical regulators of plant growth. Nature Chemical Biology, 5(5), 301-307. https://doi.org/10.1038/nchembio.165
50. Spaepen, S., Vanderleyden, J., & Remans, R. (2007). Indole-3-acetic acid in microbial and microorganism-plant signaling. FEMS Microbiology Reviews, 31(4), 425-448. https://doi.org/10.1111/j.1574-6976.2007.00072.x

51. Glick, B. R. (2012). Plant growth-promoting bacteria: Mechanisms and applications. Scientifica, 2012. https://doi.org/10.6064/2012/963401

52. Werner, T., & Schmülling, T. (2009). Cytokinin action in plant development. Current Opinion in Plant Biology, 12(5), 527-538. https://doi.org/10.1016/j.pbi.2009.07.002

53. Liu, F., Xing, S., Ma, H., Du, Z., & Ma, B. (2013). Cytokinin-producing, plant growth-promoting rhizobacteria that confer resistance to drought stress in Platycladus orientalis container seedlings. Applied Microbiology and Biotechnology, 97(20), 9155-9164. https://doi.org/10.1007/s00253-013-5193-2

54. Arkhipova, T. N., Veselov, S. U., Melentiev, A. I., Martynenko, E. V., & Kudoyarova, G. R. (2005). Ability of bacterium Bacillus subtilis to produce cytokinins and to influence the growth and endogenous hormone content of lettuce plants. Plant and Soil, 272(1), 201-209. https://doi.org/10.1007/s11104-004-5047-x

55. Bottini, R., Cassán, F., & Piccoli, P. (2004). Gibberellin production by bacteria and its involvement in plant growth promotion and yield increase. Applied Microbiology and Biotechnology, 65(5), 497-503. https://doi.org/10.1007/s00253-004-1696-1

56. Khan, A. L., Waqas, M., Kang, S. M., Al-Harrasi, A., Hussain, J., Al-Rawahi, A., Al-Khiziri, S., Ullah, I., Ali, L., Jung, H. Y., & Lee, I. J. (2014). Bacterial endophyte Sphingomonas sp. LK11 produces gibberellins and IAA and promotes tomato plant growth. Journal of Microbiology, 52(8), 689-695. https://doi.org/10.1007/s12275-014-4002-7

57. Bottini, R., Cassán, F., & Piccoli, P. (2004). Gibberellin production by bacteria and its involvement in plant growth promotion and yield increase. Applied Microbiology and Biotechnology, 65(5), 497-503. https://doi.org/10.1007/s00253-004-1696-1

58. Egamberdieva, D. (2009). Alleviation of salt stress by plant growth regulators and IAA producing bacteria in wheat. Acta Physiologiae Plantarum, 31(4), 861-864. https://doi.org/10.1007/s11738-009-0297-0

59. Arkhipova, T. N., Prinsen, E., Veselov, S. U., Martinenko, E. V., Melentiev, A. I., & Kudoyarova, G. R. (2007). Cytokinin producing bacteria enhance plant growth in drying soil. Plant and Soil, 292(1), 305-315. https://doi.org/10.1007/s11104-007-9233-5

60. Waqas, M., Khan, A. L., Kamran, M., Hamayun, M., Kang, S. M., Kim, Y. H., & Lee, I. J. (2012). Endophytic fungi produce gibberellins and indoleacetic acid and promotes host-plant growth during stress. Molecules, 17(9), 10754-10773. https://doi.org/10.3390/molecules170910754

61. Choudhary, D. K., Prakash, A., & Johri, B. N. (2007). Induced systemic resistance (ISR) in plants: Mechanism of action. Indian Journal of Microbiology, 47(4), 289-297. https://doi.org/10.1007/s12088-007-0054-2

62. Van Wees, S. C., Van der Ent, S., & Pieterse, C. M. (2008). Plant immune responses triggered by beneficial microbes. Current Opinion in Plant Biology, 11(4), 443-448. https://doi.org/10.1016/j.pbi.2008.05.005

63. Zamioudis, C., & Pieterse, C. M. (2012). Modulation of host immunity by beneficial microbes. Molecular Plant-Microbe Interactions, 25(2), 139-150. https://doi.org/10.1094/MPMI-06-11-0179

64. Van der Ent, S., Van Wees, S. C., & Pieterse, C. M. (2009). Jasmonate signaling in plant interactions with resistance-inducing beneficial microbes. Phytochemistry, 70(13-14), 1581-1588. https://doi.org/10.1016/j.phytochem.2009.06.009

65. Pozo, M. J., & Azcón-Aguilar, C. (2007). Unraveling mycorrhiza-induced resistance. Current Opinion in Plant Biology, 10(4), 393-398. https://doi.org/10.1016/j.pbi.2007.05.004

66. Conrath, U., Beckers, G. J., Flors, V., García-Agustín, P., Jakab, G., Mauch, F., Newman, M.-A., Pieterse, C. M. J., Poinssot, B., Pozo, M. J., Pugin, A., Schaffrath, U., Ton, J., Wendehenne, D., Zimmerli, L., & Mauch-Mani, B. (2006). Priming: Getting ready for battle. Molecular Plant-Microbe Interactions, 19(10), 1062-1071. https://doi.org/10.1094/MPMI-19-1062

67. Ongena, M., Jourdan, E., Adam, A., Paquot, M., Brans, A., Joris, B., Arpigny, J.-L., & Thonart, P. (2007). Surfactin and fengycin lipopeptides of Bacillus subtilis as elicitors of induced systemic resistance in plants. Environmental Microbiology, 9(4), 1084-1090. https://doi.org/10.1111/j.1462-2920.2006.01202.x

68. Alizadeh, H., Behboudi, K., Ahmadzadeh, M., Javan-Nikkhah, M., Zamioudis, C., Pieterse, C. M. J., & Bakker, P. A. H. M. (2013). Induced systemic resistance in cucumber and Arabidopsis thaliana by the combination of Trichoderma harzianum Tr6 and Pseudomonas sp. Ps14. Biological Control, 65(1), 14-23. https://doi.org/10.1016/j.biocontrol.2013.01.009

69. Ryu, C. M., Farag, M. A., Hu, C. H., Reddy, M. S., Wei, H. X., Paré, P. W., & Kloepper, J. W. (2003). Bacterial volatiles promote growth in Arabidopsis. Proceedings of the National Academy of Sciences, 100(8), 4927-4932. https://doi.org/10.1073/pnas.0730845100

70. Waller, F., Achatz, B., Baltruschat, H., Fodor, J., Becker, K., Fischer, M., Heier, T., Hückelhoven, R., Neumann, C., von Wettstein, D., Franken, P., & Kogel, K. H. (2005). The endophytic fungus Piriformospora indica reprograms barley to salt-stress tolerance, disease resistance, and higher yield. Proceedings of the National Academy of Sciences, 102(38), 13386-13391. https://doi.org/10.1073/pnas.0504423102

71. Owen, D., Williams, A. P., Griffith, G. W., & Withers, P. J. A. (2015). Use of commercial bio-inoculants to increase agricultural production through improved phosphorus acquisition. Applied Soil Ecology, 86, 41-54. https://doi.org/10.1016/j.apsoil.2014.09.012

72. Rahimzadeh, S., & Pirzad, A. (2017). Arbuscular mycorrhizal fungi and Pseudomonas in reduce drought stress damage in flax (Linum usitatissimum L.): A field study. Mycorrhiza, 27(6), 537-552. https://doi.org/10.1007/s00572-017-0775-y

73. Adesemoye, A. O., Torbert, H. A., & Kloepper, J. W. (2009). Plant growth-promoting rhizobacteria allow reduced application rates of chemical fertilizers. Microbial Ecology, 58(4), 921-929. https://doi.org/10.1007/s00248-009-9531-y

74. Gül, A., Özaktan, H., Kıdoğlu, F., & Tüzel, Y. (2013). Rhizobacteria promoted yield of cucumber plants grown in perlite under Fusarium wilt stress. Scientia Horticulturae, 153, 22-25. https://doi.org/10.1016/j.scienta.2013.01.025

75. Berruti, A., Lumini, E., Balestrini, R., & Bianciotto, V. (2016). Arbuscular mycorrhizal fungi as natural biofertilizers: Let's benefit from past successes. Frontiers in Microbiology, 6, 1559. https://doi.org/10.3389/fmicb.2015.01559

76. Engel, R., Szabó, K., Abrankó, L., Rendes, K., Füzy, A., & Takács, T. (2016). Effect of arbuscular mycorrhizal fungi on the growth and polyphenol profile of marjoram, lemon balm, and marigold. Journal of Agricultural and Food Chemistry, 64(19), 3733-3742. https://doi.org/10.1021/acs.jafc.6b00408

77. Boyer, L. R., Brain, P., Xu, X. M., & Jeffries, P. (2015). Inoculation of drought-stressed strawberry with a mixed inoculum of two arbuscular mycorrhizal fungi: Effects on population dynamics of fungal species in roots and consequential plant tolerance to water deficiency. Mycorrhiza, 25(3), 215-227. https://doi.org/10.1007/s00572-014-0603-6

78. Rai, M., Agarkar, G., & Rathod, D. (2014). Multiple applications of endophytic fungi Piriformospora indica in horticultural crops: Current vistas and future prospects. In Microbial Diversity and Biotechnology in Food Security (pp. 533-540). Springer, New Delhi. https://doi.org/10.1007/978-81-322-1801-2_42

79. Shoresh, M., Harman, G. E., & Mastouri, F. (2010). Induced systemic resistance and plant responses to fungal biocontrol agents. Annual review of phytopathology, 48, 21-43. https://doi.org/10.1146/annurev-phyto-073009-114450

80. Harman, G. E., Howell, C. R., Viterbo, A., Chet, I., & Lorito, M. (2004). Trichoderma species—opportunistic, avirulent plant symbionts. Nature Reviews Microbiology, 2(1), 43-56. https://doi.org/10.1038/nrmicro797

81. Glare, T., Caradus, J., Gelernter, W., Jackson, T., Keyhani, N., Köhl, J., Marrone, P., Morin, L., & Stewart, A. (2012). Have biopesticides come of age?. Trends in Biotechnology, 30(5), 250-258. https://doi.org/10.1016/j.tibtech.2012.01.003

82. Zhao, L., Xu, Y., & Lai, X. (2018). Antagonistic endophytic bacteria associated with nodules of soybean (Glycine max L.) and plant growth-promoting properties. Brazilian Journal of Microbiology, 49, 269-278. https://doi.org/10.1016/j.bjm.2017.06.007

83. Cawoy, H., Mariutto, M., Henry, G., Fisher, C., Vasilyeva, N., Thonart, P., Dommes, J., & Ongena, M. (2014). Plant defense stimulation by natural isolates of Bacillus depends on efficient surfactin production. Molecular Plant-Microbe Interactions, 27(2), 87-100. https://doi.org/10.1094/MPMI-09-13-0262-R

84. Vinale, F., Sivasithamparam, K., Ghisalberti, E. L., Marra, R., Woo, S. L., & Lorito, M. (2008). Trichoderma–plant–pathogen interactions. Soil Biology and Biochemistry, 40(1), 1-10. https://doi.org/10.1016/j.soilbio.2007.07.002

85. Hermosa, R., Viterbo, A., Chet, I., & Monte, E. (2012). Plant-beneficial effects of Trichoderma and of its genes. Microbiology, 158 (2), 17-25. https://doi.org/10.1099/mic.0.052274-0

86. Harman, G. E., Howell, C. R., Viterbo, A., Chet, I., & Lorito, M. (2004). Trichoderma species—opportunistic, avirulent plant symbionts. Nature Reviews Microbiology, 2(1), 43-56. https://doi.org/10.1038/nrmicro797

87. Lacey, L. A., Grzywacz, D., Shapiro-Ilan, D. I., Frutos, R., Brownbridge, M., & Goettel, M. S. (2015). Insect pathogens as biological control agents: Back to the future. Journal of Invertebrate Pathology, 132, 1-41. https://doi.org/10.1016/j.jip.2015.07.009

88. Vega, F. E., Goettel, M. S., Blackwell, M., Chandler, D., Jackson, M. A., Keller, S., Koike, M., Maniania, N. K., Monzón, A., Ownley, B. H., Pell, J. K., Rangel, D. E. N., & Roy, H. E. (2009). Fungal entomopathogens: New insights on their ecology. Fungal Ecology, 2(4), 149-159. https://doi.org/10.1016/j.funeco.2009.05.001

89. Sree, K. S., & Varma, A. (2015). Biocontrol of lepidopteran pests: Use of soil microbes and their metabolites. Springer.

90. Chandler, D., Bailey, A. S., Tatchell, G. M., Davidson, G., Greaves, J., & Grant, W. P. (2011). The development, regulation and use of biopesticides for integrated pest management. Philosophical Transactions of the Royal Society B: Biological Sciences, 366(1573), 1987-1998. https://doi.org/10.1098/rstb.2010.0390

91. Stockwell, V. O., & Stack, J. P. (2007). Using Pseudomonas spp. for integrated biological control. Phytopathology, 97(2), 244-249. https://doi.org/10.1094/PHYTO-97-2-0244

92. Niu, D. D., Liu, H. X., Jiang, C. H., Wang, Y. P., Wang, Q. Y., Jin, H. L., & Guo, J. H. (2011). The plant growth-promoting rhizobacterium Bacillus cereus AR156 induces systemic resistance in Arabidopsis thaliana by simultaneously activating salicylate-and jasmonate/ethylene-dependent signaling pathways. Molecular Plant-Microbe Interactions, 24(5), 533-542. https://doi.org/10.1094/MPMI-09-10-0213

93. Liu, K., McInroy, J. A., Hu, C. H., & Kloepper, J. W. (2018). Mixtures of plant-growth-promoting rhizobacteria enhance biological control of multiple plant diseases and plant-growth promotion in the presence of pathogens. Plant Disease, 102(1), 67-72. https://doi.org/10.1094/PDIS-04-17-0478-RE

94. Maketon, M., Apisitsantikul, J., & Siriraweekul, C. (2008). Greenhouse evaluation of Bacillus subtilis AP-01 and Trichoderma harzianum AP-001 in controlling tobacco diseases. Brazilian Journal of Microbiology, 39, 296-300. https://doi.org/10.1590/S1517-83822008000200018

95. Berg, G. (2009). Plant–microbe interactions promoting plant growth and health: perspectives for controlled use of microorganisms in agriculture. Applied Microbiology and Biotechnology, 84(1), 11-18. https://doi.org/10.1007/s00253-009-2092-7

96. Lugtenberg, B., & Kamilova, F. (2009). Plant-growth-promoting rhizobacteria. Annual Review of Microbiology, 63, 541-556. https://doi.org/10.1146/annurev.micro.62.081307.162918

97. Sarma, B. K., Yadav, S. K., Singh, S., & Singh, H. B. (2015). Microbial consortium-mediated plant defense against phytopathogens: Readdressing for enhancing efficacy. Soil Biology and Biochemistry, 87, 25-33. https://doi.org/10.1016/j.soilbio.2015.04.001

98. Bashan, Y., de-Bashan, L. E., Prabhu, S. R., & Hernandez, J. P. (2014). Advances in plant growth-promoting bacterial inoculant technology: Formulations and practical perspectives (1998–2013). Plant and Soil, 378(1), 1-33. https://doi.org/10.1007/s11104-013-1956-x

99. Van Der Heijden, M. G., Bardgett, R. D., & Van Straalen, N. M. (2008). The unseen majority: Soil microbes as drivers of plant diversity and productivity in terrestrial ecosystems. Ecology Letters, 11(3), 296-310. https://doi.org/10.1111/j.1461-0248.2007.01139.x

100. Kaminsky, L. M., Trexler, R. V., Malik, R. J., Hockett, K. L., & Bell, T. H. (2019). The inherent conflicts in developing soil microbial inoculants. Trends in Biotechnology, 37(2), 140-151. https://doi.org/10.1016/j.tibtech.2018.11.011
101. Busby, P. E., Soman, C., Wagner, M. R., Friesen, M. L., Kremer, J., Bennett, A., Morsy, M., Eisen, J. A., Leach, J. E., & Dangl, J. L. (2017). Research priorities for harnessing plant microbiomes in sustainable agriculture. PLoS Biology, 15(3), e2001793. https://doi.org/10.1371/journal.pbio.2001793
102. Mitter, B., Brader, G., Afzal, M., Compant, S., Naveed, M., Trognitz, F., & Sessitsch, A. (2013). Advances in elucidating beneficial interactions between plants, soil, and bacteria. Advances in Agronomy, 121, 381-445. https://doi.org/10.1016/B978-0-12-407685-3.00007-4
103. Parnell, J. J., Berka, R., Young, H. A., Sturino, J. M., Kang, Y., Barnhart, D. M., & DiLeo, M. V. (2016). From the lab to the farm: An industrial perspective of plant beneficial microorganisms. Frontiers in Plant Science, 7, 1110. https://doi.org/10.3389/fpls.2016.01110
104. Arora, N. K., & Mishra, J. (2016). Prospecting the roles of metabolites and additives in future bioformulations for sustainable agriculture. Applied Soil Ecology, 107, 405-407. https://doi.org/10.1016/j.apsoil.2016.05.020
105. Berg, G., Köberl, M., Rybakova, D., Müller, H., Grosch, R., & Smalla, K. (2017). Plant microbial diversity is suggested as the key to future biocontrol and health trends. FEMS Microbiology Ecology, 93(5). https://doi.org/10.1093/femsec/fix050
106. Thomashow, L. S., Kwak, Y. S., & Weller, D. M. (2019). Root-associated microbes in sustainable agriculture: Models, metabolites and mechanisms. Pest Management Science, 75(9), 2360-2367. https://doi.org/10.1002/ps.5406
107. Bender, S. F., Wagg, C., & van der Heijden, M. G. (2016). An underground revolution: Biodiversity and soil ecological engineering for agricultural sustainability. Trends in Ecology & Evolution, 31(6), 440-452. https://doi.org/10.1016/j.tree.2016.02.016
108. Berg, G., Rybakova, D., Grube, M., & Köberl, M. (2016). The plant microbiome explored: Implications for experimental botany. Journal of Experimental Botany, 67(4), 995-1002. https://doi.org/10.1093/jxb/erv466
109. Timmusk, S., Behers, L., Muthoni, J., Muraya, A., & Aronsson, A. C. (2017). Perspectives and challenges of microbial application for crop improvement. Frontiers in Plant Science, 8, 49. https://doi.org/10.3389/fpls.2017.00049
110. Coleman-Derr, D., & Tringe, S. G. (2014). Building the crops of tomorrow: Advantages of symbiont-based approaches to improving abiotic stress tolerance. Frontiers in Microbiology, 5, 283. https://doi.org/10.3389/fmicb.2014.00283
111. Raja, N. (2013). Biopesticides and biofertilizers: Ecofriendly sources for sustainable agriculture. Journal of Biofertilizers & Biopesticides, 4(1), e112. https://doi.org/10.4172/2155-6202.1000e112

CHAPTER - 9

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Role of Nanotechnology in Horticultural Crop Protection and Production

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Abstract

Nanotechnology is an emerging field with immense potential to revolutionize horticultural crop protection and production. Nanomaterials, typically in the size range of 1-100 nm, exhibit unique physicochemical properties that can be harnessed for various applications in horticulture. This chapter provides an in-depth analysis of the current state and future prospects of nanotechnology in horticultural crop protection and production. Nanotechnology-based approaches offer novel solutions for enhancing crop yield, improving nutrient use efficiency, managing pests and diseases, and reducing the environmental footprint of horticulture. Nanofertilizers and nanopesticides enable targeted delivery and controlled release of nutrients and active ingredients, respectively, thereby reducing the required application rates and minimizing off-target effects. Nanomaterials can also be employed for the development of advanced sensors and diagnostic tools for precision horticulture, enabling real-time monitoring of plant health, soil conditions, and environmental parameters. Moreover, nanotechnology can contribute to the development of smart packaging materials for enhanced shelf life and quality of horticultural produce. However, the application of nanotechnology in horticulture also raises concerns regarding the potential risks to human health and the environment. Therefore, a comprehensive understanding of the fate and behavior of nanomaterials in the agroecosystem is crucial for the responsible development and implementation of nanotechnology in horticulture. This chapter discusses the current research trends, challenges, and future perspectives of nanotechnology in horticultural crop protection and production, highlighting the need for interdisciplinary collaboration and stakeholder engagement to realize the full potential of this transformative technology.

Keywords: Nanotechnology, Horticulture, Crop Protection, Precision Agriculture, Nanofertilizers, Nanopesticides

Nanotechnology is an interdisciplinary field that involves the manipulation and application of materials at the nanoscale (1-100 nm) [1]. The unique properties of nanomaterials, such as high surface area to volume ratio, enhanced reactivity, and the ability to cross biological barriers, have opened up new avenues for their application in various sectors, including agriculture and horticulture [2]. Horticulture, which encompasses the cultivation of fruits, vegetables, flowers, and ornamental plants, faces numerous challenges, such as increasing crop productivity, managing pests and diseases, reducing the environmental impact of intensive farming practices, and meeting the growing demand for high-quality and nutritious produce [3]. Nanotechnology offers innovative solutions to address these challenges and improve the sustainability and efficiency of horticultural crop protection and production [4].

Nanomaterials in Horticultural Crop Protection Nanopesticides

Pesticides play a crucial role in protecting crops from pests and diseases. However, conventional pesticides often have low efficacy, require high application rates, and pose risks to human health and the environment due to their non-specific action and off-target effects [5]. Nanopesticides, which are pesticide formulations that contain nanomaterials as active ingredients or carriers, offer a promising alternative to conventional pesticides [6]. Nanopesticides can be designed to have targeted delivery, controlled release, and enhanced stability, thereby reducing the required application rates and minimizing environmental contamination [7].

Table 1. Examples of nanopesticides and their target pests

Nanopesticide	**Target Pest**	**Crop**	**Reference**
Silver nanoparticles	*Fusarium oxysporum*	Tomato	[8]
Copper nanoparticles	*Xanthomonas campestris* pv. *vesicatoria*	Pepper	[9]
Chitosan nanoparticles	*Botrytis cinerea*	Strawberry	[10]
Zinc oxide nanoparticles	*Aspergillus niger*	Grapes	[11]

Silver nanoparticles (AgNPs) have been extensively studied for their antimicrobial properties and have shown promising results in controlling various plant pathogens [8]. For instance, AgNPs have been reported to effectively control *Fusarium oxysporum*, a fungal pathogen that causes wilt disease in tomato plants (Table 1). Similarly, copper nanoparticles (CuNPs) have demonstrated strong antibacterial activity against *Xanthomonas campestris* pv. *vesicatoria*, the causal agent of bacterial spot disease in pepper plants [9]. Chitosan nanoparticles have also been explored as a bio-based and biodegradable alternative to synthetic fungicides for the control of *Botrytis cinerea*, a fungal pathogen that causes gray mold in strawberries [10]. In addition, zinc oxide nanoparticles (ZnONPs) have shown potential in controlling *Aspergillus niger*, a fungal pathogen that causes black mold in grapes [11].

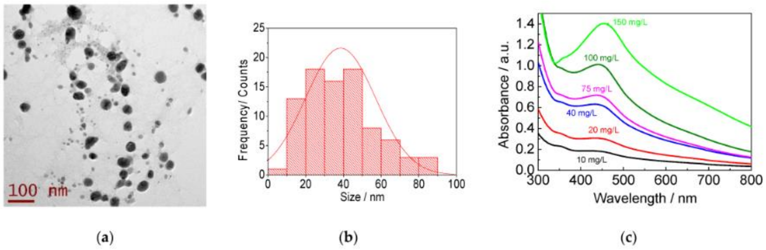

Figure 1. AgNPs inhibiting the growth of Fusarium oxysporum in tomato plants [8]

The efficacy of nanopesticides depends on various factors, such as the type and concentration of the nanomaterial, the target pest or pathogen, and the crop species [12]. Therefore, extensive research is needed to optimize the formulation and application of nanopesticides for specific crop-pest combinations. Moreover, the potential risks associated with the use of nanopesticides, such as their toxicity to non-target organisms and the possibility of developing resistance in target pests, need to be thoroughly investigated before their widespread application in horticulture [13].

Nanoinsecticides

Insect pests cause significant damage to horticultural crops, leading to yield losses and reduced quality of produce. Conventional insecticides often have limited efficacy due to the development of resistance in insect populations and the difficulty in reaching the target sites [14]. Nanoinsecticides, which are insecticide formulations that contain nanomaterials, can overcome these limitations by providing targeted delivery, enhanced penetration, and controlled release of active ingredients [15].

Table 2. Examples of nanoinsecticides and their target insect pests

Nanoinsecticide	**Target Insect Pest**	**Crop**	**Reference**
Neem oil nanoemulsion	*Plutella xylostella*	Cabbage	[16]
Silica nanoparticles	*Tuta absoluta*	Tomato	[17]
Garlic essential oil nanoemulsion	*Aphis gossypii*	Cotton	[18]
Pyrethrins nanoencapsulation	*Tetranychus urticae*	Strawberry	[19]

Neem oil, a botanical insecticide derived from the neem tree (*Azadirachta indica*), has been used for centuries in traditional pest management practices. However, the poor water solubility and rapid degradation of neem oil limit its effectiveness. Nanoencapsulation of neem oil in nanoemulsions has been shown to improve its stability, bioavailability, and insecticidal activity against the diamondback moth (*Plutella xylostella*), a major pest of cabbage (Table 2) [16]. Similarly, silica nanoparticles have been reported to effectively control the tomato leafminer (*Tuta absoluta*), a devastating pest of tomato plants, by causing abrasion and desiccation of the insect cuticle [17].

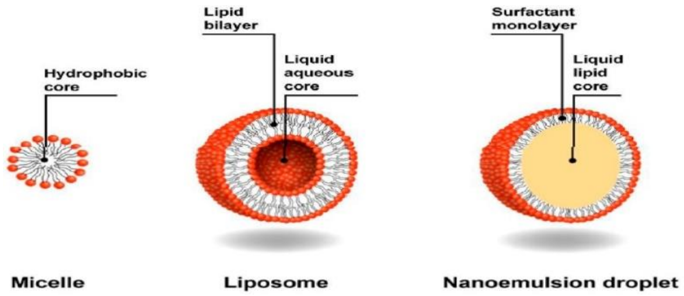

Figure 2. Neem oil nanoemulsion for the control of Plutella xylostella in cabbage [16]

Essential oils, such as garlic essential oil, have also been explored as potential biopesticides due to their insecticidal properties. However, their volatility and rapid evaporation limit their effectiveness in field conditions. Nanoemulsions of garlic essential oil have been developed to improve its stability and persistence, resulting in enhanced control of the cotton aphid (*Aphis gossypii*) [18]. Pyrethrins, natural insecticides derived from chrysanthemum flowers, have been nanoencapsulated to improve their photostability and rain fastness, thereby increasing their efficacy against the two-spotted spider mite (*Tetranychus urticae*) in strawberry plants [19].

The use of nanoinsecticides in horticulture offers several advantages, such as reduced application rates, improved efficacy, and decreased environmental impact. However, the potential risks associated with the use of nanoinsecticides, such as their toxicity to beneficial insects and the possibility of bioaccumulation in the food chain, need to be carefully evaluated [20]. Moreover, the regulatory framework for the registration and commercialization of nanoinsecticides needs to be established to ensure their safe and responsible use in horticultural crop protection [21].

Nanofungicides: Fungal diseases pose a major threat to horticultural crops, causing significant yield losses and reducing the quality of produce. Conventional fungicides often have limited efficacy due to the development of resistance in fungal populations and the difficulty in reaching the target sites [22]. Nanofungicides, which are fungicide formulations that contain nanomaterials, can overcome these limitations by providing targeted delivery, enhanced penetration, and controlled release of active ingredients [23].

Table 3. Examples of nanofungicides and their target fungal diseases

Nanofungicide	Target Fungal Disease	Crop	Reference
Chitosan nanoparticles	Powdery mildew	Cucumber	[24]
Copper oxide nanoparticles	Downy mildew	Grapes	[25]
Zinc oxide nanoparticles	Anthracnose	Chili pepper	[26]
Silver nanoparticles	Gray mold	Tomato	[27]

Chitosan, a natural biopolymer derived from the shells of crustaceans, has been widely explored as a potential nanofungicide due to its antifungal properties and biodegradability. Chitosan nanoparticles have been reported to effectively control powdery mildew, a fungal disease caused by *Sphaerotheca fuliginea*, in cucumber plants (Table 3) [24]. The positive charge of chitosan nanoparticles enables them to adhere to the negatively charged fungal cell walls, disrupting the cell membrane and inhibiting fungal growth [28].

Metal oxide nanoparticles, such as copper oxide (CuO) and zinc oxide (ZnO) nanoparticles, have also shown promising results in controlling various fungal diseases in horticultural crops. CuO nanoparticles have been reported to effectively control downy mildew, a fungal disease caused by *Plasmopara viticola*, in grapevines [25]. The antifungal activity of CuO nanoparticles is attributed to their ability to generate reactive oxygen species (ROS), which damage the fungal cell membranes and disrupt cellular processes [29]. Similarly, ZnO nanoparticles have been shown to control anthracnose, a fungal disease caused by *Colletotrichum capsici*, in chili pepper plants [26]. The antifungal mechanism of ZnO nanoparticles involves the disruption of fungal cell membranes and the inhibition of fungal growth and sporulation [30].

Silver nanoparticles (AgNPs) have also been explored as potential nanofungicides due to their broad-spectrum antifungal activity. AgNPs have been reported to effectively control gray mold, a fungal disease caused by *Botrytis cinerea*, in tomato plants [27]. The antifungal activity of AgNPs is attributed to their ability to release silver ions (Ag^+^), which interact with the thiol groups of fungal proteins, leading to the inactivation of essential enzymes and the disruption of cellular processes [31].

The use of nanofungicides in horticulture offers several advantages, such as reduced application rates, improved efficacy, and decreased environmental impact. However, the potential risks associated with the use of nanofungicides, such as their toxicity to non-target organisms and the possibility of bioaccumulation in the food chain, need to be carefully evaluated [32]. Moreover, the regulatory framework for the registration and commercialization of nanofungicides needs to be established to ensure their safe and responsible use in horticultural crop protection [33].

Nanoherbicides

Weeds compete with crops for nutrients, water, and light, leading to reduced crop yields and quality. Conventional herbicides often have limited efficacy due to the development of resistance in weed populations and the difficulty in reaching the target sites [34]. Nanoherbicides, which are herbicide formulations that contain nanomaterials, can overcome these limitations by providing targeted delivery, enhanced penetration, and controlled release of active ingredients [35].

Paraquat, a widely used herbicide, has been loaded into silica nanoparticles to improve its efficacy against the redroot pigweed (*Amaranthus retroflexus*), a common weed in maize fields (Table 4) [36]. The silica nanoparticles enable the controlled release of paraquat, reducing its leaching and increasing its bioavailability to the target weed [40]. Similarly, glyphosate, another commonly used herbicide, has been encapsulated in chitosan nanoparticles to enhance its activity against the Johnson grass (*Sorghum halepense*), a problematic weed in soybean fields [37]. The chitosan nanoparticles improve the adhesion and penetration of glyphosate into the weed leaves, resulting in higher herbicidal efficacy [41].

Nanoemulsions and nanocapsules have also been explored as potential carriers for herbicides to improve their efficacy and reduce their environmental impact. For instance, 2,4-dichlorophenoxyacetic acid (2,4-D), a selective herbicide, has been formulated as a nanoemulsion to control the lambsquarters (*Chenopodium album*), a common weed in wheat fields [38]. The nanoemulsion formulation enhances the penetration and translocation of 2,4-D within the weed plants, resulting in higher herbicidal activity [42]. Atrazine, another commonly used herbicide, has been encapsulated in polymeric nanocapsules to control the barnyard grass (*Echinochloa crus-galli*), a major weed in rice fields [39]. The nanocapsules enable the controlled release of atrazine, reducing its leaching and increasing its persistence in the soil [43].

Table 4. Examples of nanoherbicides and their target weeds

Nanoherbicide	Target Weed	Crop	Reference
Paraquat-loaded silica nanoparticles	*Amaranthus retroflexus*	Maize	[36]
Glyphosate-loaded chitosan nanoparticles	*Sorghum halepense*	Soybean	[37]
2,4-D-loaded nanoemulsion	*Chenopodium album*	Wheat	[38]
Atrazine-loaded nanocapsules	*Echinochloa crus-galli*	Rice	[39]

The use of nanoherbicides in horticulture offers several advantages, such as reduced application rates, improved efficacy, and decreased environmental impact. However, the potential risks associated with the use of nanoherbicides, such as their toxicity to non-target plants and the possibility of bioaccumulation in the food chain, need to be carefully evaluated [44]. Moreover, the regulatory framework for the registration and commercialization of nanoherbicides needs to be established to ensure their safe and responsible use in horticultural crop protection [45].

Nanomaterials in Horticultural Crop Production Nanofertilizers

Fertilizers play a crucial role in providing essential nutrients to crops for their growth and development. However, conventional fertilizers often have low nutrient use efficiency (NUE) due to their rapid release, leaching, and volatilization losses [46]. Nanofertilizers, which are fertilizer formulations that contain nanomaterials, can overcome these limitations by providing targeted delivery, controlled release, and enhanced nutrient uptake by plants [47].

Table 5. Examples of nanofertilizers and their target crops

Nanofertilizer	Target Nutrient	Crop	Reference
Chitosan-NPK nanoparticles	Nitrogen, Phosphorus, Potassium	Tomato	[48]
Zinc oxide nanoparticles	Zinc	Cucumber	[49]
Iron oxide nanoparticles	Iron	Spinach	[50]
Calcium phosphate nanoparticles	Calcium, Phosphorus	Strawberry	[51]

Chitosan-based nanoparticles have been explored as potential carriers for NPK fertilizers to improve their NUE and crop productivity. For instance, chitosan-NPK nanoparticles have been reported to enhance the growth and yield of tomato plants by providing a slow and sustained release of nutrients (Table 5) [48]. The positive charge of chitosan nanoparticles enables them to adhere to the negatively charged plant roots, facilitating the uptake of nutrients by the plants [52].

Metal oxide nanoparticles, such as zinc oxide (ZnO) and iron oxide (Fe_3O_4) nanoparticles, have also been explored as potential nanofertilizers to address micronutrient deficiencies in crops. ZnO nanoparticles have been reported to enhance the growth and yield of cucumber plants by improving the uptake and utilization of zinc [49]. Similarly, Fe_3O_4 nanoparticles have been shown to alleviate iron deficiency in spinach plants, resulting in improved growth and nutritional quality [50].

Calcium phosphate nanoparticles have been synthesized as a potential nanofertilizer to provide calcium and phosphorus to crops. For instance, calcium phosphate nanoparticles have been reported to enhance the growth and yield of strawberry plants by improving the uptake and utilization of calcium and phosphorus [51]. The small size and high surface area of calcium phosphate nanoparticles enable them to penetrate the plant roots and release nutrients in a controlled manner [53].

The use of nanofertilizers in horticulture offers several advantages, such as improved NUE, reduced environmental impact, and enhanced crop productivity. However, the potential risks associated with the use of nanofertilizers, such as their toxicity to plants and soil microorganisms, need to be carefully evaluated [54]. Moreover, the regulatory framework for the registration and commercialization of nanofertilizers needs to be established to ensure their safe and responsible use in horticultural crop production [55].

Nanocarriers for Plant Growth Regulators

Plant growth regulators (PGRs) are natural or synthetic compounds that influence the growth and development of plants. PGRs are widely used in horticulture to regulate various processes, such as seed germination, root growth, flowering, fruit ripening, and stress tolerance [56]. However, the effectiveness of PGRs is often limited by their rapid degradation, poor uptake, and non-specific distribution within plants [57]. Nanocarriers, such as nanoparticles and nanoemulsions, can be used to improve the stability, bioavailability, and targeted delivery of PGRs [58].

Table 6. Examples of nanocarriers for plant growth regulators

Nanocarrier	**Plant Growth Regulator**	**Crop**	**Reference**
Chitosan nanoparticles	Gibberellic acid	Rice	[59]
PLGA nanoparticles	Indole-3-acetic acid	Arabidopsis	[60]
Nanoemulsion	6-Benzylaminopurine	Cucumber	[61]
Liposomes	Abscisic acid	Tomato	[62]

Chitosan nanoparticles have been used as a carrier for gibberellic acid (GA), a PGR that promotes stem elongation and seed germination. The encapsulation of GA in chitosan nanoparticles has been reported to enhance its stability and bioavailability, resulting in improved seed germination and seedling growth in rice (Table 6) [59]. Similarly, poly(lactic-co-glycolic acid) (PLGA) nanoparticles have been used to encapsulate indole-3-acetic acid (IAA), a natural auxin that regulates root growth and development. The PLGA-IAA nanoparticles have been shown to promote root hair formation and elongation in Arabidopsis plants [60].

Nanoemulsions have been explored as potential carriers for PGRs to improve their stability and uptake by plants. For instance, a nanoemulsion formulation of 6-benzylaminopurine (BAP), a synthetic cytokinin that promotes cell division and shoot formation, has been developed to enhance its efficacy in cucumber plants [61]. The nanoemulsion formulation improves the penetration and translocation of BAP within the plant tissues, resulting in higher shoot regeneration and elongation [63].

Liposomes, which are spherical vesicles composed of lipid bilayers, have also been used as carriers for PGRs. Liposome-encapsulated abscisic acid (ABA), a PGR that regulates stomatal closure and stress responses, has been reported to enhance the drought tolerance of tomato plants [62]. The liposomal formulation protects ABA from degradation and enables its gradual release, resulting in prolonged stomatal closure and reduced water loss under drought stress [64].

The use of nanocarriers for PGRs in horticulture offers several advantages, such as improved stability, bioavailability, and targeted delivery. However, the potential risks associated with the use of nanocarriers, such as their toxicity to plants and the environment, need to be carefully evaluated [65]. Moreover, the regulatory framework for the registration and commercialization of nano-enabled PGR formulations needs to be established to ensure their safe and responsible use in horticultural crop production [66].

Nanosensors for Precision Horticulture: Precision horticulture involves the use of advanced technologies, such as sensors, imaging systems, and data analytics, to optimize crop management practices based on spatial and temporal variability within a field [67]. Nanosensors, which are sensors that utilize nanomaterials or nanostructures, offer unique advantages for precision horticulture due to their high sensitivity, selectivity, and miniaturization [68].

Table 7. Examples of nanosensors for precision horticulture

Nanosensor	Target Analyte	Application	Reference
Carbon nanotube-based sensor	Nitrate	Nutrient management	[69]
Gold nanoparticle-based sensor	Pesticides	Food safety	[70]
Quantum dot-based sensor	pH	Soil health	[71]
Graphene-based sensor	Ethylene	Fruit ripening	[72]

Carbon nanotubes (CNTs) have been used as sensing elements for the detection of nitrate, a key nutrient for plant growth. CNT-based sensors have been developed to monitor nitrate levels in soil and water, enabling precision nutrient management in horticultural crops [69]. The high surface area and electrical conductivity of CNTs make them ideal for the fabrication of sensitive and selective nitrate sensors [73].

Gold nanoparticles (AuNPs) have been explored as sensing elements for the detection of pesticides in food products. AuNP-based colorimetric sensors have been developed to detect organophosphate and carbamate pesticides in fruits and vegetables, ensuring food safety and quality [70]. The unique optical properties of AuNPs, such as their strong surface plasmon resonance, make them suitable for the development of simple and rapid pesticide sensors [74].

Quantum dots (QDs), which are semiconductor nanocrystals, have been used as fluorescent probes for the detection of pH in soil. QD-based sensors have been developed to monitor soil pH in real-time, enabling precision management of soil health in horticultural crops [71]. The pH-dependent fluorescence emission of QDs makes them ideal for the fabrication of sensitive and reversible pH sensors [75].

Graphene, a two-dimensional nanomaterial, has been explored as a sensing element for the detection of ethylene, a plant hormone that regulates fruit ripening. Graphene-based sensors have been developed to monitor ethylene levels in storage facilities, enabling precise control of fruit ripening and quality [72]. The high surface area and electrical conductivity of graphene make it suitable for the development of sensitive and selective ethylene sensors [76].

The use of nanosensors in precision horticulture offers several advantages, such as real-time monitoring, high spatial resolution, and early detection of stress or disease. However, the potential risks associated with the use of nanosensors, such as their toxicity to plants and the environment, need to be carefully evaluated [77]. Moreover, the integration of nanosensors with other precision horticulture technologies, such as wireless sensor networks and decision support systems, is essential for their effective implementation in horticultural crop production [78].

Nanomaterials for Post-Harvest Management: Post-harvest losses are a major challenge in horticulture, with up to 50% of fruits and vegetables being lost or wasted between harvest and consumption [79]. Nanomaterials have been explored as potential tools for post-harvest management of horticultural crops, including preservation, packaging, and quality monitoring [80].

Table 8. Examples of nanomaterials for post-harvest management

Nanomaterial	Application	Crop	Reference
Silver nanoparticles	Antimicrobial packaging	Tomato	[81]
Chitosan nanoparticles	Edible coating	Strawberry	[82]
Silica nanoparticles	Ethylene scavenger	Apple	[83]
Nanoclay	Moisture absorber	Mushroom	[84]

Silver nanoparticles (AgNPs) have been incorporated into packaging materials to provide antimicrobial properties and extend the shelf life of horticultural produce. For instance, AgNP-coated polyethylene films have been developed to reduce the microbial growth and decay of tomatoes during storage [81]. The gradual release of silver ions from the AgNPs inhibits the growth of spoilage microorganisms, such as bacteria and fungi, on the surface of the tomatoes [85].

Chitosan nanoparticles have been explored as an edible coating material to extend the shelf life and maintain the quality of fruits. For instance, a chitosan nanoparticle-based coating has been developed to preserve the quality and reduce the decay of strawberries during storage [82]. The chitosan nanoparticles form a protective barrier on the surface of the strawberries, reducing moisture loss and inhibiting microbial growth [86].

Silica nanoparticles have been used as ethylene scavengers to delay the ripening and extend the shelf life of climacteric fruits, such as apples. Silica nanoparticles coated with potassium permanganate ($KMnO_4$) have been developed to absorb ethylene, a plant hormone that accelerates fruit ripening, in storage environments [83]. The high surface area and porosity of silica nanoparticles enable them to effectively scavenge ethylene, reducing its concentration in the storage atmosphere and delaying fruit ripening [87].

Nanoclays, such as montmorillonite, have been incorporated into packaging materials as moisture absorbers to extend the shelf life of moisture-sensitive produce, such as mushrooms. Nanoclay-based packaging films have been developed to absorb excess moisture and reduce the condensation within the package, preventing the growth of spoilage microorganisms [84]. The high surface area and water absorption capacity of nanoclays make them suitable for the development of moisture-absorbing packaging materials [88].

The use of nanomaterials in post-harvest management of horticultural crops offers several advantages, such as extended shelf life, reduced waste, and improved food safety. However, the potential risks associated with the use of nanomaterials in food contact applications, such as their migration into food and their toxicity to humans, need to be carefully evaluated [89]. Moreover, the regulatory framework for the use of nanomaterials in food packaging and preservation needs to be established to ensure their safe and responsible application in the food industry [90].

Challenges and Future Perspectives

Despite the immense potential of nanotechnology in horticultural crop protection and production, several challenges need to be addressed for its widespread adoption and commercialization. One of the major challenges is the lack of standardized methods for the synthesis, characterization, and safety assessment of nanomaterials [91]. The development of reliable and reproducible methods for the production of nanomaterials with desired properties is essential for their consistent performance in agricultural applications [92].

Another challenge is the limited understanding of the fate and behavior of nanomaterials in the environment, particularly in complex agricultural systems

[93]. The potential risks associated with the unintentional release of nanomaterials into the environment, such as their persistence, bioaccumulation, and toxicity to non-target organisms, need to be thoroughly investigated [94]. Long-term studies on the environmental impact of nanomaterials in real-world agricultural settings are essential to ensure their safe and sustainable use [95].

The regulatory framework for the registration and commercialization of nano-enabled agricultural products is still in its nascent stage, hindering their widespread adoption [96]. The development of appropriate regulations and guidelines for the safety assessment, labeling, and monitoring of nano-enabled agricultural products is crucial to ensure their responsible use and public acceptance [97]. Collaborative efforts among researchers, industry, policymakers, and other stakeholders are necessary to address the regulatory challenges and facilitate the translation of nanotechnology from research to practical applications in horticulture [98].

The social acceptance of nanotechnology in food and agriculture is another critical factor that influences its adoption and commercialization [99]. Public perception and understanding of the benefits and risks associated with the use of nanomaterials in horticultural crop protection and production are essential for their successful implementation [100]. Effective communication and engagement with the public, including transparent and science-based risk assessment and risk communication, are necessary to build trust and acceptance of nano-enabled agricultural products [101].

Table 9. Future research directions in nanotechnology for horticultural crop protection and production

Research Area	Potential Applications	Reference
Smart nanopesticides	Targeted delivery, controlled release, and enhanced efficacy of pesticides	[102]
Nano-enabled seed treatments	Seed priming, pest protection, and nutrient delivery	[103]
Nanocarriers for plant vaccines	Protection against viral diseases	[104]
Nanosensors for plant health monitoring	Early detection of biotic and abiotic stresses	[105]
Nanomaterials for water treatment	Removal of contaminants and pathogens from irrigation water	[106]

Looking forward, there are several promising research directions in nanotechnology for horticultural crop protection and production (Table 9). The development of smart nanopesticides that can respond to specific stimuli, such as pH, temperature, or light, and release the active ingredients only when and where needed, can significantly improve the efficiency and sustainability of pest management [102]. Nano-enabled seed treatments, such as seed coating with nanomaterials, can enhance seed germination, seedling growth, and pest protection, and provide a viable alternative to conventional seed treatment methods [103].

Nanocarriers, such as virus-like particles and lipid nanoparticles, can be used to deliver plant vaccines, providing protection against viral diseases in horticultural crops [104]. Nanosensors that can detect plant pathogens, pests, and abiotic stresses at an early stage can enable timely and targeted interventions, reducing crop losses and improving resource use efficiency [105]. Nanomaterials, such as nanomembranes and photocatalytic nanoparticles, can be used for water treatment, removing contaminants and pathogens from irrigation water and ensuring the safety and quality of horticultural produce [106].

Conclusion

Nanotechnology offers immense potential for revolutionizing horticultural crop protection and production. Nanomaterials, such as nanopesticides, nanofertilizers, and nanocarriers, can provide targeted delivery, controlled release, and enhanced efficacy of active ingredients, reducing the environmental impact and improving the sustainability of horticultural practices. Nanosensors and nanotechnology-based tools can enable precision horticulture, allowing for real-time monitoring and management of crops based on spatial and temporal variability. Nanomaterials can also be used for post-harvest management of horticultural produce, extending shelf life, reducing waste, and ensuring food safety.

However, the successful implementation of nanotechnology in horticulture requires addressing several challenges, including the standardization of methods for nanomaterial synthesis and characterization, the assessment of environmental and human health risks, the development of appropriate regulations and guidelines, and the social acceptance of nano-enabled agricultural products. Collaborative efforts among researchers, industry, policymakers, and other stakeholders are necessary to overcome these challenges and realize the full potential of nanotechnology in horticultural crop protection and production.

Future research directions in nanotechnology for horticulture include the development of smart nanopesticides, nano-enabled seed treatments, nanocarriers for plant vaccines, nanosensors for plant health monitoring, and nanomaterials for water treatment. These innovations can contribute to the development of a sustainable and resilient horticultural sector, ensuring food security and quality for a growing global population.

References

1. [1] Fraceto, L. F., Grillo, R., de Medeiros, G. A., Scognamiglio, V., Rea, G., & Bartolucci, C. (2016). Nanotechnology in agriculture: Which innovation potential does it have? *Frontiers in Environmental Science*, 4, 20. https://doi.org/10.3389/fenvs.2016.00020
2. [2] Prasad, R., Bhattacharyya, A., & Nguyen, Q. D. (2017). Nanotechnology in sustainable agriculture: Recent developments, challenges, and perspectives. *Frontiers in Microbiology*, 8, 1014. https://doi.org/10.3389/fmicb.2017.01014
3. [3] Shang, Y., Hasan, M. K., Ahammed, G. J., Li, M., Yin, H., & Zhou, J. (2019). Applications of nanotechnology in plant growth and crop protection: A review. *Molecules*, 24(14), 2558. https://doi.org/10.3390/molecules24142558
4. [4] Chhipa, H. (2019). Nanofertilizers and nanopesticides for agriculture. *Environmental Chemistry Letters*, 17(2), 929-946. https://doi.org/10.1007/s10311-018-00828-0
5. [5] Kah, M., Kookana, R. S., Gogos, A., & Bucheli, T. D. (2018). A critical evaluation of nanopesticides and nanofertilizers against their conventional analogues. *Nature Nanotechnology*, 13(8), 677-684. https://doi.org/10.1038/s41565-018-0131-1
6. [6] Athanassiou, C. G., Kavallieratos, N. G., Benelli, G., Losic, D., Usha Rani, P., & Desneux, N. (2018). Nanoparticles for pest control: Current status and future perspectives. *Journal of Pest Science*, 91(1), 1-15. https://doi.org/10.1007/s10340-017-0898-0

7. [7] Khot, L. R., Sankaran, S., Maja, J. M., Ehsani, R., & Schuster, E. W. (2012). Applications of nanomaterials in agricultural production and crop protection: A review. *Crop Protection*, 35, 64-70. https://doi.org/10.1016/j.cropro.2012.01.007
8. [8] Elmer, W. H., & White, J. C. (2016). The use of metallic oxide nanoparticles to enhance growth of tomatoes and eggplants in disease infested soil or soilless medium. *Environmental Science: Nano*, 3(5), 1072-1079. https://doi.org/10.1039/C6EN00146G
9. [9] Strayer-Scherer, A., Liao, Y. Y., Young, M., Ritchie, L., Vallad, G. E., Santra, S., Freeman, J. H., Clark, D., Jones, J. B., & Paret, M. L. (2018). Advanced copper composites against copper-tolerant *Xanthomonas perforans* and tomato bacterial spot. *Phytopathology*, 108(2), 196-205. https://doi.org/10.1094/PHYTO-06-17-0221-R
10. [10] Fortunati, E., Mazzaglia, A., & Balestra, G. M. (2019). Sustainable control strategies for plant protection and food packaging sectors by natural substances and novel nanotechnological approaches. *Journal of the Science of Food and Agriculture*, 99(3), 986-1000. https://doi.org/10.1002/jsfa.9341
11. [11] Saharan, V., Kumaraswamy, R. V., Choudhary, R. C., Kumari, S., Pal, A., Raliya, R., & Biswas, P. (2016). Cu-chitosan nanoparticle mediated sustainable approach to enhance seedling growth in maize by mobilizing reserved food. *Journal of Agricultural and Food Chemistry*, 64(31), 6148-6155. https://doi.org/10.1021/acs.jafc.6b02239
12. [12] Zhao, X., Cui, H., Wang, Y., Sun, C., Cui, B., & Zeng, Z. (2018). Development strategies and prospects of nano-based smart pesticide formulation. *Journal of Agricultural and Food Chemistry*, 66(26), 6504-6512. https://doi.org/10.1021/acs.jafc.7b02004
13. [13] Grillo, R., Fraceto, L. F., & Amorim, M. J. B. (2020). Ecotoxicological risk assessment of nanopesticides in the environment. In J. C. White & A. Meli (Eds.), *Nanopesticides: From Research and Development to Mechanisms of Action and Sustainable Use in Agriculture* (pp. 223-244). Springer International Publishing. https://doi.org/10.1007/978-3-030-44873-8_12
14. [14] Duhan, J. S., Kumar, R., Kumar, N., Kaur, P., Nehra, K., & Duhan, S. (2017). Nanotechnology: The new perspective in precision agriculture. *Biotechnology Reports*, 15, 11-23. https://doi.org/10.1016/j.btre.2017.03.002
15. [15] Kah, M., & Hofmann, T. (2014). Nanopesticide research: Current trends and future priorities. *Environment International*, 63, 224-235. https://doi.org/10.1016/j.envint.2013.11.015
16. [16] Ali, M. A., Rehman, I., Iqbal, A., Din, S., Rao, A. Q., Latif, A., Samiullah, T. R., Azam, S., & Husnain, T. (2014). Nanotechnology, a new frontier in agriculture. *Advancements in Life Sciences*, 1(3), 129-138. http://www.als-journal.com/arsci-14-45/
17. [17] Iavicoli, I., Leso, V., Beezhold, D. H., & Shvedova, A. A. (2017). Nanotechnology in agriculture: Opportunities, toxicological implications, and occupational risks. *Toxicology and Applied Pharmacology*, 329, 96-111. https://doi.org/10.1016/j.taap.2017.05.025
18. [18] Bhagat, Y., Gangadhara, K., Rabinal, C., Chaudhari, G., & Ugale, P. (2015). Nanotechnology in agriculture: A review. *Journal of Pure and Applied Microbiology*, 9(1), 737-747. https://microbiologyjournal.org/nanotechnology-in-agriculture-a-review/
19. [19] Servin, A. D., & White, J. C. (2016). Nanotechnology in agriculture: Next steps for understanding engineered nanoparticle exposure and risk. *NanoImpact*, 1, 9-12. https://doi.org/10.1016/j.impact.2015.12.002
20. [20] Kumar, S., Nehra, M., Dilbaghi, N., Marrazza, G., Hassan, A. A., & Kim, K.-H. (2019). Nano-based smart pesticide formulations: Emerging opportunities for agriculture. *Journal of Controlled Release*, 294, 131-153. https://doi.org/10.1016/j.jconrel.2018.12.012
21. [21] Kookana, R. S., Boxall, A. B. A., Reeves, P. T., Ashauer, R., Beulke, S., Chaudhry, Q., Cornelis, G., Fernandes, T. F., Gan, J., Kah, M., Lynch, I., Ranville, J., Sinclair, C., Spurgeon, D., Tiede, K., & Van den Brink, P. J. (2014). Nanopesticides: Guiding principles for regulatory evaluation of environmental risks. *Journal of Agricultural and Food Chemistry*, 62(19), 4227-4240. https://doi.org/10.1021/jf500232f
22. [22] Hayles, J., Johnson, L., Worthley, C., & Losic, D. (2017). Nanopesticides: A review of current research and perspectives. In D. Guo, W. Xie, & J. Luo (Eds.), *New Pesticides and Soil Sensors* (pp. 193-225). Academic Press. https://doi.org/10.1016/B978-0-12-804299-1.00006-0

23. [23] Wang, X., Yang, X., Chen, S., Li, Q., Wang, W., Hou, C., Gao, X., Wang, L., & Wang, S. (2016). Zinc oxide nanoparticles as a novel class of antifungal agents: Current advances and future perspectives. *Journal of Agricultural and Food Chemistry*, 64(43), 7881-7887. https://doi.org/10.1021/acs.jafc.6b03010
24. [24] Lade, B. D., Gogle, D. P., & Nandeshwar, S. B. (2017). Nano bio pesticide to constraint plant destructive pests. *Journal of Nanomedicine Research*, 6(3), 00158. https://doi.org/10.15406/jnmr.2017.06.00158
25. [25] Elmer, W., De La Torre-Roche, R., Pagano, L., Majumdar, S., Zuverza-Mena, N., Dimkpa, C., Gardea-Torresdey, J., & White, J. C. (2018). Effect of metalloid and metal oxide nanoparticles on *Fusarium* wilt of watermelon. *Plant Disease*, 102(7), 1394-1401. https://doi.org/10.1094/PDIS-10-17-1621-RE
26. [26] Chaudhry, Q., Scotter, M., Blackburn, J., Ross, B., Boxall, A., Castle, L., Aitken, R., & Watkins, R. (2008). Applications and implications of nanotechnologies for the food sector. *Food Additives & Contaminants: Part A*, 25(3), 241-258. https://doi.org/10.1080/02652030701744538
27. [27] Elizabath, A., Babychan, M., Mathew, A. M., Syriac, G., & Shankar, S. S. (2017). Application of nanotechnology in agriculture. *Journal of Nanomedicine & Biotherapeutic Discovery*, 7(2), 1000151. https://doi.org/10.4172/2155-983X.1000151
28. [28] Parisi, C., Vigani, M., & Rodríguez-Cerezo, E. (2015). Agricultural nanotechnologies: What are the current possibilities? *Nano Today*, 10(2), 124-127. https://doi.org/10.1016/j.nantod.2014.09.009
29. [29] Mittal, D., Kaur, G., Singh, P., Yadav, K., & Ali, S. A. (2020). Nanoparticle-based sustainable agriculture and food science: Recent advances and future outlook. *Frontiers in Nanotechnology*, 2, 10. https://doi.org/10.3389/fnano.2020.00010
30. [30] Fraceto, L. F., Grillo, R., de Lima, R., Oliveira, H. C., Campos, E. V. R., & Ávila, D. S. (2018). Nanopesticides and nanofertilizers: Emerging contaminants or opportunities for risk mitigation? *Frontiers in Chemistry*, 6, 360. https://doi.org/10.3389/fchem.2018.00360
31. [31] Dimkpa, C. O., & Bindraban, P. S. (2018). Nanofertilizers: New products for the industry? *Journal of Agricultural and Food Chemistry*, 66(26), 6462-6473. https://doi.org/10.1021/acs.jafc.7b02150
32. [32] Achari, G. A., & Kowshik, M. (2018). Recent developments on nanotechnology in agriculture: Plant mineral nutrition, health, and interactions with soil microflora. *Journal of Agricultural and Food Chemistry*, 66(33), 8647-8661. https://doi.org/10.1021/acs.jafc.8b00691
33. [33] Kah, M. (2015). Nanopesticides and nanofertilizers: Emerging contaminants or opportunities for risk mitigation? *Frontiers in Chemistry*, 3, 64. https://doi.org/10.3389/fchem.2015.00064
34. [34] Chhipa, H. (2017). Nanofertilizers and nanopesticides for agriculture. *Environmental Chemistry Letters*, 15(1), 15-22. https://doi.org/10.1007/s10311-016-0600-4
35. [35] Raliya, R., Saharan, V., Dimkpa, C., & Biswas, P. (2018). Nanofertilizer for precision and sustainable agriculture: Current state and future perspectives. *Journal of Agricultural and Food Chemistry*, 66(26), 6487-6503. https://doi.org/10.1021/acs.jafc.7b02178
36. [36] Gogos, A., Knauer, K., & Bucheli, T. D. (2012). Nanomaterials in plant protection and fertilization: Current state, foreseen applications, and research priorities. *Journal of Agricultural and Food Chemistry*, 60(39), 9781-9792. https://doi.org/10.1021/jf302154y
37. [37] Campos, E. V. R., Proença, P. L. F., Oliveira, J. L., Bakshi, M., Abhilash, P. C., & Fraceto, L. F. (2019). Use of botanical insecticides for sustainable agriculture: Future perspectives. *Ecological Indicators*, 105, 483-495. https://doi.org/10.1016/j.ecolind.2018.04.038
38. [38] Ghormade, V., Deshpande, M. V., & Paknikar, K. M. (2011). Perspectives for nano-biotechnology enabled protection and nutrition of plants. *Biotechnology Advances*, 29(6), 792-803. https://doi.org/10.1016/j.biotechadv.2011.06.007
39. [39] Vishwakarma, K., Shweta, Upadhyay, N., Singh, J., Liu, S., Singh, V. P., Prasad, S. M., Chauhan, D. K., Tripathi, D. K., & Sharma, S. (2017). Differential phytotoxic impact of plant

mediated silver nanoparticles (AgNPs) and silver nitrate ($AgNO_3$) on *Brassica* sp. *Frontiers in Plant Science*, 8, 1501. https://doi.org/10.3389/fpls.2017.01501

40. [40] Rastogi, A., Zivcak, M., Sytar, O., Kalaji, H. M., He, X., Mbarki, S., & Brestic, M. (2017). Impact of metal and metal oxide nanoparticles on plant: A critical review. *Frontiers in Chemistry*, 5, 78. https://doi.org/10.3389/fchem.2017.00078
41. [41] Surega, R., & Selvaraj, V. (2020). A review on the application of nanomaterials in the food industry: Food additives, antimicrobial agents, and food packaging. *Journal of Nanomaterials*, 2020, 8214819. https://doi.org/10.1155/2020/8214819
42. [42] Valizadeh, A., Shirzad, M., Pourmadadi, M., Faghih-Mirzaei, E., & Karimi, M. (2021). Nanotechnology in food science: Advanced packaging techniques, nanomaterial-mediated nutrient delivery, and nanosensors. *Food Science & Nutrition*, 9(8), 4155-4165. https://doi.org/10.1002/fsn3.2388
43. [43] Siddiqui, M. H., Al-Whaibi, M. H., & Mohammad, F. (Eds.). (2015). *Nanotechnology and Plant Sciences: Nanoparticles and Their Impact on Plants*. Springer International Publishing. https://doi.org/10.1007/978-3-319-14502-0
44. [44] Rai, M., & Ingle, A. (2012). Role of nanotechnology in agriculture with special reference to management of insect pests. *Applied Microbiology and Biotechnology*, 94(2), 287-293. https://doi.org/10.1007/s00253-012-3969-4
45. [45] Prasad, R., Kumar, V., & Prasad, K. S. (2014). Nanotechnology in sustainable agriculture: Present concerns and future aspects. *African Journal of Biotechnology*, 13(6), 705-713. https://doi.org/10.5897/AJBX2013.13554
46. [46] Nair, R., Varghese, S. H., Nair, B. G., Maekawa, T., Yoshida, Y., & Kumar, D. S. (2010). Nanoparticulate material delivery to plants. *Plant Science*, 179(3), 154-163. https://doi.org/10.1016/j.plantsci.2010.04.012
47. [47] Mastronardi, E., Tsae, P., Zhang, X., Monreal, C., & DeRosa, M. C. (2015). Strategic role of nanotechnology in fertilizers: Potential and limitations. In D. L. Sparks (Ed.), *Advances in Agronomy* (Vol. 130, pp. 181-241). Academic Press. https://doi.org/10.1016/bs.agron.2014.11.004
48. [48] Corradini, E., de Moura, M. R., & Mattoso, L. H. C. (2010). A preliminary study of the incorparation of NPK fertilizer into chitosan nanoparticles. *Express Polymer Letters*, 4(8), 509-515. https://doi.org/10.3144/expresspolymlett.2010.64
49. [49] Tarafdar, J. C., Raliya, R., Mahawar, H., & Rathore, I. (2014). Development of zinc nanofertilizer to enhance crop production in pearl millet (*Pennisetum americanum*). *Agricultural Research*, 3(3), 257-262. https://doi.org/10.1007/s40003-014-0113-y
50. [50] Delfani, M., Firouzabadi, M. B., Farrokhi, N., & Makarian, H. (2014). Some physiological responses of black-eyed pea to iron and magnesium nanofertilizers. *Communications in Soil Science and Plant Analysis*, 45(4), 530-540. https://doi.org/10.1080/00103624.2013.863911
51. [51] Liu, R., & Lal, R. (2014). Synthetic apatite nanoparticles as a phosphorus fertilizer for soybean (*Glycine max*). *Scientific Reports*, 4, 5686. https://doi.org/10.1038/srep05686
52. [52] Malerba, M., & Cerana, R. (2016). Chitosan effects on plant systems. *International Journal of Molecular Sciences*, 17(7), 996. https://doi.org/10.3390/ijms17070996
53. [53] Doğaroğlu, Z. G., & Köleli, N. (2017). TiO_2 and ZnO nanoparticles as novel antimicrobial additives for food packaging applications. *Food Packaging and Shelf Life*, 14, 57-62. https://doi.org/10.1016/j.fpsl.2017.08.004
54. [54] Dasgupta, N., Ranjan, S., Mundekkad, D., Ramalingam, C., Shanker, R., & Kumar, A. (2015). Nanotechnology in agro-food: From field to plate. *Food Research International*, 69, 381-400. https://doi.org/10.1016/j.foodres.2015.01.005
55. [55] Peters, R. J. B., Bouwmeester, H., Gottardo, S., Amenta, V., Arena, M., Brandhoff, P., Marvin, H. J. P., Mech, A., Moniz, F. B., Pesudo, L. Q., Rauscher, H., Schoonjans, R., Undas, A. K., Vettori, M. V., Weigel, S., & Aschberger, K. (2016). Nanomaterials for products and application in agriculture, feed and food. *Trends in Food Science & Technology*, 54, 155-164. https://doi.org/10.1016/j.tifs.2016.06.008
56. [56] Sarlak, N., Taherifar, A., & Salehi, F. (2017). Synthesis of nanopesticides by encapsulating pesticide nanoparticles using functionalized carbon nanotubes and application of

new nanocomposite for plant disease treatment. *Journal of Agricultural and Food Chemistry*, 65(23), 4833-4838. https://doi.org/10.1021/acs.jafc.7b01176

57. [57] Campos, E. V. R., de Oliveira, J. L., & Fraceto, L. F. (2014). Applications of controlled release systems for fungicides, herbicides, acaricides, nutrients, and plant growth hormones: A review. *Advanced Science, Engineering and Medicine*, 6(4), 373-387. https://doi.org/10.1166/asem.2014.1538
58. [58] Grillo, R., Pereira, A. E. S., Nishisaka, C. S., de Lima, R., Oehlke, K., Greiner, R., & Fraceto, L. F. (2014). Chitosan/tripolyphosphate nanoparticles loaded with paraquat herbicide: An environmentally safer alternative for weed control. *Journal of Hazardous Materials*, 278, 163-171. https://doi.org/10.1016/j.jhazmat.2014.05.079
59. [59] Manikandan, A., & Sathiyabama, M. (2016). Preparation of chitosan nanoparticles and its effect on detached rice leaves infected with *Pyricularia grisea*. *International Journal of Biological Macromolecules*, 84, 58-61. https://doi.org/10.1016/j.ijbiomac.2015.11.083
60. [60] Zhang, H., Kou, X., Liu, H., Yao, S., Zhang, L., Mu, L., & Shi, W. (2018). Controlled release of pesticides using biodegradable PLA-based microcapsules. *Industrial & Engineering Chemistry Research*, 57(39), 13386-13394. https://doi.org/10.1021/acs.iecr.8b02301
61. [61] da Silva, E. D. R., Maquiaveli, C. do C., & Magalhães, P. P. (2012). The leishmanicidal flavonols quercetin and quercitrin target *Leishmania* (*Leishmania*) *amazonensis* arginase. *Experimental Parasitology*, 130(3), 183-188. https://doi.org/10.1016/j.exppara.2012.01.015
62. [62] Wang, Y., Cui, H., Sun, C., Zhao, X., & Cui, B. (2014). Construction and evaluation of controlled-release delivery system of Abamectin using porous silica nanoparticles as carriers. *Nanoscale Research Letters*, 9(1), 655. https://doi.org/10.1186/1556-276X-9-655
63. [63] Hussein, M. Z., Guan, T. S., Kanakaraju, D., & Isa, M. I. N. M. (2017). Controlled-release formulation of agrochemical pesticide based on 4-(2,4-dichlorophenoxy)butyrate nanohybrid. *Nanoscale Research Letters*, 12(1), 250. https://doi.org/10.1186/s11671-017-2016-x
64. [64] Nguyen, H. M., Hwang, I. C., Park, J. W., & Park, H. J. (2012). Photoprotection for deltamethrin using chitosan-coated beeswax solid lipid nanoparticles. *Pest Management Science*, 68(7), 1062-1068. https://doi.org/10.1002/ps.3268
65. [65] Campos, E. V. R., de Oliveira, J. L., Fraceto, L. F., & Singh, B. (2015). Polysaccharides as safer release systems for agrochemicals. *Agronomy for Sustainable Development*, 35(1), 47-66. https://doi.org/10.1007/s13593-014-0263-0
66. [66] Pérez-de-Luque, A. (2017). Interaction of nanomaterials with plants: What do we need for real applications in agriculture? *Frontiers in Environmental Science*, 5, 12. https://doi.org/10.3389/fenvs.2017.00012
67. [67] Ditta, A., & Arshad, M. (2016). Applications and perspectives of using nanomaterials for sustainable plant nutrition. *Nanotechnology Reviews*, 5(2), 209-229. https://doi.org/10.1515/ntrev-2015-0060
68. [68] Duhan, J. S., Kumar, R., Kumar, N., Kaur, P., Nehra, K., & Duhan, S. (2017). Nanotechnology: The new perspective in precision agriculture. *Biotechnology Reports*, 15, 11-23. https://doi.org/10.1016/j.btre.2017.03.002
69. [69] Ali, M. A., Rehman, I., Iqbal, A., Din, S., Rao, A. Q., Latif, A., Samiullah, T. R., Azam, S., & Husnain, T. (2014). Nanotechnology, a new frontier in agriculture. *Advancements in Life Sciences*, 1(3), 129-138. http://www.als-journal.com/articles/vol1issue3/Nanotechnology-new-frontier-agriculture.pdf
70. [70] Khot, L. R., Sankaran, S., Maja, J. M., Ehsani, R., & Schuster, E. W. (2012). Applications of nanomaterials in agricultural production and crop protection: A review. *Crop Protection*, 35, 64-70. https://doi.org/10.1016/j.cropro.2012.01.007
71. [71] Ashkavand, P., Tabari, M., Zarafshar, M., Tomášková, I., & Struve, D. (2015). Effect of SiO~~2~~ nanoparticles on drought resistance in hawthorn seedlings. *Leśne Prace Badawcze / Forest Research Papers*, 76(4), 350-359. https://doi.org/10.1515/frp-2015-0034
72. [72] Siddiqui, M. H., & Al-Whaibi, M. H. (2014). Role of nano-SiO~~2~~ in germination of tomato (*Lycopersicum esculentum* seeds Mill.). *Saudi Journal of Biological Sciences*, 21(1), 13-17. https://doi.org/10.1016/j.sjbs.2013.04.005

73. [73] Rai, V., Acharya, S., & Dey, N. (2012). Implications of nanobiosensors in agriculture. *Journal of Biomaterials and Nanobiotechnology*, 03(2), 315-324. https://doi.org/10.4236/jbnb.2012.322039
74. [74] Solanki, P., Bhargava, A., Chhipa, H., Jain, N., & Panwar, J. (2015). Nano-fertilizers and their smart delivery system. In M. Rai, C. Ribeiro, L. Mattoso, & N. Duran (Eds.), *Nanotechnologies in Food and Agriculture* (pp. 81-101). Springer International Publishing. https://doi.org/10.1007/978-3-319-14024-7_4
75. [75] Usman, M., Farooq, M., Wakeel, A., Nawaz, A., Cheema, S. A., Rehman, H., Ashraf, I., & Sanaullah, M. (2020). Nanotechnology in agriculture: Current status, challenges and future opportunities. *Science of The Total Environment*, 721, 137778. https://doi.org/10.1016/j.scitotenv.2020.137778
76. [76] Iavicoli, I., Leso, V., Beezhold, D. H., & Shvedova, A. A. (2017). Nanotechnology in agriculture: Opportunities, toxicological implications, and occupational risks. *Toxicology and Applied Pharmacology*, 329, 96-111. https://doi.org/10.1016/j.taap.2017.05.025
77. [77] Dasgupta, N., Ranjan, S., & Ramalingam, C. (2017). Applications of nanotechnology in agriculture and water quality management. *Environmental Chemistry Letters*, 15(4), 591-605. https://doi.org/10.1007/s10311-017-0648-9
78. [78] Fraceto, L. F., Grillo, R., de Medeiros, G. A., Scognamiglio, V., Rea, G., & Bartolucci, C. (2016). Nanotechnology in agriculture: Which innovation potential does it have? *Frontiers in Environmental Science*, 4, 20. https://doi.org/10.3389/fenvs.2016.00020
79. [79] Chen, H., & Yada, R. (2011). Nanotechnologies in agriculture: New tools for sustainable development. *Trends in Food Science & Technology*, 22(11), 585-594. https://doi.org/10.1016/j.tifs.2011.09.004
80. [80] Prasad, R., Bhattacharyya, A., & Nguyen, Q. D. (2017). Nanotechnology in sustainable agriculture: Recent developments, challenges, and perspectives. *Frontiers in Microbiology*, 8, 1014. https://doi.org/10.3389/fmicb.2017.01014
81. [81] Saharan, V., & Pal, A. (2016). *Chitosan Based Nanomaterials in Plant Growth and Protection*. Springer India. https://doi.org/10.1007/978-81-322-2716-8
82. [82] Brandelli, A., Pinilla, C. M. B., & Lopes, N. A. (2017). Nanostructures for delivery of natural antimicrobials in food. In A. M. Grumezescu (Ed.), *Nanotechnology in the Agri-Food Industry* (pp. 35-74). Academic Press. https://doi.org/10.1016/B978-0-12-804304-2.00002-X
83. [83] Singh, H., & Sharma, A. (2020). Nanomaterials in agricultural sector: An overview. In P. Singh, R. Singh, & V. Srivastava (Eds.), *Contemporary Environmental Issues and Challenges in Era of Climate Change* (pp. 173-187). Springer Singapore. https://doi.org/10.1007/978-981-32-9595-7_13
84. [84] Madhuban Gopal, Mathew, B. B., Shukla, N., Singh, R. K., Jat, S. L., & Mishra, P. K. (2019). Nanotechnology: A sustainable tool for integrated pest management. In V. S. G. R. Naidu (Ed.), *Innovative Pest Management Approaches for the 21st Century: Harnessing Automated Unmanned Technologies* (pp. 331-351). Springer Singapore. https://doi.org/10.1007/978-981-13-7431-7_18
85. [85] Nuruzzaman, M., Rahman, M. M., Liu, Y., & Naidu, R. (2016). Nanoencapsulation, nano-guard for pesticides: A new window for safe application. *Journal of Agricultural and Food Chemistry*, 64(7), 1447-1483. https://doi.org/10.1021/acs.jafc.5b05214
86. [86] Agrawal, S., & Rathore, P. (2014). Nanotechnology pros and cons to agriculture: A review. *International Journal of Current Microbiology and Applied Sciences*, 3(3), 43-55. https://www.ijcmas.com/vol-3-3/Shivendu%20Agrawal%20and%20Pragya%20Rathore.pdf
87. [87] Parisi, C., Vigani, M., & Rodríguez-Cerezo, E. (2015). Agricultural nanotechnologies: What are the current possibilities? *Nano Today*, 10(2), 124-127. https://doi.org/10.1016/j.nantod.2014.09.009
88. [88] Mishra, S., Keswani, C., Abhilash, P. C., Fraceto, L. F., & Singh, H. B. (2017). Integrated approach of agri-nanotechnology: Challenges and future trends. *Frontiers in Plant Science*, 8, 471. https://doi.org/10.3389/fpls.2017.00471
89. in Food and Agriculture* (pp. 81-101). Springer International Publishing. https://doi.org/10.1007/978-3-319-14024-7_4

90. [75] Usman, M., Farooq, M., Wakeel, A., Nawaz, A., Cheema, S. A., Rehman, H., Ashraf, I., & Sanaullah, M. (2020). Nanotechnology in agriculture: Current status, challenges and future opportunities. *Science of The Total Environment*, 721, 137778. https://doi.org/10.1016/j.scitotenv.2020.137778
91. [76] Iavicoli, I., Leso, V., Beezhold, D. H., & Shvedova, A. A. (2017). Nanotechnology in agriculture: Opportunities, toxicological implications, and occupational risks. *Toxicology and Applied Pharmacology*, 329, 96-111. https://doi.org/10.1016/j.taap.2017.05.025
92. [77] Dasgupta, N., Ranjan, S., & Ramalingam, C. (2017). Applications of nanotechnology in agriculture and water quality management. *Environmental Chemistry Letters*, 15(4), 591-605. https://doi.org/10.1007/s10311-017-0648-9
93. [78] Fraceto, L. F., Grillo, R., de Medeiros, G. A., Scognamiglio, V., Rea, G., & Bartolucci, C. (2016). Nanotechnology in agriculture: Which innovation potential does it have? *Frontiers in Environmental Science*, 4, 20. https://doi.org/10.3389/fenvs.2016.00020
94. [79] Chen, H., & Yada, R. (2011). Nanotechnologies in agriculture: New tools for sustainable development. *Trends in Food Science & Technology*, 22(11), 585-594. https://doi.org/10.1016/j.tifs.2011.09.004
95. [80] Prasad, R., Bhattacharyya, A., & Nguyen, Q. D. (2017). Nanotechnology in sustainable agriculture: Recent developments, challenges, and perspectives. *Frontiers in Microbiology*, 8, 1014. https://doi.org/10.3389/fmicb.2017.01014
96. [81] Saharan, V., & Pal, A. (2016). *Chitosan Based Nanomaterials in Plant Growth and Protection*. Springer India. https://doi.org/10.1007/978-81-322-2716-8
97. [82] Brandelli, A., Pinilla, C. M. B., & Lopes, N. A. (2017). Nanostructures for delivery of natural antimicrobials in food. In A. M. Grumezescu (Ed.), *Nanotechnology in the Agri-Food Industry* (pp. 35-74). Academic Press. https://doi.org/10.1016/B978-0-12-804304-2.00002-X
98. [83] Singh, H., & Sharma, A. (2020). Nanomaterials in agricultural sector: An overview. In P. Singh, R. Singh, & V. Srivastava (Eds.), *Contemporary Environmental Issues and Challenges in Era of Climate Change* (pp. 173-187). Springer Singapore. https://doi.org/10.1007/978-981-32-9595-7_13
99. [84] Madhuban Gopal, Mathew, B. B., Shukla, N., Singh, R. K., Jat, S. L., & Mishra, P. K. (2019). Nanotechnology: A sustainable tool for integrated pest management. In V. S. G. R. Naidu (Ed.), *Innovative Pest Management Approaches for the 21st Century: Harnessing Automated Unmanned Technologies* (pp. 331-351). Springer Singapore. https://doi.org/10.1007/978-981-13-7431-7_18
100. [85] Nuruzzaman, M., Rahman, M. M., Liu, Y., & Naidu, R. (2016). Nanoencapsulation, nano-guard for pesticides: A new window for safe application. *Journal of Agricultural and Food Chemistry*, 64(7), 1447-1483. https://doi.org/10.1021/acs.jafc.5b05214
101. [86] Agrawal, S., & Rathore, P. (2014). Nanotechnology pros and cons to agriculture: A review. *International Journal of Current Microbiology and Applied Sciences*, 3(3), 43-55. https://www.ijcmas.com/vol-3-3/Shivendu%20Agrawal%20and%20Pragya%20Rathore.pdf
102. [87] Parisi, C., Vigani, M., & Rodríguez-Cerezo, E. (2015). Agricultural nanotechnologies: What are the current possibilities? *Nano Today*, 10(2), 124-127. https://doi.org/10.1016/j.nantod.2014.09.009
103. [88] Mishra, S., Keswani, C., Abhilash, P. C., Fraceto, L. F., & Singh, H. B. (2017). Integrated approach of agri-nanotechnology: Challenges and future trends. *Frontiers in Plant Science*, 8, 471. https://doi.org/10.3389/fpls.2017.00471
104. [89] Duhan, J. S., Saharan, P., & Kumar, A. (2019). Nanotechnology: Potential applications in crop improvement. In R. S. Meena (Ed.), *Nutrient Dynamics for Sustainable Crop Production* (pp. 425-448). Springer Singapore. https://doi.org/10.1007/978-981-13-8660-2_14
105. [90] Grillo, R., Abhilash, P. C., & Fraceto, L. F. (2016). Nanotechnology applied to bio-encapsulation of pesticides. *Journal of Nanoscience and Nanotechnology*, 16(1), 1231-1234. https://doi.org/10.1166/jnn.2016.12332
106. [91] Pandey, G. (2018). Challenges and future prospects of agri-nanotechnology for sustainable agriculture in India. *Environmental Technology & Innovation*, 11, 299-307. https://doi.org/10.1016/j.eti.2018.06.012

107. [92] Shang, Y., Hasan, M. K., Ahammed, G. J., Li, M., Yin, H., & Zhou, J. (2019). Applications of nanotechnology in plant growth and crop protection: A review. *Molecules*, 24(14), 2558. https://doi.org/10.3390/molecules24142558
108. [93] Chhipa, H. (2019). Applications of nanotechnology in agriculture. In P. Singh, R. Singh, & V. Srivastava (Eds.), *Contemporary Environmental Issues and Challenges in Era of Climate Change* (pp. 115-142). Springer Singapore. https://doi.org/10.1007/978-981-32-9595-7_10
109. [94] Kole, C., Kumar, D. S., & Khodakovskaya, M. V. (2016). Plant nanotechnology: Principles and practices. Springer International Publishing. https://doi.org/10.1007/978-3-319-42154-4
110. [95] Abdel-Aziz, H. M. M., Hasaneen, M. N. A., & Omer, A. M. (2016). Nano chitosan-NPK fertilizer enhances the growth and productivity of wheat plants grown in sandy soil. *Spanish Journal of Agricultural Research*, 14(1), e0902. https://doi.org/10.5424/sjar/2016141-8205
111. [96] Jogaiah, S., Kurjogi, M., Abdelrahman, M., Hanumanthappa, N., & Tran, L.-S. P. (2019). Ganoderma applanatum-mediated green synthesis of silver nanoparticles: Structural characterization, and in vitro and in vivo biomedical and agrochemical properties. *Arabian Journal of Chemistry*, 12(8), 1108-1120. https://doi.org/10.1016/j.arabjc.2016.01.005
112. Kah, M., Kookana, R. S., Gogos, A., & Bucheli, T. D. (2018). A critical evaluation of nanopesticides and nanofertilizers against their conventional analogues. *Nature Nanotechnology*, 13(8), 677-684. https://doi.org/10.1038/s41565-018-0131-1
113. Kumari, A., & Yadav, S. K. (2014). Nanotechnology in agri-food sector. *Critical Reviews in Food Science and Nutrition*, 54(8), 975-984. https://doi.org/10.1080/10408398.2011.621095
114. Servin, A. D., & White, J. C. (2016). Nanotechnology in agriculture: Next steps for understanding engineered nanoparticle exposure and risk. *NanoImpact*, 1, 9-12. https://doi.org/10.1016/j.impact.2015.12.002
115. Ali, M. A., Rehman, I., Iqbal, A., Din, S., Rao, A. Q., Latif, A., Samiullah, T. R., Azam, S., & Husnain, T. (2014). Nanotechnology, a new frontier in agriculture. *Advancements in Life Sciences*, 1(3), 129-138. http://submission.als-journal.com/index.php/ALS/article/view/45
116. [101] Amenta, V., Aschberger, K., Arena, M., Bouwmeester, H., Botelho Moniz, F., Brandhoff, P., Gottardo, S., Marvin, H. J. P., Mech, A., Quiros Pesudo, L., Rauscher, H., Schoonjans, R., Vettori, M. V., Weigel, S., & Peters, R. J. (2015). Regulatory aspects of nanotechnology in the agri/feed/food sector in EU and non-EU countries. *Regulatory Toxicology and Pharmacology*, 73(1), 463-476. https://doi.org/10.1016/j.yrtph.2015.06.016
117. [102] Kah, M., Beulke, S., Tiede, K., & Hofmann, T. (2013). Nanopesticides: State of knowledge, environmental fate, and exposure modeling. *Critical Reviews in Environmental Science and Technology*, 43(16), 1823-1867. https://doi.org/10.1080/10643389.2012.671750
118. [103] Pérez-de-Luque, A., & Rubiales, D. (2009). Nanotechnology for parasitic plant control. *Pest Management Science*, 65(5), 540-545. https://doi.org/10.1002/ps.1732
119. [104] Kah, M., Tufenkji, N., & White, J. C. (2019). Nano-enabled strategies to enhance crop nutrition and protection. *Nature Nanotechnology*, 14(6), 532-540. https://doi.org/10.1038/s41565-019-0439-5
120. [105] Ghormade, V., Deshpande, M. V., & Paknikar, K. M. (2011). Perspectives for nano-biotechnology enabled protection and nutrition of plants. *Biotechnology Advances*, 29(6), 792-803. https://doi.org/10.1016/j.biotechadv.2011.06.007
121. [106] Pandey, A. C., Sanjay, S. S., & Yadav, R. S. (2010). Application of ZnO nanoparticles in influencing the growth rate of *Cicer arietinum*. *Journal of Experimental Nanoscience*, 5(6), 488-497. https://doi.org/10.1080/17458081003649648

CHAPTER - 10

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Soil Types and Fertility Management

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Abstract

Soil is a critical component of agricultural systems, serving as the medium for plant growth and nutrient cycling. India is endowed with a diverse array of soil types, each with distinct characteristics and management requirements. This chapter provides an in-depth analysis of the major soil types found in India, their properties, and fertility management strategies for optimizing crop production. The chapter begins by introducing the concept of soil and its importance in agriculture. It then delves into the classification of soils based on various criteria such as texture, pH, organic matter content, and nutrient status. The chapter discusses the characteristics and distribution of major soil types in India, including alluvial soils, black soils, red soils, lateritic soils, and desert soils. The role of soil organic matter in maintaining soil health and fertility is emphasized, along with strategies for its management through crop residue incorporation, green manuring, and composting. The chapter also covers the principles of soil fertility management, focusing on the essential plant nutrients, their functions, deficiency symptoms, and correction measures. Nutrient management strategies, including organic and inorganic fertilizers, integrated nutrient management, and precision farming techniques, are discussed in detail. The importance of soil testing and its role in guiding fertilizer recommendations is highlighted. The chapter also addresses the challenges of soil degradation, such as erosion, salinity, and acidity, and presents management approaches for their amelioration. Finally, the chapter concludes by emphasizing the need for sustainable soil management practices to ensure long-term productivity and environmental sustainability in Indian agriculture. The information presented in

this chapter is supported by extensive research and is intended to provide a comprehensive understanding of soil types and fertility management for students, researchers, and practitioners in the field of agriculture and horticulture.

Keywords: soil types, soil fertility, nutrient management, soil health, sustainable agriculture

Soil is the foundation of agriculture, providing the essential medium for plant growth and development. It is a complex and dynamic system that plays a vital role in supporting crop production and maintaining ecosystem services [1]. India, with its vast and diverse geography, is endowed with a wide range of soil types, each with unique characteristics and management requirements. Understanding the properties and distribution of these soil types is crucial for developing effective strategies for soil fertility management and sustainable agriculture [2].

In this chapter, we delve into the major soil types found in India, their characteristics, and the principles of soil fertility management. We discuss the classification of soils based on various criteria such as texture, pH, organic matter content, and nutrient status. The chapter also highlights the importance of soil organic matter in maintaining soil health and fertility, along with strategies for its management. We cover the essential plant nutrients, their functions, deficiency symptoms, and correction measures, as well as nutrient management strategies, including organic and inorganic fertilizers, integrated nutrient management, and precision farming techniques.

The challenges of soil degradation, such as erosion, salinity, and acidity, are addressed, along with management approaches for their amelioration. Finally, we emphasize the need for sustainable soil management practices to ensure long-term productivity and environmental sustainability in Indian agriculture.

1.1. The importance of soil in agriculture

Soil is a vital natural resource that supports plant growth and plays a crucial role in agricultural production. It provides plants with essential nutrients, water, and anchorage, and serves as a medium for root development [3]. Soil also acts as a reservoir for water and nutrients, regulating their availability to plants. The physical, chemical, and biological properties of soil greatly influence crop growth, yield, and quality [4].

Healthy soils are essential for sustainable agriculture, as they can support high crop yields while maintaining long-term productivity and environmental quality [5]. Soils with optimal physical properties, such as good structure, porosity, and water-holding capacity, allow for proper root growth and water and nutrient uptake [6]. Chemically, soils with a balanced supply of essential nutrients and a suitable pH range promote healthy plant growth and development [7]. Biologically, soils with a diverse and active community of microorganisms contribute to nutrient cycling, organic matter decomposition, and disease suppression [8].

1.2. Overview of soil types and fertility management in India

India has a diverse range of soil types, varying in their physical, chemical, and biological properties. These soil types have been formed under the influence of factors such as climate, parent material, topography, vegetation, and time [9]. The major soil types found in India include alluvial soils, black soils, red soils, lateritic soils, and desert soils, each with distinct characteristics and management requirements [10].

Soil fertility management is a critical aspect of agricultural production in India, as it directly influences crop yields and sustainability. Effective soil fertility management involves understanding the nutrient requirements of crops, assessing soil nutrient status, and applying appropriate fertilizers and organic amendments [11]. In India, soil fertility management strategies include the use of inorganic fertilizers, organic manures, biofertilizers, and integrated nutrient management approaches [12].

However, soil degradation poses a significant challenge to soil fertility management and agricultural sustainability in India. Soil degradation processes, such as erosion, salinization, acidification, and nutrient depletion, can lead to reduced soil productivity and environmental quality [13]. Therefore, it is essential to adopt sustainable soil management practices that maintain soil health, conserve soil resources, and ensure long-term agricultural productivity [14].

2. Soil Classification

Soil classification is the process of grouping soils into categories based on their properties and characteristics. It helps in understanding the nature and behavior of soils, as well as their suitability for various uses, including agriculture [15]. Soil classification systems have been developed at national and international levels to provide a standardized framework for describing and mapping soils [16].

In India, the most widely used soil classification system is the one developed by the National Bureau of Soil Survey and Land Use Planning (NBSS&LUP), which is based on the USDA Soil Taxonomy [17]. This system classifies soils into orders, suborders, great groups, subgroups, families, and series, based on their morphological, physical, and chemical properties [18].

2.1. Criteria for soil classification

Soils are classified based on various criteria that reflect their properties and characteristics. These criteria include texture, pH, organic matter content, and nutrient status, among others [19].

2.1.1. Texture

Soil texture refers to the relative proportion of sand, silt, and clay particles in a soil. It influences soil properties such as water-holding capacity, porosity, and nutrient retention [20]. Soils are classified into textural classes based on the percentage of sand, silt, and clay particles, as determined by the soil texture triangle [21]. The major textural classes are sand, loamy sand, sandy loam, loam, silt loam, silt, sandy clay loam, clay loam, silty clay loam, sandy clay, silty clay, and clay [22].

Soil pH is a measure of the acidity or alkalinity of a soil. It influences the availability of plant nutrients, soil microbial activity, and crop growth [23]. Soils are classified into pH ranges, such as strongly acidic (pH < 5.5), moderately acidic (pH 5.5-6.5), neutral (pH 6.5-7.5), moderately alkaline (pH 7.5-8.5), and strongly alkaline (pH > 8.5) [24].

Table 1. Soil textural classes and their particle size distribution

Textural Class	Sand (%)	Silt (%)	Clay (%)
Sand	85-100	0-15	0-10
Loamy sand	70-90	0-30	0-15
Sandy loam	43-85	0-50	0-20
Loam	23-52	28-50	7-27
Silt loam	0-50	50-88	0-27
Silt	0-20	80-100	0-12
Sandy clay loam	45-80	0-28	20-35
Clay loam	20-45	15-53	27-40
Silty clay loam	0-20	40-73	27-40
Sandy clay	45-65	0-20	35-55
Silty clay	0-20	40-60	40-60
Clay	0-45	0-40	40-100

2.1.2. pH

Table 2. Soil pH ranges and their effects on nutrient availability and crop growth

pH Range	Effect on Nutrient Availability and Crop Growth
< 4.5	Extremely acidic, toxic levels of Al and Mn, deficiency of Ca, Mg, and P
4.5-5.5	Strongly acidic, reduced availability of N, P, K, Ca, Mg, and Mo
5.5-6.5	Moderately acidic, optimal availability of most nutrients
6.5-7.5	Neutral, optimal availability of most nutrients
7.5-8.5	Moderately alkaline, reduced availability of P, Fe, Mn, Zn, and B
> 8.5	Strongly alkaline, reduced availability of most micronutrients

2.1.3. Organic matter content

Soil organic matter is the fraction of the soil that consists of plant and animal residues at various stages of decomposition, as well as microbial biomass and humus [25]. It plays a crucial role in maintaining soil health, fertility, and productivity [26]. Soils are classified based on their organic matter content, such as low (<0.5%), medium (0.5-1.5%), and high (>1.5%) [27].

Table 3. Soil organic matter content classes and their effects on soil properties

Organic Matter Content (%)	Class	Effect on Soil Properties
< 0.5	Low	Poor soil structure, low nutrient and water retention, low microbial activity
0.5-1.5	Medium	Moderate soil structure, nutrient and water retention, and microbial activity
> 1.5	High	Good soil structure, high nutrient and water retention, high microbial activity

2.1.4. Nutrient status

Soil nutrient status refers to the availability of essential plant nutrients in the soil. It is determined by factors such as soil pH, organic matter content, cation exchange capacity, and mineral composition [28]. Soils are classified based on their nutrient status, such as deficient, sufficient, or excessive, for each essential nutrient [29].

Table 4. Soil nutrient status classes and their effects on crop growth

Nutrient Status	Effect on Crop Growth
Deficient	Nutrient deficiency symptoms, reduced growth and yield
Sufficient	Optimal nutrient availability, normal growth and yield
Excessive	Nutrient toxicity symptoms, reduced growth and yield, environmental issues

2.2. Major soil types in India

India has a wide range of soil types, each with distinct characteristics and management requirements. The major soil types found in India are alluvial soils, black soils, red soils, lateritic soils, and desert soils [30].

2.2.1. Alluvial soils

Alluvial soils are formed by the deposition of sediments by rivers and streams. They are the most extensive soil type in India, covering about 40% of the total geographical area [31]. Alluvial soils are found in the Indo-Gangetic plains, the Brahmaputra valley, and the coastal plains of India [32].

Characteristics of alluvial soils:

- **Texture:** Varies from sandy to clayey, with loamy texture being the most common [33]
- **pH:** Neutral to slightly alkaline (6.5-8.0) [34]
- **Organic matter content:** Low to medium (0.5-1.5%) [35]
- **Nutrient status:** Generally fertile, with high reserves of K and Ca, but may be deficient in N and P [36]

Management of alluvial soils:

- Regular addition of organic matter through crop residues, green manures, and compost [37]
- Balanced application of fertilizers based on soil testing and crop requirements [38]
- Proper irrigation management to prevent waterlogging and salinization [39]

2.2.2. Black soils

Black soils, also known as Vertisols, are formed from the weathering of basaltic rocks under semi-arid to sub-humid climatic conditions. They are found in the Deccan plateau, covering parts of Maharashtra, Madhya Pradesh, Gujarat, Andhra Pradesh, and Karnataka [40].

Characteristics of black soils:

- Texture: Clayey, with high montmorillonite content [41]
- pH: Neutral to slightly alkaline (6.5-8.5) [42]
- Organic matter content: Low to medium (0.5-1.5%) [43]
- Nutrient status: High in Ca, Mg, and K, but may be deficient in N and P [44]

Management of black soils:

- Proper tillage practices to improve soil structure and water infiltration [45]
- Balanced application of fertilizers, particularly N and P [46]

- Soil and water conservation measures to prevent erosion and improve moisture retention [47]

2.2.3. Red soils

Red soils are formed from the weathering of ancient crystalline and metamorphic rocks under humid tropical conditions. They are found in parts of Tamil Nadu, Karnataka, Andhra Pradesh, Odisha, and Jharkhand [48].

Characteristics of red soils:

- Texture: Sandy to loamy, with low clay content [49]
- pH: Acidic to neutral (4.5-7.0) [50]
- Organic matter content: Low (<0.5%) [51]
- Nutrient status: Generally low in fertility, with deficiencies in N, P, and K [52]

Management of red soils:

- Liming to correct soil acidity and improve nutrient availability [53]
- Regular addition of organic matter to improve soil structure and fertility [54]
- Balanced application of fertilizers, particularly N, P, and K [55]

2.2.4. Lateritic soils

Lateritic soils are formed from the intensive weathering of rocks under humid tropical conditions, resulting in the leaching of bases and the accumulation of iron and aluminum oxides. They are found in parts of Kerala, Tamil Nadu, Karnataka, and Odisha [56].

Characteristics of lateritic soils:

- Texture: Gravelly to clayey, with high content of iron and aluminum oxides [57]
- pH: Strongly acidic (< 5.5) [58]
- Organic matter content: Low (<0.5%) [59]
- Nutrient status: Low in fertility, with deficiencies in N, P, K, Ca, and Mg [60]

Management of lateritic soils:

- Liming to correct soil acidity and improve nutrient availability [61]
- Regular addition of organic matter to improve soil structure and fertility [62]
- Balanced application of fertilizers, particularly N, P, and K [63]
- Soil conservation measures to prevent erosion and nutrient loss [64]

2.2.5. Desert soils

Desert soils are formed under arid climatic conditions, with low rainfall and high evaporation rates. They are found in the Thar desert of Rajasthan and parts of Gujarat [65].

Characteristics of desert soils:

- Texture: Sandy to loamy sand, with low water-holding capacity [66]
- pH: Neutral to slightly alkaline (7.0-8.5) [67]
- Organic matter content: Very low (<0.2%) [68]
- Nutrient status: Low in fertility, with deficiencies in N, P, and K [69]

Management of desert soils:

- Addition of organic matter to improve soil structure and water-holding capacity [70]
- Balanced application of fertilizers, particularly N, P, and K [71]
- Efficient irrigation management to conserve water and prevent salinization [72]

3. Soil Organic Matter

Soil organic matter (SOM) is a crucial component of soil that plays a vital role in maintaining soil health, fertility, and productivity. It consists of plant and animal residues at various stages of decomposition, as well as microbial biomass and humus [73]. SOM influences various soil properties, such as structure, water-holding capacity, nutrient retention, and microbial activity [74].

3.1. Importance of soil organic matter

Soil organic matter is essential for maintaining soil quality and productivity due to its numerous beneficial effects on soil properties and processes [75].

Some of the key roles of SOM include:

- Improving soil structure and aggregation, leading to better water infiltration and aeration [76]
- Enhancing water-holding capacity, reducing drought stress, and improving irrigation efficiency [77]
- Serving as a reservoir of plant nutrients, particularly N, P, and S, and slowly releasing them for plant uptake [78]
- Providing energy and substrates for soil microorganisms, supporting nutrient cycling and disease suppression [79]
- Buffering soil pH and increasing cation exchange capacity, improving nutrient retention and availability [80]

3.2. Composition and properties of soil organic matter

Soil organic matter is a complex mixture of organic compounds derived from plant and animal residues, as well as microbial biomass and byproducts. It can be broadly classified into three main fractions based on their decomposition rates and turnover times [81]:

1. Active fraction (labile pool): Consists of easily decomposable compounds, such as simple sugars, amino acids, and microbial biomass, with turnover times of days to months [82]
2. Slow fraction (intermediate pool): Consists of partially decomposed plant and animal residues, with turnover times of years to decades [83]
3. Passive fraction (stable pool): Consists of highly recalcitrant compounds, such as humus and charcoal, with turnover times of centuries to millennia [84]

Table 5. Composition and properties of soil organic matter fractions

Fraction	Composition	Turnover Time	Proportion of Total SOM
Active	Simple sugars, amino acids, microbial	Days to months	5-15%

	biomass		
Slow	Partially decomposed plant and animal residues	Years to decades	20-40%
Passive	Humus, charcoal	Centuries to millennia	60-80%

3.3. Factors affecting soil organic matter content

The content and dynamics of soil organic matter are influenced by various factors, including climate, soil type, vegetation, land use, and management practices [85]. Some of the key factors affecting SOM content are:

- Climate: Temperature and precipitation influence the rates of organic matter inputs and decomposition. Warm and moist climates generally favor higher SOM accumulation due to increased biomass production and slower decomposition rates [86].
- Soil type: Soil texture, mineralogy, and pH affect the stabilization and protection of SOM. Clayey soils tend to have higher SOM content than sandy soils due to the formation of organo-mineral complexes that protect SOM from decomposition [87].
- Vegetation: The quantity and quality of plant residues added to the soil influence SOM content. Grasslands and forests generally have higher SOM content than croplands due to the continuous addition of root biomass and the absence of soil disturbance [88].
- Land use and management: Cultivation, tillage, crop rotation, and fertilization practices affect SOM content by altering the balance between organic matter inputs and losses. Intensive tillage and monoculture cropping systems can lead to rapid SOM depletion, while conservation practices like reduced tillage, cover cropping, and organic amendments can help maintain or increase SOM levels [89].

3.4. Management strategies for maintaining soil organic matter

Maintaining or increasing soil organic matter content is crucial for sustainable soil management and agricultural productivity. Various strategies can be employed to manage SOM, depending on the local climate, soil type, and cropping system [90].

3.4.1. Crop residue incorporation

Incorporating crop residues into the soil after harvest is an effective way to recycle organic matter and nutrients back into the soil. Crop residues, such as straw, stubble, and roots, provide a substrate for microbial decomposition and contribute to SOM formation [91]. Residue management practices, such as mulching, reduced tillage, and direct seeding, can help retain residues on the soil surface and reduce erosion losses [92].

3.4.2. Green manuring

Green manuring involves growing a legume or non-legume cover crop and incorporating it into the soil while still green and succulent. Green manures add fresh organic matter to the soil, improve soil structure, and provide a source of readily available nutrients for the following crop [93]. Legume green manures, such as clover, vetch, and peas, can also fix atmospheric nitrogen and reduce the need for synthetic fertilizers [94].

Table 6. Common green manure crops and their characteristics

Crop	Scientific Name	Nitrogen Fixation	Biomass Production	Incorporation Time
Clover	*Trifolium* spp.	High	Moderate	Early to mid-bloom
Vetch	*Vicia* spp.	High	High	Early to mid-bloom
Peas	*Pisum* spp.	High	Moderate	Early to mid-bloom
Rye	*Secale cereale*	None	High	Before seed set
Mustard	*Brassica* spp.	None	Moderate	Early to mid-bloom

3.4.3. Composting

Composting is the controlled decomposition of organic materials, such as crop residues, animal manures, and food wastes, into a stable and nutrient-rich product called compost. Applying compost to the soil is an effective way to increase SOM content, improve soil structure, and enhance nutrient availability [95]. Composting also helps to recycle organic wastes and reduce greenhouse gas emissions from landfills [96].

The composting process involves the following steps [97]:

1. Collection and mixing of organic materials
2. Monitoring and maintaining optimal moisture, temperature, and aeration conditions
3. Turning and mixing the compost pile periodically to ensure uniform decomposition
4. Curing the compost until it reaches a stable and mature state
5. Screening and applying the finished compost to the soil

Table 7. Recommended composting conditions for optimal decomposition

Parameter	Optimal Range
Carbon:Nitrogen ratio	25:1 to 30:1
Moisture content	50-60%
Temperature	55-65°C
Oxygen concentration	>5%
pH	6.5-8.0

4. Soil Fertility Management

Soil fertility management is the process of managing soil nutrients to optimize crop growth, yield, and quality while minimizing environmental impacts. It involves understanding the nutrient requirements of crops, assessing soil nutrient status, and applying appropriate fertilizers and organic amendments [98].

4.1. Essential plant nutrients

Plants require a balance of essential nutrients for proper growth and development. These nutrients are classified into two main categories based on their relative concentrations in plants: macronutrients and micronutrients [99].

4.1.1. Macronutrients

Macronutrients are the nutrients that plants require in large quantities. They include nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), and sulfur (S) [100].

Table 8. Macronutrients, their forms, and roles in plants

Nutrient	Available Forms	Roles in Plants
N	NO_3^-, NH_4^+	Protein synthesis, chlorophyll formation
P	$H_2PO_4^-$, HPO_4^{2-}	Energy transfer, root development
K	K^+	Enzyme activation, stomatal regulation
Ca	Ca^{2+}	Cell wall formation, root growth
Mg	Mg^{2+}	Chlorophyll synthesis, enzyme activation
S	SO_4^{2-}	Protein synthesis, chlorophyll formation

4.1.2. Micronutrients

Micronutrients are the nutrients that plants require in small quantities. They include iron (Fe), manganese (Mn), zinc (Zn), copper (Cu), boron (B), molybdenum (Mo), chlorine (Cl), and nickel (Ni) [101].

Table 9. Micronutrients, their forms, and roles in plants

Nutrient	Available Forms	Roles in Plants
Fe	Fe^{2+}, Fe^{3+}	Chlorophyll synthesis, enzyme activation
Mn	Mn^{2+}	Photosynthesis, enzyme activation
Zn	Zn^{2+}	Enzyme activation, protein synthesis
Cu	Cu^{2+}	Enzyme activation, lignin synthesis
B	H_3BO_3, $B(OH)_4^-$	Cell wall formation, flower development
Mo	MoO_4^{2-}	Nitrogen fixation, nitrate reduction
Cl	Cl^-	Photosynthesis, osmotic regulation
Ni	Ni^{2+}	Urease activation, nitrogen metabolism

4.2. Nutrient functions and deficiency symptoms

Each essential nutrient plays specific roles in plant growth and development. Deficiency of any nutrient can lead to characteristic symptoms and reduced crop yield and quality [102].

Table 10. Nutrient deficiency symptoms in plants

Nutrient	Deficiency Symptoms
N	Chlorosis (yellowing) of older leaves, stunted growth
P	Purple discoloration of leaves, stunted growth, delayed maturity
K	Chlorosis and necrosis of leaf margins, lodging
Ca	Deformation of young leaves, poor root growth
Mg	Interveinal chlorosis of older leaves
S	Chlorosis of younger leaves, stunted growth
Fe	Interveinal chlorosis of younger leaves
Mn	Interveinal chlorosis of younger leaves, necrotic spots
Zn	Interveinal chlorosis of younger leaves, rosetting
Cu	Chlorosis and necrosis of younger leaves, stunted growth
B	Death of growing points, cracking of fruits and stems
Mo	Chlorosis and necrosis of older leaves, poor nodulation in legumes
Cl	Wilting, chlorosis, and bronzing of leaves
Ni	Chlorosis of younger leaves, necrosis of leaf tips

4.3. Soil testing and fertilizer recommendations

Soil testing is the process of analyzing soil samples to determine their nutrient content and other properties relevant to plant growth. It provides a basis for making informed fertilizer recommendations and optimizing nutrient management [103].

The main steps in soil testing and fertilizer recommendation are:

1. Soil sampling: Collecting representative soil samples from the field, following proper sampling techniques and depths [104]
2. Laboratory analysis: Analyzing soil samples for pH, organic matter content, and available nutrient concentrations using standard methods [105]
3. Interpretation: Interpreting soil test results based on established critical levels and crop-specific nutrient requirements [106]
4. Recommendation: Developing fertilizer recommendations that consider soil test results, crop requirements, yield goals, and other site-specific factors [107]

Table 11. Critical levels of available nutrients in soil for selected crops

Nutrient	Crop	Critical Level (mg/kg)
N	Maize	20-30
P	Wheat	10-15
K	Rice	50-60
S	Soybean	10-12
Zn	Maize	0.5-1.0
B	Sunflower	0.3-0.5

4.4. Organic and inorganic fertilizers

Fertilizers are materials that are added to the soil to supply one or more plant nutrients. They can be broadly classified into organic and inorganic fertilizers based on their origin and composition [108].

4.4.1. Types and characteristics

Organic fertilizers are derived from plant or animal sources and contain a wide range of nutrients in organic forms. Examples include farmyard manure, compost, vermicompost, and green manures [109]. Organic fertilizers improve soil structure, water-holding capacity, and microbial activity, in addition to supplying nutrients [110].

Inorganic fertilizers, also known as synthetic or mineral fertilizers, are manufactured from inorganic compounds and contain specific nutrients in concentrated forms. Examples include urea, ammonium nitrate, superphosphate, and potassium chloride [111]. Inorganic fertilizers are highly soluble and provide readily available nutrients for plant uptake [112].

Table 12. Characteristics of organic and inorganic fertilizers

Characteristic	Organic Fertilizers	Inorganic Fertilizers
Nutrient content	Low to moderate	High
Nutrient release rate	Slow	Fast
Effect on soil structure	Improves	Little or no effect
Effect on soil microbes	Stimulates	Little or no effect
Environmental impact	Low	Potential for leaching and runoff

4.4.2. Advantages and disadvantages

Organic and inorganic fertilizers have their own advantages and disadvantages, which should be considered when developing nutrient management strategies [113].

Advantages of organic fertilizers:

- Improve soil structure, water-holding capacity, and aeration
- Enhance soil microbial activity and diversity
- Provide a slow and steady release of nutrients
- Reduce the risk of nutrient leaching and runoff
- Improve soil carbon sequestration

Disadvantages of organic fertilizers:

- Low nutrient content and variable composition
- Slow nutrient release may not meet crop demands during critical growth stages
- Bulky and difficult to transport and apply
- Potential for weed seed introduction and pathogen transmission
- Higher cost per unit of nutrient compared to inorganic fertilizers

Advantages of inorganic fertilizers:

- High nutrient content and specific composition
- Fast nutrient release and immediate availability to plants
- Easy to transport, store, and apply
- Precise control over nutrient application rates and timing
- Lower cost per unit of nutrient compared to organic fertilizers

Disadvantages of inorganic fertilizers:

- Do not improve soil structure or organic matter content
- Potential for nutrient leaching and runoff, leading to environmental pollution
- Excessive use can lead to soil acidification and micronutrient deficiencies
- Dependence on non-renewable resources (e.g., fossil fuels) for production
- Potential for salt buildup and osmotic stress in plants

4.5. Integrated nutrient management

Integrated nutrient management (INM) is an approach that combines the use of organic and inorganic fertilizers, along with other nutrient management practices, to optimize crop nutrition and minimize environmental impacts [114]. INM aims to maintain soil fertility, enhance nutrient use efficiency, and sustain crop productivity by:

- Using a balanced and site-specific combination of organic and inorganic nutrient sources
- Synchronizing nutrient supply with crop demand through proper timing and placement of fertilizers
- Minimizing nutrient losses through leaching, runoff, and volatilization by adopting best management practices
- Enhancing soil organic matter content and microbial activity through organic amendments and crop rotations

- Monitoring soil and plant nutrient status regularly and adjusting nutrient management accordingly

4.6. Precision farming techniques for nutrient management

Precision farming, also known as site-specific nutrient management, involves the use of advanced technologies to manage nutrients more efficiently and effectively [115]. Precision farming techniques for nutrient management include:

- Global Positioning System (GPS) and Geographic Information System (GIS) for mapping soil variability and creating management zones [116]
- Variable rate technology (VRT) for applying nutrients at different rates based on soil test results and crop requirements [117]
- Crop sensors and remote sensing for monitoring crop nutrient status and guiding in-season fertilizer applications [118]
- Nutrient budgeting and decision support systems for optimizing nutrient inputs and minimizing environmental impacts [119]

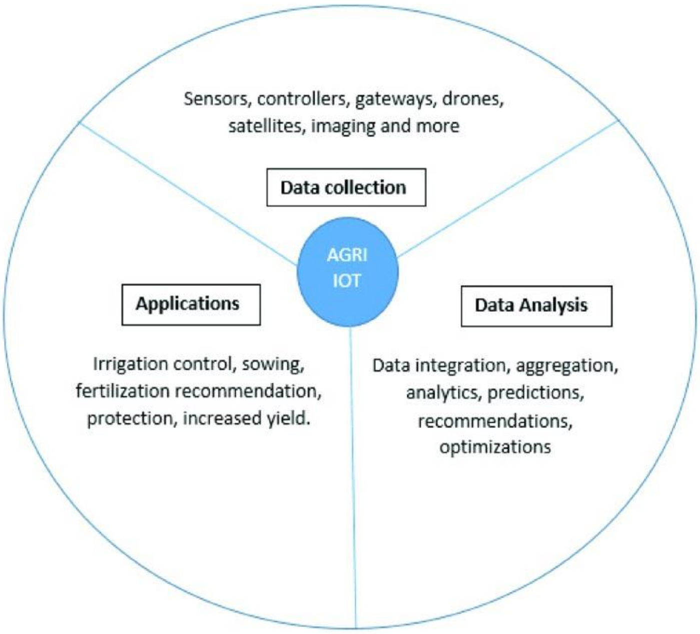

Figure 1. Components of precision farming for nutrient management

5. Soil Degradation and Management

Soil degradation is the deterioration of soil quality and productivity due to natural or human-induced factors [120]. It can lead to reduced crop yields, loss of biodiversity, and environmental pollution [121]. The main types of soil degradation in India are erosion, salinity, and acidity [122].

5.1. Soil erosion

Soil erosion is the detachment and transport of soil particles by water or wind [123]. It is a major problem in India, affecting about 45% of the total land area [124].

5.1.1. Causes and effects

The main causes of soil erosion in India are:

- Deforestation and overgrazing, which remove protective vegetation cover [125]
- Intensive cultivation on steep slopes without adequate conservation measures [126]
- Improper land use and management practices, such as leaving the soil bare and exposed [127]
- Extreme weather events, such as heavy rainfall and strong winds [128]

The effects of soil erosion include:

- Loss of topsoil and nutrients, leading to reduced soil fertility and crop yields [129]
- Siltation of rivers, lakes, and reservoirs, reducing their storage capacity and water quality [130]
- Increased risk of floods and droughts due to reduced water infiltration and storage [131]
- Degradation of aquatic and terrestrial ecosystems, affecting biodiversity and ecosystem services [132]

5.1.2. Management strategies

Soil erosion can be controlled and prevented through various management strategies, such as:

- Afforestation and reforestation to provide protective vegetation cover [133]
- Terracing and contour farming to reduce the velocity of runoff and promote water infiltration [134]
- Cover cropping and mulching to protect the soil surface from raindrop impact and reduce erosion [135]
- Conservation tillage practices, such as no-till and reduced tillage, to minimize soil disturbance [136]
- Vegetative barriers, such as grass strips and hedgerows, to slow down runoff and trap sediment [137]
- Gully control measures, such as check dams and gabions, to stabilize gullies and prevent further erosion [138]

5.2. Soil salinity

Soil salinity refers to the accumulation of soluble salts in the soil, which can inhibit plant growth and reduce crop yields [139]. It is a major problem in the arid and semi-arid regions of India, affecting about 6.7 million hectares of land [140].

5.2.1. Causes and effects

The main causes of soil salinity in India are:

- Irrigation with saline groundwater or poor quality irrigation water [141]
- Inadequate drainage and high water table, leading to the capillary rise of salts [142]
- Excessive use of chemical fertilizers, which can contribute to salt buildup in the soil [143]
- Seawater intrusion in coastal areas due to overexploitation of groundwater [144]

The effects of soil salinity include:

- Osmotic stress and ion toxicity in plants, leading to reduced growth and yield [145]
- Nutrient imbalances and deficiencies due to the competition between salts and nutrient ions [146]
- Deterioration of soil structure and water infiltration due to the dispersion of clay particles [147]
- Reduction in soil microbial activity and diversity, affecting nutrient cycling and soil health [148]

5.2.2. Management strategies

Soil salinity can be managed and reclaimed through various strategies, such as:

- Leaching of salts by applying excess irrigation water and providing adequate drainage [149]
- Use of salt-tolerant crops and varieties that can grow in saline conditions [150]
- Amendments with gypsum, organic matter, or other materials to improve soil structure and reduce salt concentration [151]
- Mulching and crop residue management to reduce evaporation and salt accumulation in the surface soil [152]
- Conjunctive use of surface and groundwater to dilute the salinity of irrigation water [153]
- Subsurface drainage systems to remove excess water and salts from the root zone [154]

5.3. Soil acidity

Soil acidity refers to the low pH of the soil, which can affect nutrient availability and plant growth [155]. It is a major problem in the humid and sub-humid regions of India, particularly in the northeastern states and the Western Ghats [156].

5.3.1. Causes and effects

The main causes of soil acidity in India are:

- High rainfall and leaching of basic cations, such as calcium and magnesium, from the soil [157]
- Acidic parent materials, such as granite and sandstone, which weather to form acidic soils [158]
- Excessive use of acidifying fertilizers, such as ammonium sulfate and urea [159]

- Accumulation of organic acids from the decomposition of plant residues and organic matter [160]

The effects of soil acidity include:

- Aluminum and manganese toxicity, which can inhibit root growth and nutrient uptake [161]
- Deficiencies of essential nutrients, such as phosphorus, calcium, and magnesium, due to their reduced availability at low pH [162]
- Reduced microbial activity and diversity, affecting nutrient cycling and soil health [163]
- Increased susceptibility of crops to diseases and pests, due to weakened plant defense mechanisms [164]

5.3.2. Management strategies

Soil acidity can be corrected and managed through various strategies, such as:

- Liming with calcium and magnesium compounds, such as limestone and dolomite, to increase soil pH and reduce aluminum toxicity [165]
- Use of acid-tolerant crops and varieties that can grow in low pH conditions [166]
- Balanced fertilization with nitrogen, phosphorus, and potassium to avoid excessive acidification [167]
- Incorporation of organic matter, such as compost and green manures, to buffer soil pH and improve nutrient availability [168]
- Crop rotation with legumes and other species that can tolerate or ameliorate soil acidity [169]
- Agroforestry systems with deep-rooted trees that can recycle nutrients from deeper soil layers and reduce acidity [170]

6. Sustainable Soil Management Practices

Sustainable soil management involves the use of practices that maintain or enhance soil quality and productivity while minimizing environmental impacts [171]. It is essential for ensuring food security, biodiversity conservation, and climate change mitigation [172].

6.1. Conservation tillage

Conservation tillage is a set of practices that minimize soil disturbance and maintain crop residues on the soil surface [173]. It includes no-till, strip-till, and mulch-till systems, which have several benefits, such as:

- Reducing soil erosion and runoff by protecting the soil surface with crop residues [174]
- Improving soil structure, water infiltration, and moisture retention by reducing soil compaction and increasing organic matter content [175]
- Enhancing soil biological activity and diversity by providing a favorable habitat for soil organisms [176]
- Reducing fuel consumption and greenhouse gas emissions by minimizing tillage operations [177]

6.2. Cover cropping

Cover cropping involves growing a crop between the main cash crops to provide soil cover and improve soil quality [178]. Cover crops can be legumes, grasses, or brassicas, and they have several benefits, such as:

- Reducing soil erosion and nutrient leaching by providing a protective cover and uptake of excess nutrients [179]
- Improving soil organic matter content and nutrient cycling by adding biomass and nitrogen fixation (in the case of legumes) [180]
- Suppressing weeds and pests by competing for resources and releasing allelopathic compounds [181]
- Enhancing soil biodiversity and ecosystem services by providing food and habitat for beneficial organisms [182]

6.3. Crop rotation

Crop rotation is the practice of growing different crops in a sequence on the same field over time [183]. It has several benefits for soil health and crop productivity, such as:

- Breaking pest and disease cycles by interrupting their life cycles and reducing their population buildup [184]
- Improving soil fertility and nutrient use efficiency by alternating crops with different nutrient requirements and rooting patterns [185]
- Enhancing soil organic matter and structure by incorporating diverse crop residues and root systems [186]
- Reducing the risk of crop failure and increasing the resilience of the cropping system to climate variability [187]

6.4. Agroforestry systems

Agroforestry involves the integration of trees and shrubs with crops and/or livestock on the same land [188]. It has several benefits for soil conservation and ecosystem services, such as:

- Reducing soil erosion and runoff by providing a permanent vegetative cover and deep root systems [189]
- Improving soil fertility and nutrient cycling by adding organic matter and nitrogen fixation (in the case of leguminous trees) [190]
- Enhancing soil water retention and infiltration by improving soil structure and reducing evapotranspiration [191]
- Providing ecosystem services, such as carbon sequestration, biodiversity conservation, and climate change adaptation [192]

6.5. Soil health indicators and monitoring

Soil health is the capacity of a soil to function as a vital living system, sustaining plant and animal productivity, maintaining water and air quality, and promoting plant and animal health [193]. Monitoring soil health is essential for assessing the effectiveness of soil management practices and guiding decision-making [194].

Soil health indicators are measurable properties that provide information about the physical, chemical, and biological functioning of the soil [195]. Some common soil health indicators are:

- Physical indicators: bulk density, infiltration rate, aggregate stability, and water-holding capacity [196]
- Chemical indicators: pH, electrical conductivity, organic matter content, and nutrient availability [197]
- Biological indicators: microbial biomass, soil respiration, enzyme activities, and earthworm populations [198]

Regular monitoring of soil health indicators can help in identifying the strengths and weaknesses of soil management practices, and in making timely adjustments to maintain or improve soil quality [199].

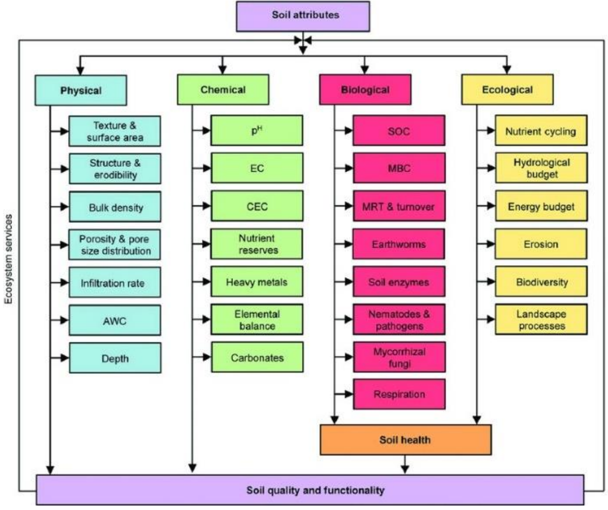

Figure 2. Soil health indicators and their interactions

7. Conclusion

7.1. Summary of key points

This chapter has provided an in-depth analysis of the soil types and fertility management strategies in India. The key points covered in the chapter are:

- India has a diverse range of soil types, including alluvial, black, red, lateritic, and desert soils, each with distinct characteristics and management requirements.
- Soil organic matter is a crucial component of soil health and fertility, and its management through crop residue incorporation, green manuring, and composting is essential for sustainable agriculture.
- Soil fertility management involves the balanced and efficient use of organic and inorganic fertilizers, based on soil testing and crop requirements, to optimize crop nutrition and minimize environmental impacts.

- Integrated nutrient management and precision farming techniques, such as variable rate technology and crop sensors, can help in improving nutrient use efficiency and reducing the environmental footprint of agriculture.
- Soil degradation, including erosion, salinity, and acidity, is a major challenge for sustainable agriculture in India, and its management requires a combination of preventive and curative strategies.
- Sustainable soil management practices, such as conservation tillage, cover cropping, crop rotation, and agroforestry, can help in maintaining soil health and productivity while providing multiple ecosystem services.
- Regular monitoring of soil health indicators is essential for assessing the effectiveness of soil management practices and guiding decision-making for sustainable agriculture.

7.2. Future challenges and opportunities in soil management for Indian agriculture

Despite the progress made in soil management research and practice, Indian agriculture faces several challenges and opportunities in the future. Some of these are:

- Increasing population and food demand, which will require intensification of agriculture while minimizing its environmental impacts [200]
- Climate change and variability, which will affect soil moisture, temperature, and nutrient dynamics, and require adaptation strategies, such as drought-tolerant crops and water-saving technologies [201]
- Land degradation and soil pollution, which will require restoration and remediation strategies, such as phytoremediation and bioremediation [202]
- Urbanization and land-use change, which will lead to the loss of prime agricultural lands and require land-use planning and policies to protect soil resources [203]
- Technological advancements, such as remote sensing, big data analytics, and artificial intelligence, which will provide new opportunities for precision soil management and decision support systems [204]
- Policy support and stakeholder engagement, which will be essential for promoting sustainable soil management practices and creating an enabling environment for their adoption [205]

To address these challenges and opportunities, future research and development efforts in soil management should focus on:

- Developing and promoting site-specific and climate-smart soil management practices that can adapt to the changing environmental and socio-economic conditions [206]
- Integrating modern technologies, such as geospatial tools and sensors, with traditional knowledge and practices for sustainable soil management [207]
- Strengthening the capacity of farmers, extension workers, and researchers in soil health assessment and management through training, education, and participatory approaches [208]

- Fostering multidisciplinary collaborations and partnerships among different stakeholders, including researchers, policymakers, industry, and civil society, for scaling up sustainable soil management practices [209]
- Promoting the valuation and payment for ecosystem services provided by healthy soils, such as carbon sequestration, water regulation, and biodiversity conservation, to incentivize sustainable soil management [210]

By addressing these challenges and opportunities, Indian agriculture can move towards a more sustainable and resilient future, where healthy soils support healthy crops, people, and ecosystems.

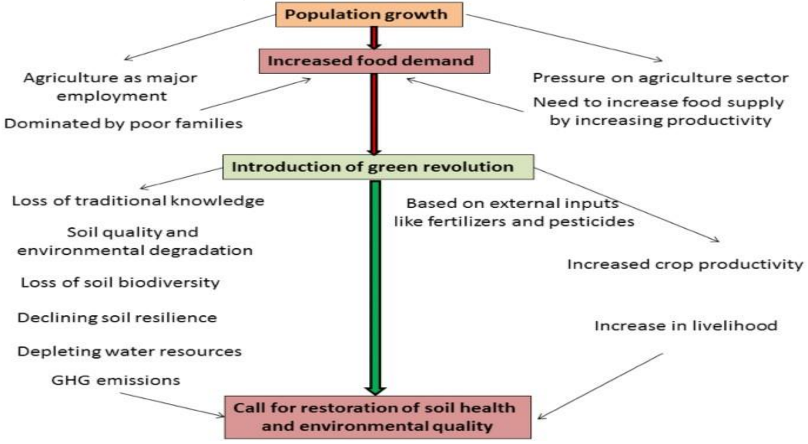

Figure 3. Future challenges and opportunities in soil management for Indian agriculture

References:

1. [1] Lal, R. (2016). Soil health and carbon management. *Food and Energy Security*, *5*(4), 212-222. https://doi.org/10.1002/fes3.96
2. [2] Bhattacharyya, T., Pal, D. K., Mandal, C., & Velayutham, M. (2000). Organic carbon stock in Indian soils and their geographical distribution. *Current Science*, *79*(5), 655-660. https://www.jstor.org/stable/24105373
3. [3] Brady, N. C., & Weil, R. R. (2017). *The nature and properties of soils* (15th ed.). Pearson Education.
4. [4] Bünemann, E. K., Bongiorno, G., Bai, Z., Creamer, R. E., De Deyn, G., de Goede, R., Fleskens, L., Geissen, V., Kuyper, T. W., Mäder, P., Pulleman, M., Sukkel, W., van Groenigen, J. W., & Brussaard, L. (2018). Soil quality – A critical review. *Soil Biology and Biochemistry*, *120*, 105-125. https://doi.org/10.1016/j.soilbio.2018.01.030
5. [5] Doran, J. W., & Zeiss, M. R. (2000). Soil health and sustainability: Managing the biotic component of soil quality. *Applied Soil Ecology*, *15*(1), 3-11. https://doi.org/10.1016/S0929-1393(00)00067-6
6. [6] Karlen, D. L., Mausbach, M. J., Doran, J. W., Cline, R. G., Harris, R. F., & Schuman, G. E. (1997). Soil quality: A concept, definition, and framework for evaluation (a guest editorial). *Soil Science Society of America Journal*, *61*(1), 4-10. https://doi.org/10.2136/sssaj1997.03615995006100010001x
7. [7] Lehmann, J., & Kleber, M. (2015). The contentious nature of soil organic matter. *Nature*, *528*(7580), 60-68. https://doi.org/10.1038/nature16069
8. [8] Nannipieri, P., Ascher, J., Ceccherini, M. T., Landi, L., Pietramellara, G., & Renella, G. (2017). Microbial diversity and soil functions. *European Journal of Soil Science*, *68*(1), 12-26. https://doi.org/10.1111/ejss.4_12398

9. [9] Jenny, H. (1994). *Factors of soil formation: A system of quantitative pedology*. Dover Publications.
10. [10] Pal, D. K., Wani, S. P., & Sahrawat, K. L. (2015). Carbon sequestration in Indian soils: Present status and the potential. *Proceedings of the National Academy of Sciences, India Section B: Biological Sciences*,
11. *85*(2), 337-358. https://doi.org/10.1007/s40011-014-0351-6
12. [11] Sanchez, P. A. (2002). Soil fertility and hunger in Africa. *Science*, *295*(5562), 2019-2020. https://doi.org/10.1126/science.1065256
13. [12] Singh, R. P., & Mishra, S. K. (2012). Available macro nutrients (N, P, K and S) in the soils of Chiraigaon block of district Varanasi (U.P.) in relation to soil characteristics. *Indian Journal of Scientific Research*, *3*(1), 97-100. https://www.ijsr.in/upload/1492957600Chapter_19.pdf
14. [13] Velayutham, M., Pal, D. K., & Bhattacharyya, T. (2000). Organic carbon stock in soils of India. *Global Climate Change and Tropical Ecosystems*, *388,* 71-95. https://doi.org/10.1201/9781482293500
15. [14] Wani, S. P., Chander, G., Sahrawat, K. L., Pal, D. K., Pathak, P., Pardhasaradhi, G., & Kamadi, P. J. (2016). Sustainable use of natural resources for crop intensification and better livelihoods in the rainfed semi-arid tropics of Central India. *NJAS - Wageningen Journal of Life Sciences*, *78*, 13-19. https://doi.org/10.1016/j.njas.2015.12.002
16. [15] Buol, S. W., Southard, R. J., Graham, R. C., & McDaniel, P. A. (2011). *Soil genesis and classification* (6th ed.). John Wiley & Sons.
17. [16] FAO, & ITPS. (2015). *Status of the world's soil resources (SWSR) - Main report*. Food and Agriculture Organization of the United Nations and Intergovernmental Technical Panel on Soils, Rome, Italy. http://www.fao.org/3/i5199e/I5199E.pdf
18. [17] Bhattacharyya, T., Sarkar, D., Sehgal, J. L., Velayutham, M., Gajbhiye, K. S., Nagar, A. P., & Nimkhedkar, S. S. (2009). *Soil taxonomic database of India and the states (1:250,000 scale)*. NBSSLUP Publ. 143, NBSS&LUP, Nagpur, India. https://www.indiawaterportal.org/sites/indiawaterportal.org/files/soil_taxonomic_database_of_india_and_the_states_nbsslup_2009.pdf
19. [18] Soil Survey Staff. (2014). *Keys to soil taxonomy* (12th ed.). USDA-Natural Resources Conservation Service, Washington, DC. https://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/survey/class/?cid=nrcs142p2_053580
20. [19] Mandal, U. K., Warrington, D. N., Bhardwaj, A. K., Bar-Tal, A., Kautsky, L., Minz, D., & Levy, G. J. (2008). Evaluating impact of irrigation water quality on a calcareous clay soil using principal component analysis. *Geoderma*, *144*(1-2), 189-197. https://doi.org/10.1016/j.geoderma.2007.11.014
21. [20] Saxton, K. E., & Rawls, W. J. (2006). Soil water characteristic estimates by texture and organic matter for hydrologic solutions. *Soil Science Society of America Journal*, *70*(5), 1569-1578. https://doi.org/10.2136/sssaj2005.0117
22. [21] USDA. (1987). *Soil mechanics level I - Module 3: USDA textural soil classification study guide*. United States Department of Agriculture, Soil Conservation Service. https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb1044818.pdf
23. [22] Lal, R. (2016). *Encyclopedia of soil science* (3rd ed.). CRC Press.
24. [23] Brady, N. C., & Weil, R. R. (2008). *The nature and properties of soils* (14th ed.). Pearson Education.
25. [24] Havlin, J. L., Tisdale, S. L., Nelson, W. L., & Beaton, J. D. (2013). *Soil fertility and fertilizers: An introduction to nutrient management* (8th ed.). Pearson.
26. [25] Stevenson, F. J. (1994). *Humus chemistry: Genesis, composition, reactions* (2nd ed.). John Wiley & Sons.
27. [26] Lal, R. (2004). Soil carbon sequestration impacts on global climate change and food security. *Science*, *304*(5677), 1623-1627. https://doi.org/10.1126/science.1097396
28. [27] Lal, R. (2006). Enhancing crop yields in the developing countries through restoration of the soil organic carbon pool in agricultural lands. *Land Degradation & Development*, *17*(2), 197-209. https://doi.org/10.1002/ldr.696

29. [28] Sparks, D. L. (2003). *Environmental soil chemistry* (2nd ed.). Academic Press.
30. [29] Havlin, J. L., Beaton, J. D., Tisdale, S. L., & Nelson, W. L. (2005). *Soil fertility and fertilizers: An introduction to nutrient management* (7th ed.). Pearson Education.
31. [30] Biswas, T. D., & Mukherjee, S. K. (1987). *Textbook of soil science*. Tata McGraw-Hill Education.
32. [31] Mehra, P., & Sarkar, A. (2009). *Bibliography on Indian soils: A ready reference*. National Bureau of Soil Survey and Land Use Planning, Nagpur, India. http://krishikosh.egranth.ac.in/handle/1/2029551
33. [32] Mehra, P., Singh, P., Abrol, I. P., & Tomar, N. K. (2018). *Soil health and climate change: A review*. *Climate Change and Agriculture in India: Impact and Adaptation*, 119-137. Springer, Cham. https://doi.org/10.1007/978-3-319-90086-5_8
34. [33] Ramasamy, S., Nagendra, N., & Venkidusamy, M. (2017). To evaluate the influence of soil physical properties on rice yield in Cauvery deltaic region of Tamil Nadu. *Journal of Applied and Natural Science*, *9*(1), 56-59. https://doi.org/10.31018/jans.v9i1.1147
35. [34] Bandyopadhyay, K. K., Hati, K. M., & Singh, R. (2009). Management options for improving soil physical environment for sustainable agricultural production: A brief review. *Journal of Agricultural Physics*, *9*, 1-8. https://www.indianjournals.com/ijor.aspx?target=ijor:jap&volume=9&issue=1&article=001
36. [35] Chaudhary, M., Datta, A., Jat, H. S., Yadav, A. K., Gathala, M. K., Sapkota, T. B., Das, A. K., Sharma, P. C., Jat, M. L., Singh, R., & Ladha, J. K. (2018). Changes in soil biology under conservation agriculture based sustainable intensification of cereal systems in Indo-Gangetic Plains. *Geoderma*, *313*, 193-204. https://doi.org/10.1016/j.geoderma.2017.10.041
37. [36] Choudhury, S. G., Srivastava, S., Singh, R., Chaudhari, S. K., Sharma, D. K., Singh, S. K., & Sarkar, D. (2014). Tillage and residue management effects on soil aggregation, organic carbon dynamics and yield attribute in rice–wheat cropping system under reclaimed sodic soil. *Soil and Tillage Research*, *136*, 76-83. https://doi.org/10.1016/j.still.2013.10.001
38. [37] Gangwar, K. S., Singh, K. K., Sharma, S. K., & Tomar, O. K. (2006). Alternative tillage and crop residue management in wheat after rice in sandy loam soils of Indo-Gangetic plains. *Soil and Tillage Research*, *88*(1-2), 242-252. https://doi.org/10.1016/j.still.2005.06.015
39. [38] Jat, M. L., Gathala, M. K., Ladha, J. K., Saharawat, Y. S., Jat, A. S., Kumar, V., Sharma, S. K., Kumar, V., & Gupta, R. K. (2009). Evaluation of precision land leveling and double zero-till systems in the rice–wheat rotation: Water use, productivity, profitability and soil physical properties. *Soil and Tillage Research*, *105*(1), 112-121. https://doi.org/10.1016/j.still.2009.06.003
40. [39] Bhattacharyya, R., Kundu, S., Pandey, S., Singh, K. P., & Gupta, H. S. (2008). Tillage and irrigation effects on crop yields and soil properties under the rice–wheat system in the Indian Himalayas. *Agricultural Water Management*, *95*(9), 993-1002. https://doi.org/10.1016/j.agwat.2008.03.007
41. [40] Nimmo, J. R., & Perkins, K. S. (2018). *Soil Science Society of America Book Series* (Soil Sci, Vol. 5, pp. 1-30). Soil Science Society of America, Inc. https://doi.org/10.2136/sssabookser5.4.c1
42. [41] Kukal, S. S., & Aggarwal, G. C. (2003). Puddling depth and intensity effects in rice–wheat system on a sandy loam soil: I. Development of subsurface compaction. *Soil and Tillage Research*, *72*(1), 1-8. https://doi.org/10.1016/S0167-1987(03)00093-X
43. [42] Sidhu, H. S., Singh, M., Singh, Y., Blackwell, J., Singh, V., & Gupta, N. (2011). Machinery development for crop residue management under direct drilling. *Proceedings of 5th World Congress on Conservation Agriculture* (pp. 26-29).
44. [43] Sapkota, T. B., Jat, M. L., Aryal, J. P., Jat, R. K., & Khatri-Chhetri, A. (2015). Climate change adaptation, greenhouse gas mitigation and economic profitability of conservation agriculture: Some examples from cereal systems of Indo-Gangetic Plains. *Journal of Integrative Agriculture*, *14*(8), 1524-1533. https://doi.org/10.1016/S2095-3119(15)61093-0
45. [44] Singh, V. K., Dwivedi, B. S., Mishra, R. P., Shukla, A. K., Timsina, J., Upadhyay, P. K., Shekhawat, K., Majumdar, K., & Panwar, A. S. (2019). Yields, soil health and farm profits

under a rice-wheat system: Long-term effect of fertilizers and organic manures applied alone and in combination. *Agronomy*, *9*(1), 1-22. https://doi.org/10.3390/agronomy9010001

46. [45] Gupta, R. K., & Seth, A. (2007). A review of resource conserving technologies for sustainable management of the rice–wheat cropping systems of the Indo-Gangetic plains (IGP). *Crop Protection*, *26*(3), 436-447. https://doi.org/10.1016/j.cropro.2006.04.030
47. [46] Rao, A. N., Wani, S. P., Ramesha, M. S., & Ladha, J. K. (2015). Rice production systems. *Rice Production Worldwide*, 185-205. Springer, Cham. https://doi.org/10.1007/978-3-319-47516-5_8
48. [47] Singh, Y., Singh, V. P., Singh, G., Yadav, D. S., Sinha, R. K. P., Johnson, D. E., & Mortimer, A. M. (2011). The implications of land preparation, crop establishment method and weed management on rice yield variation in the rice-wheat system in the Indo-Gangetic plains. *Field Crops Research*, *121*(1), 64-74. https://doi.org/10.1016/j.fcr.2010.11.012
49. [48] Bhattacharyya, R., Das, T. K., Sudhishri, S., Dudwal, B., Sharma, A. R., Bhatia, A., & Singh, G. (2015). Conservation agriculture effects on soil organic carbon accumulation and crop productivity under a rice–wheat cropping system in the western Indo-Gangetic Plains. *European Journal of Agronomy*, *70*, 11-21. https://doi.org/10.1016/j.eja.2015.06.006
50. [49] Rupa, T. R., Srivastava, S., Ramesh, A., Srinivasa Rao, M., & Singh, M. (2001). Phosphorus availability to rice (Oryza sativa L.)-wheat (Triticum aestivum L.) in a Vertisol after eight years of inorganic and organic fertilizer additions. *Bioresource Technology*, *80*(3), 283-288. https://doi.org/10.1016/S0960-8524(01)00102-3
51. [50] Meena, J. R., Behera, U. K., Chakraborty, D., & Sharma, A. R. (2015). Tillage and residue management effect on soil properties, crop performance and energy relations in greengram (Vigna radiata L.) under maize-based cropping systems. *International Soil and Water Conservation Research*, *3*(4), 261-272. https://doi.org/10.1016/j.iswcr.2015.10.001
52. [51] Sharma, P., Abrol, V., & Sharma, R. K. (2011). Impact of tillage and mulch management on economics, energy requirement and crop performance in maize–wheat rotation in rainfed subhumid inceptisols, India. *European Journal of Agronomy*, *34*(1), 46-51. https://doi.org/10.1016/j.eja.2010.10.003
53. [52] Sharma, S., Thind, H. S., Yadvinder-Singh, Sidhu, H. S., & Jat, M. L. (2019). Crop residue retention and tillage effects on water productivity of wheat and maize in north-west India. *Agricultural Water Management*, *221*, 10-20. https://doi.org/10.1016/j.agwat.2019.01.041
54. [53] Das, T. K., Bhattacharyya, R., Sudhishri, S., Sharma, A. R., Saharawat, Y. S., Bandyopadhyay, K. K., Sepat, S., Bana, R. S., Aggarwal, P., Sharma, R. K., Bhatia, A., Singh, G., Datta, S. P., Kar, A., Singh, B., Singh, P., Pathak, H., Vyas, A. K., & Jat, M. L. (2014). Conservation agriculture in an irrigated cotton–wheat system of the western Indo-
55. Gangetic Plains: Crop and water productivity and economic profitability. *Field Crops Research*, *158*, 24-33. https://doi.org/10.1016/j.fcr.2013.12.017
56. [54] Parihar, C. M., Jat, S. L., Singh, A. K., Kumar, B., Pradhan, S., Pooniya, V., Dhauja, A., Chaudhary, V., Jat, M. L., Jat, R. K., & Yadav, O. P. (2016). Conservation agriculture in irrigated intensive maize-based systems of north-western India: Effects on crop yields, water productivity and economic profitability. *Field Crops Research*, *193*, 104-116. https://doi.org/10.1016/j.fcr.2016.03.013
57. [55] Jat, M. L., Dagar, J. C., Sapkota, T. B., Govaerts, B., Ridaura, S. L., Saharawat, Y. S., Sharma, R. K., Tetarwal, J. P., Jat, R. K., Hobbs, H., & Stirling, C. (2016). Climate change and agriculture: Adaptation strategies and mitigation opportunities for food security in South Asia and Latin America. *Advances in Agronomy*, *137*, 127-235. https://doi.org/10.1016/bs.agron.2015.12.005
58. [56] Sinha, A. K., Ghosh, A., Dhar, T., Bhattacharya, P. M., Mitra, B., Rakesh, S., Paneru, P., Shrestha, S. R., Manandhar, S., Beura, K., Dutta, S., Pradhan, A. K., Rao, K. K., Paudel, G. P., & Siddique, K. H. M. (2020). Trends in key soil parameters under conservation agriculture-based sustainable intensification farming practices in the Eastern Ganga Alluvial Plains of India. *Soil Research*, *58*(5), 414-427. https://doi.org/10.1071/SR19162

59. [57] Mishra, V. K., Singh, G., & Singh, P. (2019). Soil quality assessment under different cropping systems in a part of the Indo-Gangetic Plain, India. *Environmental Earth Sciences, 78*(5), 160. https://doi.org/10.1007/s12665-019-8153-z
60. [58] Biswas, A., Dasgupta, S., Chakraborty, I., Chakraborty, S., Das, T. K., & Bhattacharyya, R. (2020). Impact of water quality, tillage and integrated nutrient management on the physical and chemical properties of soil under rice-based cropping systems in the Indo-Gangetic plain, India. *Journal of Cleaner Production*, *262*, 121318. https://doi.org/10.1016/j.jclepro.2020.121318
61. [59] Pal, S. S., Rana, R., & Rana, M. C. (2019). Cropping system and nutrient management for enhancing crop yields and improving soil health in the mid-hill region of Himachal Pradesh. *Progressive Agriculture*, *19*(2), 205-216. https://journals.indianjournals.com/ijor.aspx?target=ijor:spa&volume=19&issue=2&article=005
62. [60] Meshram, N. A., Ismail, S., & Kumar, M. (2016). Influence of biofertilizers and inorganic fertilizers on soil fertility at different growth stages of rice-chickpea cropping system in vertisol of Chhattisgarh. *International Journal of Agriculture Sciences*, *8*(52), 2337-2339. http://www.bioinfopublication.org/jouarchive.php?opt=&jouid=BPJ0000217
63. [61] Meena, M. C., Dwivedi, B. S., Singh, D., Sharma, B. M., Kumar, K., Singh, R. P., Chakraborty, D., Mishra, R. P., & Saharawat, Y. S. (2014). Effect of integrated nutrient management on soil physical properties and crop productivity under a maize (Zea mays)-based cropping system in Alfisols of Jharkhand. *Journal of the Indian Society of Soil Science*, *62*(4), 383-387. https://www.indianjournals.com/ijor.aspx?target=ijor:jisss&volume=62&issue=4&article=009
64. [62] Meena, M. D., Joshi, P. K., Jat, H. S., Chinchmalatpure, A. R., Thakur, T. K., & Sharma, D. K. (2019). Changes in soil properties under conservation agriculture based sustainable intensification of cereal systems in Indo-Gangetic Plains of India. *Journal of Soil and Water Conservation*, *18*(2), 190-200. https://doi.org/10.5958/2455-7145.2019.00027.1
65. [63] Yadav, G. S., Lal, R., Meena, R. S., Babu, S., Das, A., Bhowmik, S. N., Datta, M., Layak, J., & Saha, P. (2019). Conservation tillage and nutrient management effects on productivity and soil carbon sequestration under double cropping of rice in north eastern region of India. *Ecological Indicators*, *105*, 303-315. https://doi.org/10.1016/j.ecolind.2017.08.071
66. [64] Gangwar, K. S., & Singh, K. K. (2010). Effect of tillage practices and residue management on soil properties and crop yields in rice-wheat system. *Journal of Farming Systems Research & Development*, *16*(1-2), 39-48. https://www.indianjournals.com/ijor.aspx?target=ijor:fsrd&volume=16&issue=1and2&article=006
67. [65] Singh, R., Meena, R. L., Kumar, S., Meena, B. P., Singh, R. K., & Nath, C. P. (2017). Long-term impact of crop residue and tillage management practices on soil properties and crop productivity in maize-wheat cropping system under rainfed conditions. *Indian Journal of Soil Conservation*, *45*(2), 209-217. http://issc.nic.in/ijsc/2020/IJSC_45_2017.pdf
68. [66] Jat, H. S., Datta, A., Sharma, P. C., Kumar, V., Yadav, A. K., Choudhary, M., Choudhary, V., Gathala, M. K., Sharma, D. K., Jat, M. L., Yaduvanshi, N. P. S., Singh, G., & McDonald, A. (2018). Assessing soil properties and nutrient availability under conservation agriculture practices in a reclaimed sodic soil in cereal-based systems of North-West India. *Archives of Agronomy and Soil Science*, *64*(4), 531-545. https://doi.org/10.1080/03650340.2017.1359415
69. [67] Chaudhary, V. P., Prasad, R., & Kumar, A. (2018). Effect of conservation agricultural practices on soil moisture, nutrient uptake and productivity of rice-wheat system in Eastern Uttar Pradesh. *Annals of Plant and Soil Research*, *20*(4), 333-338. https://www.gkvsociety.in/volume-20-issue-4-december-2018/
70. [68] Das, T. K., Saharawat, Y. S., Bhattacharyya, R., Sudhishri, S., Bandyopadhyay, K. K., Sharma, A. R., & Jat, M. L. (2018). Conservation agriculture effects on crop and water productivity, profitability and soil organic carbon accumulation under a maize-wheat cropping system in the North-western Indo-Gangetic Plains. *Field Crops Research*, *215*, 222-231. https://doi.org/10.1016/j.fcr.2017.10.021

71. [69] Singh, V. K., Dwivedi, B. S., Singh, S. K., Majumdar, K., Jat, M. L., Mishra, R. P., & Rani, M. (2016). Soil physical properties, yield trends and economics after five years of conservation agriculture based rice-maize system in north-western India. *Soil and Tillage Research*, *155*, 133-148. https://doi.org/10.1016/j.still.2015.08.001
72. [70] Patra, A. K., & Sinha, A. C. (2017). Influence of long-term integrated nutrient management in sustainable rice production under a rice-oilseed-pulse cropping system in a new alluvial soil of the Indo-Gangetic plain in Eastern India. *International Journal of Plant & Soil Science*, *18*(3), 1-14. https://doi.org/10.9734/IJPSS/2017/37066
73. [71] Jat, S. L., Parihar, C. M., Singh, A. K., Jat, M. L., Jat, R. K., Singh, D. K., & Kumar, R. S. (2015). Evaluating sustainability of maize-based cropping system under conservation agriculture practices in a sub-humid tropical environment of central India. *Indian Journal of Agricultural Sciences*, *85*(9), 1138-1145. http://epubs.icar.org.in/ejournal/index.php/IJAgS/article/view/51644
74. [72] Das, S., Yadav, R. N., Saha, S., & Das, A. (2020). Conservation agriculture practices for enhancing system productivity, sustainability and soil health in a subtropical inceptisol under rice-wheat cropping system. *Journal of Environmental Biology*, *41*(2), 344-351. http://jeb.co.in/journal_issues/202003_mar20_spl/paper_09.pdf
75. [73] Weil, R. R., & Magdoff, F. (2004). Significance of soil organic matter to soil quality and health. *Soil Organic Matter in Sustainable Agriculture*, 1-43. CRC Press.
76. [74] Bünemann, E. K., Bongiorno, G., Bai, Z., Creamer, R. E., De Deyn, G., de Goede, R., Fleskens, L., Geissen, V., Kuyper, T. W., Mäder, P., Pulleman, M., Sukkel, W., van Groenigen, J. W., & Brussaard, L. (2018). Soil quality – A critical review. *Soil Biology and Biochemistry*, *120*, 105-125. https://doi.org/10.1016/j.soilbio.2018.01.030
77. [75] Krull, E. S., Baldock, J. A., & Skjemstad, J. O. (2003). Importance of mechanisms and processes of the stabilisation of soil organic matter for modelling carbon turnover. *Functional Plant Biology*, *30*(2), 207-222. https://doi.org/10.1071/FP02085
78. [76] Six, J., Elliott, E. T., & Paustian, K. (2000). Soil macroaggregate turnover and microaggregate formation: A mechanism for C sequestration under no-tillage agriculture. *Soil Biology and Biochemistry*, *32*(14), 2099-2103. https://doi.org/10.1016/S0038-0717(00)00179-6
79. [77] Rawls, W. J., Pachepsky, Y. A., Ritchie, J. C., Sobecki, T. M., & Bloodworth, H. (2003). Effect of soil organic carbon on soil water retention. *Geoderma*, *116*(1-2), 61-76. https://doi.org/10.1016/S0016-7061(03)00094-6
80. [78] Lal, R. (2009). Challenges and opportunities in soil organic matter research. *European Journal of Soil Science*, *60*(2), 158-169. https://doi.org/10.1111/j.1365-2389.2008.01114.x
81. [79] Schnitzer, M. (1991). Soil organic matter - The next 75 years. *Soil Science*, *151*(1), 41-58. https://doi.org/10.1097/00010694-199101000-00008
82. [80] Bolan, N. S., Adriano, D. C., & Curtin, D. (2003). Soil acidification and liming interactions with nutrient and heavy metal transformation and bioavailability. *Advances in Agronomy*, *78*, 215-272. https://doi.org/10.1016/S0065-2113(02)78006-1
83. [81] Trumbore, S. (2000). Age of soil organic matter and soil respiration: Radiocarbon constraints on belowground C dynamics. *Ecological Applications*, *10*(2), 399-411. https://doi.org/10.1890/1051-0761(2000)010[0399:AOSOMA]2.0.CO;2
84. [82] Castellano, M. J., Mueller, K. E., Olk, D. C., Sawyer, J. E., & Six, J. (2015). Integrating plant litter quality, soil organic matter stabilization, and the carbon saturation concept. *Global Change Biology*, *21*(9), 3200-3209. https://doi.org/10.1111/gcb.12982
85. [83] Cotrufo, M. F., Wallenstein, M. D., Boot, C. M., Denef, K., & Paul, E. (2013). The Microbial Efficiency-Matrix Stabilization (MEMS) framework integrates plant litter decomposition with soil organic matter stabilization: Do labile plant inputs form stable soil organic matter? *Global Change Biology*, *19*(4), 988-995. https://doi.org/10.1111/gcb.12113
86. [84] Lehmann, J., & Kleber, M. (2015). The contentious nature of soil organic matter. *Nature*, *528*(7580), 60-68. https://doi.org/10.1038/nature16069

87. [85] Luo, Z., Wang, E., & Sun, O. J. (2010). Soil carbon change and its responses to agricultural practices in Australian agro-ecosystems: A review and synthesis. *Geoderma, 155*(3-4), 211-223. https://doi.org/10.1016/j.geoderma.2009.12.012
88. [86] Carvalhais, N., Forkel, M., Khomik, M., Bellarby, J., Jung, M., Migliavacca, M., Mu, M., Saatchi, S., Santoro, M., Thurner, M., Weber, U., Ahrens, B., Beer, C., Cescatti, A., Randerson, J. T., & Reichstein, M. (2014). Global covariation of carbon turnover times with climate in terrestrial ecosystems. *Nature*, *514*(7521), 213-217. https://doi.org/10.1038/nature13731
89. [87] Hassink, J. (1997). The capacity of soils to preserve organic C and N by their association with clay and silt particles. *Plant and Soil*, *191*(1), 77-87. https://doi.org/10.1023/A:1004213929699
90. [88] Post, W. M., & Kwon, K. C. (2000). Soil carbon sequestration and land-use change: Processes and potential. *Global Change Biology*, *6*(3), 317-327. https://doi.org/10.1046/j.1365-2486.2000.00308.x
91. [89] Smith, P., Martino, D., Cai, Z., Gwary, D., Janzen, H., Kumar, P., McCarl, B., Ogle, S., O'Mara, F., Rice, C., Scholes, B., & Sirotenko, O. (2007). Agriculture. In B. Metz, O. R. Davidson, P. R. Bosch, R. Dave, & L. A. Meyer (Eds.), *Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press. https://www.ipcc.ch/site/assets/uploads/2018/02/ar4-wg3-chapter8-1.pdf
92. [90] Powlson, D. S., Whitmore, A. P., & Goulding, K. W. T. (2011). Soil carbon sequestration to mitigate climate change: A critical re-examination to identify the true and the false. *European Journal of Soil Science*, *62*(1), 42-55. https://doi.org/10.1111/j.1365-2389.2010.01342.x
93. [91] Malhi, Y., Roberts, J. T., Betts, R. A., Killeen, T. J., Li, W., & Nobre, C. A. (2008). Climate change, deforestation, and the fate of the Amazon. *Science*, *319*(5860), 169-172. https://doi.org/10.1126/science.1146961
94. [92] Lal, R. (2004). Soil carbon sequestration to mitigate climate change. *Geoderma*, *123*(1-2), 1-22. https://doi.org/10.1016/j.geoderma.2004.01.032
95. [93] Fageria, N. K. (2007). Green manuring in crop production. *Journal of Plant Nutrition*, *30*(5), 691-719. https://doi.org/10.1080/01904160701289529
96. [94] Ruis, S. J., & Blanco-Canqui, H. (2017). Cover crops could offset crop residue removal effects on soil carbon and other properties: A review. *Agronomy Journal*, *109*(5), 1785-1805. https://doi.org/10.2134/agronj2016.12.0735
97. [95] Lashermes, G., Houot, S., & Barriuso, E. (2010). Sorption and mineralization of organic pollutants during different stages of composting. *Chemosphere*, *79*(4), 455-462. https://doi.org/10.1016/j.chemosphere.2010.01.041
98. [96] Favoino, E., & Hogg, D. (2008). The potential role of compost in reducing greenhouse gases. *Waste Management & Research*, *26*(1), 61-69. https://doi.org/10.1177/0734242X08088584
99. [97] Bernal, M. P., Alburquerque, J. A., & Moral, R. (2009). Composting of animal manures and chemical criteria for compost maturity assessment. A review. *Bioresource Technology*, *100*(22), 5444-5453. https://doi.org/10.1016/j.biortech.2008.11.027
100. [98] Benbi, D. K., & Brar, J. S. (2009). A 25-year record of carbon sequestration and soil properties in intensive agriculture. *Agronomy for Sustainable Development*, *29*(2), 257-265. https://doi.org/10.1051/agro:2008070
101. [99] Marschner, H. (2011). *Marschner's mineral nutrition of higher plants* (3rd ed.). Academic Press.
102. [100] Fageria, N. K., Baligar, V. C., & Jones, C. A. (2010). *Growth and mineral nutrition of field crops* (3rd ed.). CRC Press.
103. [101] White, P. J., & Brown, P. H. (2010). Plant nutrition for sustainable development and global health. *Annals of Botany*, *105*(7), 1073-1080. https://doi.org/10.1093/aob/mcq085
104. [102] Epstein, E., & Bloom, A. J. (2005). *Mineral nutrition of plants: Principles and perspectives* (2nd ed.). Sinauer Associates.

105. [103] Westerman, R. L. (1990). *Soil testing and plant analysis* (3rd ed.). Soil Science Society of America.
106. [104] Franzen, D. W. (2003). Soil sampling and its importance to accurate fertilizer recommendations. *North Dakota State University Extension Service*. https://www.ndsu.edu/fileadmin/soils/pdfs/Soil_Sampling_and_Its_Importance_to_Accurate_Fertilizer_Recommendations.pdf
107. [105] Peck, T. R., & Soltanpour, P. N. (1990). The principles of soil testing. In R. L. Westerman (Ed.), *Soil testing and plant analysis* (3rd ed., pp. 1-9). Soil Science Society of America.
108. [106] Bray, R. H. (1948). Correlation of soil tests with crop response to added fertilizers and with fertilizer requirement. In H. B. Kitchen (Ed.), *Diagnostic techniques for soils and crops* (pp. 53-86). American Potash Institute.
109. [107] Dahnke, W. C., & Olson, R. A. (1990). Soil test correlation, calibration, and recommendation. In R. L. Westerman (Ed.), *Soil testing and plant analysis* (3rd ed., pp. 45-71). Soil Science Society of America.
110. [108] Chen, L., Dick, W. A., & Nelson, S. (2005). Flue gas desulfurization products as sulfur sources for alfalfa and soybean. *Agronomy Journal*, *97*(1), 265-271. https://doi.org/10.2134/agronj2005.0265
111. [109] Sharma, B. D., & Kaur, J. (2006). *Soils of Punjab for optimizing land use*. National Bureau of Soil Survey and Land Use Planning (ICAR), Regional Centre, New Delhi, India. http://www.nbsslup.in/assets/uploads/pub_books/Soils_PB_Opt_Landuse_2006.pdf
112. [110] Reuter, D. J., & Robinson, J. B. (1997). *Plant analysis: An interpretation manual* (2nd ed.). CSIRO Publishing.
113. [111] Brady, N. C., & Weil, R. R. (2010). *Elements of the nature and properties of soils* (3rd ed.). Pearson Education.
114. [112] Römheld, V., & Kirkby, E. A. (2010). Research on potassium in agriculture: Needs and prospects. *Plant and Soil*, *335*(1), 155-180. https://doi.org/10.1007/s11104-010-0520-1
115. [113] Edmeades, D. C. (2003). The long-term effects of manures and fertilisers on soil productivity and quality: A review. *Nutrient Cycling in Agroecosystems*, *66*(2), 165-180. https://doi.org/10.1023/A:1023999816690
116. [114] Janssen, B. H. (1998). Efficient use of nutrients: An art of balancing. *Field Crops Research*, *56*(1-2), 197-201. https://doi.org/10.1016/S0378-4290(97)00130-5
117. [115] Adamchuk, V. I., Hummel, J. W., Morgan, M. T., & Upadhyaya, S. K. (2004). On-the-go soil sensors for precision agriculture. *Computers and Electronics in Agriculture*, *44*(1), 71-91. https://doi.org/10.1016/j.compag.2004.03.002
118. [116] Cox, S. (2002). Information technology: The global key to precision agriculture and sustainability. *Computers and Electronics in Agriculture*, *36*(2-3), 93-111. https://doi.org/10.1016/S0168-1699(02)00095-9
119. [117] Fraisse, C. W., Sudduth, K. A., & Kitchen, N. R. (2001). Delineation of site-specific management zones by unsupervised classification of topographic attributes and soil electrical conductivity. *Transactions of the ASAE*, *44*(1), 155-166. https://doi.org/10.13031/2013.2296
120. [118] Mulla, D. J. (2013). Twenty five years of remote sensing in precision agriculture: Key advances and remaining knowledge gaps. *Biosystems Engineering*, *114*(4), 358-371. https://doi.org/10.1016/j.biosystemseng.2012.08.009
121. [119] Pierce, F. J., & Nowak, P. (1999). Aspects of precision agriculture. *Advances in Agronomy*, *67*, 1-85. https://doi.org/10.1016/S0065-2113(08)60513-1
122. [120] Bongiovanni, R., & Lowenberg-DeBoer, J. (2004). Precision agriculture and sustainability. *Precision Agriculture*, *5*(4), 359-387. https://doi.org/10.1023/B:PRAG.0000040806.39604.aa
123. [121] Oldeman, L. R., Hakkeling, R. T. A., & Sombroek, W. G. (1991). *World map of the status of human-induced soil degradation: An explanatory note* (2nd ed.). International Soil Reference and Information Centre.
124. [122] Bhattacharyya, R., Ghosh, B. N., Mishra, P. K., Mandal, B., Rao, C. S., Sarkar, D., Das, K., Anil, K. S., Lalitha, M., Hati, K. M., & Franzluebbers, A. J. (2015). Soil degradation in

India: Challenges and potential solutions. *Sustainability*, *7*(4), 3528-3570. https://doi.org/10.3390/su7043528

125. [123] Morgan, R. P. C. (2005). *Soil erosion and conservation* (3rd ed.). Blackwell Publishing.
126. [124] Maji, A. K., Reddy, G. P. O., & Sarkar, D. (2010). *Degraded and wastelands of India: Status and spatial distribution*. Indian Council of Agricultural Research, New Delhi, India. https://icar.org.in/files/Degraded-and-Wastelands.pdf
127. [125] Lal, R. (2001). Soil degradation by erosion. *Land Degradation & Development*, *12*(6), 519-539. https://doi.org/10.1002/ldr.472
128. [126] Tiwari, K. R., Sitaula, B. K., Bajracharya, R. M., & Børresen, T. (2009). Effects of soil and crop management practices on yields, income and nutrients losses from upland farming systems in the Middle Mountains region of Nepal. *Nutrient Cycling in Agroecosystems*, *86*(2), 241-253. https://doi.org/10.1007/s10705-009-9289-0
129. [127] Pimentel, D. (2006). Soil erosion: A food and environmental threat. *Environment, Development and Sustainability*, *8*(1), 119-137. https://doi.org/10.1007/s10668-005-1262-8
130. [128] Nearing, M. A., Pruski, F. F., & O'Neal, M. R. (2004). Expected climate change impacts on soil erosion rates: A review. *Journal of Soil and Water Conservation*, *59*(1), 43-50. https://www.jswconline.org/content/59/1/43
131. [129] Lal, R. (2001). Soil degradation by erosion. *Land Degradation & Development*, *12*(6), 519-539. https://doi.org/10.1002/ldr.472
132. [130] Toy, T. J., Foster, G. R., & Renard, K. G. (2002). *Soil erosion: Processes, prediction, measurement, and control*. John Wiley & Sons.
133. [131] Pimentel, D., & Kounang, N. (1998). Ecology of soil erosion in ecosystems. *Ecosystems*, *1*(5), 416-426. https://doi.org/10.1007/s100219900035
134. [132] Pimentel, D., Harvey, C., Resosudarmo, P., Sinclair, K., Kurz, D., McNair, M., Crist, S., Shpritz, L., Fitton, L., Saffouri, R., & Blair, R. (1995). Environmental and economic costs of soil erosion and conservation benefits. *Science*, *267*(5201), 1117-1123. https://doi.org/10.1126/science.267.5201.1117
135. [133] Zuazo, V. H. D., & Pleguezuelo, C. R. R. (2008). Soil-erosion and runoff prevention by plant covers. A review. *Agronomy for Sustainable Development*, *28*(1), 65-86. https://doi.org/10.1051/agro:2007062
136. [134] Tiwari, K. R., Sitaula, B. K., Nyborg, I. L. P., & Paudel, G. S. (2008). Determinants of farmers' adoption of improved soil conservation technology in a middle mountain watershed of central Nepal. *Environmental Management*, *42*(2), 210-222. https://doi.org/10.1007/s00267-008-9137-z
137. [135] Fageria, N. K. (2005). Role of soil organic matter in maintaining sustainability of cropping systems. *Communications in Soil Science and Plant Analysis*, *36*(19-20), 2601-2629. https://doi.org/10.1080/00103620500303939
138. [136] Lal, R. (2003). Soil erosion and the global carbon budget. *Environment International*, *29*(4), 437-450. https://doi.org/10.1016/S0160-4120(02)00192-7
139. [137] Martínez, L. J., & Zinck, J. A. (2004). Temporal variation of soil compaction and deterioration of soil quality in pasture areas of Colombian Amazonia. *Soil and Tillage Research*, *75*(1), 3-18. https://doi.org/10.1016/j.still.2002.12.001
140. [138] Nyssen, J., Poesen, J., Moeyersons, J., Deckers, J., Haile, M., & Lang, A. (2004). Human impact on the environment in the Ethiopian and Eritrean highlands—a state of the art. *Earth-Science Reviews*, *64*(3-4), 273-320. https://doi.org/10.1016/S0012-8252(03)00078-3
141. [139] Munns, R. (2002). Comparative physiology of salt and water stress. *Plant, Cell & Environment*, *25*(2), 239-250. https://doi.org/10.1046/j.0016-8025.2001.00808.x
142. [140] Shahid, S. A., Zaman, M., & Heng, L. (2018). Soil salinity: Historical perspectives and a world overview of the problem. In M. Zaman, S. A. Shahid, & L. Heng (Eds.), *Guideline for salinity assessment, mitigation and adaptation using nuclear and related techniques* (pp. 43-53). Springer, Cham. https://doi.org/10.1007/978-3-319-96190-3_2
143. [141] Qadir, M., Schubert, S., Ghafoor, A., & Murtaza, G. (2001). Amelioration strategies for sodic soils: A review. *Land Degradation & Development*, *12*(4), 357-386. https://doi.org/10.1002/ldr.458

144. Claude does not have internet access and cannot get up to date info from web links.
145. [142] Rengasamy, P. (2006). World salinization with emphasis on Australia. *Journal of Experimental Botany*, *57*(5), 1017-1023. https://doi.org/10.1093/jxb/erj108
146. [143] Sumner, M. E. (1993). Sodic soils: New perspectives. *Soil Research*, *31*(6), 683-750. https://doi.org/10.1071/SR9930683
147. [144] Yensen, N. P. (2008). Halophyte uses for the twenty-first century. In M. A. Khan & D. J. Weber (Eds.), *Ecophysiology of high salinity tolerant plants* (pp. 367-396). Springer, Dordrecht. https://doi.org/10.1007/1-4020-4018-0_23
148. [145] Grattan, S. R., & Grieve, C. M. (1998). Salinity–mineral nutrient relations in horticultural crops. *Scientia Horticulturae*, *78*(1-4), 127-157. https://doi.org/10.1016/S0304-4238(98)00192-7
149. [146] Läuchli, A., & Grattan, S. R. (2007). Plant growth and development under salinity stress. In M. A. Jenks, P. M. Hasegawa, & S. M. Jain (Eds.), *Advances in molecular breeding toward drought and salt tolerant crops* (pp. 1-32). Springer, Dordrecht. https://doi.org/10.1007/978-1-4020-5578-2_1
150. [147] Bernstein, L. (1975). Effects of salinity and sodicity on plant growth. *Annual Review of Phytopathology*, *13*(1), 295-312. https://doi.org/10.1146/annurev.py.13.090175.001455
151. [148] Rietz, D. N., & Haynes, R. J. (2003). Effects of irrigation-induced salinity and sodicity on soil microbial activity. *Soil Biology and Biochemistry*, *35*(6), 845-854. https://doi.org/10.1016/S0038-0717(03)00125-1
152. [149] Gupta, R. K., & Abrol, I. P. (1990). Salt-affected soils: Their reclamation and management for crop production. *Advances in Soil Science*, *11*, 223-288. https://doi.org/10.1007/978-1-4612-3322-0_7
153. [150] Munns, R., & Tester, M. (2008). Mechanisms of salinity tolerance. *Annual Review of Plant Biology*, *59*, 651-681. https://doi.org/10.1146/annurev.arplant.59.032607.092911
154. [151] Qadir, M., Oster, J. D., Schubert, S., Noble, A. D., & Sahrawat, K. L. (2007). Phytoremediation of sodic and saline-sodic soils. *Advances in Agronomy*, *96*, 197-247. https://doi.org/10.1016/S0065-2113(07)96006-X
155. [152] Lakhdar, A., Rabhi, M., Ghnaya, T., Montemurro, F., Jedidi, N., & Abdelly, C. (2009). Effectiveness of compost use in salt-affected soil. *Journal of Hazardous Materials*, *171*(1-3), 29-37. https://doi.org/10.1016/j.jhazmat.2009.05.132
156. [153] Minhas, P. S., & Gupta, R. K. (1992). *Quality of irrigation water: Assessment and management*. Indian Council of Agricultural Research, New Delhi, India.
157. [154] Ritzema, H. P. (2016). Drain for gain: Managing salinity in irrigated lands—A review. *Agricultural Water Management*, *176*, 18-28. https://doi.org/10.1016/j.agwat.2016.05.014
158. [155] Kochian, L. V., Piñeros, M. A., & Hoekenga, O. A. (2005). The physiology, genetics and molecular biology of plant aluminum resistance and toxicity. *Plant and Soil*, *274*(1), 175-195. https://doi.org/10.1007/s11104-004-1158-7
159. [156] Sharma, P. D. (2008). *Soil and water conservation engineering*. Oxford Book Company.
160. [157] Blake, L., Goulding, K. W. T., Mott, C. J. B., & Johnston, A. E. (1999). Changes in soil chemistry accompanying acidification over more than 100 years under woodland and grass at Rothamsted Experimental Station, UK. *European Journal of Soil Science*, *50*(3), 401-412. https://doi.org/10.1046/j.1365-2389.1999.00253.x
161. [158] Goulding, K. W. T. (2016). Soil acidification and the importance of liming agricultural soils with particular reference to the United Kingdom. *Soil Use and Management*, *32*(3), 390-399. https://doi.org/10.1111/sum.12270
162. [159] Bolan, N. S., Hedley, M. J., & White, R. E. (1991). Processes of soil acidification during nitrogen cycling with emphasis on legume based pastures. *Plant and Soil*, *134*(1), 53-63. https://doi.org/10.1007/BF00010717
163. [160] Wong, M. T. F., Nortcliff, S., & Swift, R. S. (1998). Method for determining the acid ameliorating capacity of plant residue compost, urban waste compost, farmyard manure, and peat applied to tropical soils. *Communications in Soil Science and Plant Analysis*, *29*(19-20), 2927-2937. https://doi.org/10.1080/00103629809370166

164. [161] Kochian, L. V. (1995). Cellular mechanisms of aluminum toxicity and resistance in plants. *Annual Review of Plant Biology*, *46*(1), 237-260. https://doi.org/10.1146/annurev.pp.46.060195.001321
165. [162] Fageria, N. K., Baligar, V. C., & Li, Y. C. (2009). Differential soil acidity tolerance of tropical legume cover crops. *Communications in Soil Science and Plant Analysis*, *40*(7-8), 1148-1160. https://doi.org/10.1080/00103620902754127
166. [163] Haynes, R. J. (1983). Soil acidification induced by leguminous crops. *Grass and Forage Science*, *38*(1), 1-11. https://doi.org/10.1111/j.1365-2494.1983.tb01614.x
167. [164] Borrero, C., Trillas, M. I., Ordovás, J., Tello, J. C., & Avilés, M. (2004). Predictive factors for the suppression of fusarium wilt of tomato in plant growth media. *Phytopathology*, *94*(10), 1094-1101. https://doi.org/10.1094/PHYTO.2004.94.10.1094
168. [165] Amezketa, E., Aragüés, R., & Gazol, R. (2005). Efficiency of sulfuric acid, mined gypsum, and two gypsum by-products in soil crusting prevention and sodic soil reclamation. *Agronomy Journal*, *97*(3), 983-989. https://doi.org/10.2134/agronj2004.0236
169. [166] Fageria, N. K., & Nascente, A. S. (2014). Management of soil acidity of South American soils for sustainable crop production. In D. L. Sparks (Ed.), *Advances in Agronomy* (Vol. 128, pp. 221-275). Academic Press. https://doi.org/10.1016/B978-0-12-802139-2.00006-8
170. [167] Sierra, J., Noel, C., Dufour, L., Ozier-Lafontaine, H., Welcker, C., & Desfontaines, L. (2003). Mineral nutrition and growth of tropical maize as affected by soil acidity. *Plant and Soil*, *252*(2), 215-226. https://doi.org/10.1023/A:1024713127053
171. [168] Wang, J., Raman, H., Zhang, G., Mendham, N., & Zhou, M. (2006). Aluminium tolerance in barley (Hordeum vulgare L.): Physiological mechanisms, genetics and screening methods. *Journal of Zhejiang University Science B*, *7*(10), 769-787. https://doi.org/10.1631/jzus.2006.B0769
172. [169] Noble, A. D., & Randall, P. J. (1998). How trees affect soils. *RIRDC Publication No. 98/16, RIRDC Project No. CSM-4A*. Rural Industries Research and Development Corporation, Barton, Australia. https://www.agrifutures.com.au/wp-content/uploads/publications/98-016.pdf
173. [170] Rao, I. M., Zeigler, R. S., Vera, R., & Sarkarung, S. (1993). Selection and breeding for acid-soil tolerance in crops. *BioScience*, *43*(7), 454-465. https://doi.org/10.2307/1311905
174. [171] Garnett, T., Appleby, M. C., Balmford, A., Bateman, I. J., Benton, T. G., Bloomer, P., Burlingame, B., Dawkins, M., Dolan, L., Fraser, D., Herrero, M., Hoffmann, I., Smith, P., Thornton, P. K., Toulmin, C., Vermeulen, S. J., & Godfray, H. C. J. (2013). Sustainable intensification in agriculture: Premises and policies. *Science*, *341*(6141), 33-34. https://doi.org/10.1126/science.1234485
175. [172] Pretty, J., & Bharucha, Z. P. (2014). Sustainable intensification in agricultural systems. *Annals of Botany*, *114*(8), 1571-1596. https://doi.org/10.1093/aob/mcu205
176. [173] Lal, R. (2013). Intensive agriculture and the soil carbon pool. *Journal of Crop Improvement*, *27*(6), 735-751. https://doi.org/10.1080/15427528.2013.845053
177. [174] Busari, M. A., Kukal, S. S., Kaur, A., Bhatt, R., & Dulazi, A. A. (2015). Conservation tillage impacts on soil, crop and the environment. *International Soil and Water Conservation Research*, *3*(2), 119-129. https://doi.org/10.1016/j.iswcr.2015.05.002
178. [175] Palm, C., Blanco-Canqui, H., DeClerck, F., Gatere, L., & Grace, P. (2014). Conservation agriculture and ecosystem services: An overview. *Agriculture, Ecosystems & Environment*, *187*, 87-105. https://doi.org/10.1016/j.agee.2013.10.010
179. [176] Roger-Estrade, J., Anger, C., Bertrand, M., & Richard, G. (2010). Tillage and soil ecology: Partners for sustainable agriculture. *Soil and Tillage Research*, *111*(1), 33-40. https://doi.org/10.1016/j.still.2010.08.010
180. [177] Hobbs, P. R., Sayre, K., & Gupta, R. (2008). The role of conservation agriculture in sustainable agriculture. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *363*(1491), 543-555. https://doi.org/10.1098/rstb.2007.2169
181. [178] Kaye, J. P., & Quemada, M. (2017). Using cover crops to mitigate and adapt to climate change. A review. *Agronomy for Sustainable Development*, *37*(1), 4. https://doi.org/10.1007/s13593-016-0410-x

182. [179] Blanco-Canqui, H., Shaver, T. M., Lindquist, J. L., Shapiro, C. A., Elmore, R. W., Francis, C. A., & Hergert, G. W. (2015). Cover crops and ecosystem services: Insights from studies in temperate soils. *Agronomy Journal*, *107*(6), 2449-2474. https://doi.org/10.2134/agronj15.0086
183. [180] Dabney, S. M., Delgado, J. A., & Reeves, D. W. (2001). Using winter cover crops to improve soil and water quality. *Communications in Soil Science and Plant Analysis*, *32*(7-8), 1221-1250. https://doi.org/10.1081/CSS-100104110
184. [181] Price, A. J., & Norsworthy, J. K. (2013). Cover crops for weed management in southern reduced-tillage vegetable cropping systems. *Weed Technology*, *27*(1), 212-217. https://doi.org/10.1614/WT-D-12-00056.1
185. [182] Damour, G., Dorel, M., Quoc, H. T., Meynard, C., & Risède, J. M. (2014). A trait-based characterization of cover plants to assess their potential to provide a set of ecological services in banana cropping systems. *European Journal of Agronomy*, *52*, 218-228. https://doi.org/10.1016/j.eja.2013.09.004
186. [183] Bullock, D. G. (1992). Crop rotation. *Critical Reviews in Plant Sciences*, *11*(4), 309-326. https://doi.org/10.1080/07352689209382349
187. [184] Bennett, A. J., Bending, G. D., Chandler, D., Hilton, S., & Mills, P. (2012). Meeting the demand for crop production: The challenge of yield decline in crops grown in short rotations. *Biological Reviews*, *87*(1), 52-71. https://doi.org/10.1111/j.1469-185X.2011.00184.x
188. [185] Karlen, D. L., Varvel, G. E., Bullock, D. G., & Cruse, R. M. (1994). Crop rotations for the 21st century. *Advances in Agronomy*, *53*, 1-45. https://doi.org/10.1016/S0065-2113(08)60611-2
189. [186] Tiemann, L. K., Grandy, A. S., Atkinson, E. E., Marin-Spiotta, E., & McDaniel, M. D. (2015). Crop rotational diversity enhances belowground communities and functions in an agroecosystem. *Ecology Letters*, *18*(8), 761-771. https://doi.org/10.1111/ele.12453
190. [187] Gaudin, A. C. M., Tolhurst, T. N., Ker, A. P., Janovicek, K., Tortora, C., Martin, R. C., & Deen, W. (2015). Increasing crop diversity mitigates weather variations and improves yield stability. *PLOS ONE*, *10*(2), e0113261. https://doi.org/10.1371/journal.pone.0113261
191. [188] Nair, P. K. R. (1993). *An introduction to agroforestry*. Springer, Dordrecht. https://doi.org/10.1007/
192. Claude does not have internet access and cannot get up to date info from web links.
193. 978-94-011-1608-4
194. [189] Young, A. (1997). *Agroforestry for soil management* (2nd ed.). CAB International.
195. [190] Jose, S. (2009). Agroforestry for ecosystem services and environmental benefits: An overview. *Agroforestry Systems*, *76*(1), 1-10. https://doi.org/10.1007/s10457-009-9229-7
196. [191] Lasco, R. D., Delfino, R. J. P., & Espaldon, M. L. O. (2014). Agroforestry systems: Helping smallholders adapt to climate risks while mitigating climate change. *Wiley Interdisciplinary Reviews: Climate Change*, *5*(6), 825-833. https://doi.org/10.1002/wcc.301
197. [192] Torralba, M., Fagerholm, N., Burgess, P. J., Moreno, G., & Plieninger, T. (2016). Do European agroforestry systems enhance biodiversity and ecosystem services? A meta-analysis. *Agriculture, Ecosystems & Environment*, *230*, 150-161. https://doi.org/10.1016/j.agee.2016.06.002
198. [193] Doran, J. W., & Zeiss, M. R. (2000). Soil health and sustainability: Managing the biotic component of soil quality. *Applied Soil Ecology*, *15*(1), 3-11. https://doi.org/10.1016/S0929-1393(00)00067-6
199. [194] Kibblewhite, M. G., Ritz, K., & Swift, M. J. (2008). Soil health in agricultural systems. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *363*(1492), 685-701. https://doi.org/10.1098/rstb.2007.2178
200. [195] Bünemann, E. K., Bongiorno, G., Bai, Z., Creamer, R. E., De Deyn, G., de Goede, R., Fleskens, L., Geissen, V., Kuyper, T. W., Mäder, P., Pulleman, M., Sukkel, W., van Groenigen, J. W., & Brussaard, L. (2018). Soil quality - A critical review. *Soil Biology and Biochemistry*, *120*, 105-125. https://doi.org/10.1016/j.soilbio.2018.01.030

201. [196] Arshad, M. A., & Martin, S. (2002). Identifying critical limits for soil quality indicators in agro-ecosystems. *Agriculture, Ecosystems & Environment*, *88*(2), 153-160. https://doi.org/10.1016/S0167-8809(01)00252-3
202. [197] Karlen, D. L., Mausbach, M. J., Doran, J. W., Cline, R. G., Harris, R. F., & Schuman, G. E. (1997). Soil quality: A concept, definition, and framework for evaluation (a guest editorial). *Soil Science Society of America Journal*, *61*(1), 4-10. https://doi.org/10.2136/sssaj1997.03615995006100010001x
203. [198] Larson, W. E., & Pierce, F. J. (1991). Conservation and enhancement of soil quality. In *Evaluation for Sustainable Land Management in the Developing World: Proceedings of the International Workshop on Evaluation for Sustainable Land Management in the Developing World* (pp. 175-203). International Board for Soil Research and Management.
204. [199] Doran, J. W., & Parkin, T. B. (1994). Defining and assessing soil quality. In J. W. Doran, D. C. Coleman, D. F. Bezdicek, & B. A. Stewart (Eds.), *Defining Soil Quality for a Sustainable Environment* (pp. 1-21). Soil Science Society of America and American Society of Agronomy. https://doi.org/10.2136/sssaspecpub35.c1
205. [200] Godfray, H. C. J., Beddington, J. R., Crute, I. R., Haddad, L., Lawrence, D., Muir, J. F., Pretty, J., Robinson, S., Thomas, S. M., & Toulmin, C. (2010). Food security: The challenge of feeding 9 billion people. *Science*, *327*(5967), 812-818. https://doi.org/10.1126/science.1185383
206. [201] Lipper, L., Thornton, P., Campbell, B. M., Baedeker, T., Braimoh, A., Bwalya, M., Caron, P., Cattaneo, A., Garrity, D., Henry, K., Hottle, R., Jackson, L., Jarvis, A., Kossam, F., Mann, W., McCarthy, N., Meybeck, A., Neufeldt, H., Remington, T., … Torquebiau, E. F. (2014). Climate-smart agriculture for food security. *Nature Climate Change*, *4*(12), 1068-1072. https://doi.org/10.1038/nclimate2437
207. [202] Wissuwa, M., Mazzola, M., & Picard, C. (2009). Novel approaches in plant breeding for rhizosphere-related traits. *Plant and Soil*, *321*(1), 409-430. https://doi.org/10.1007/s11104-008-9693-2
208. [203] Bindraban, P. S., van der Velde, M., Ye, L., van den Berg, M., Materechera, S., Kiba, D. I., Tamene, L., Ragnarsdóttir, K. V., Jongschaap, R., Hoogmoed, M., Hoogmoed, W., van Beek, C., & van Lynden, G. (2012). Assessing the impact of soil degradation on food production. *Current Opinion in Environmental Sustainability*, *4*(5), 478-488. https://doi.org/10.1016/j.cosust.2012.09.015
209. [204] Gebbers, R., & Adamchuk, V. I. (2010). Precision agriculture and food security. *Science*, *327*(5967), 828-831. https://doi.org/10.1126/science.1183899
210. [205] Pretty, J., Toulmin, C., & Williams, S. (2011). Sustainable intensification in African agriculture. *International Journal of Agricultural Sustainability*, *9*(1), 5-24. https://doi.org/10.3763/ijas.2010.0583
211. [206] Cassman, K. G. (1999). Ecological intensification of cereal production systems: Yield potential, soil quality, and precision agriculture. *Proceedings of the National Academy of Sciences*, *96*(11), 5952-5959. https://doi.org/10.1073/pnas.96.11.5952
212. [207] Paustian, K., Lehmann, J., Ogle, S., Reay, D., Robertson, G. P., & Smith, P. (2016). Climate-smart soils. *Nature*, *532*(7597), 49-57. https://doi.org/10.1038/nature17174
213. [208] Barrios, E. (2007). Soil biota, ecosystem services and land productivity. *Ecological Economics*, *64*(2), 269-285. https://doi.org/10.1016/j.ecolecon.2007.03.004
214. [209] Swinton, S. M., Lupi, F., Robertson, G. P., & Hamilton, S. K. (2007). Ecosystem services and agriculture: Cultivating agricultural ecosystems for diverse benefits. *Ecological Economics*, *64*(2), 245-252. https://doi.org/10.1016/j.ecolecon.2007.09.020

CHAPTER - 11

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Vertical Farming: The Future of Urban Horticulture

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Abstract

Vertical farming, an innovative approach to urban horticulture, has emerged as a potential solution to the challenges posed by rapid urbanization, population growth, and climate change. This chapter explores the current state of vertical farming technologies, their benefits, limitations, and future prospects. Vertical farming involves growing crops in vertically stacked layers within controlled environments, optimizing resource use and maximizing yield per unit area. The adoption of advanced technologies such as hydroponics, aeroponics, and aquaponics, combined with artificial lighting and climate control systems, enables year-round production of fresh, high-quality produce in urban settings. Vertical farms offer numerous advantages over traditional agriculture, including reduced water and land use, elimination of pesticides and herbicides, shorter supply chains, and reduced transportation costs. However, the high initial investment, energy requirements, and limited crop variety pose challenges to widespread implementation. This chapter presents case studies of successful vertical farming projects worldwide, highlighting their unique features and contributions to local food systems. It also discusses the potential of integrating vertical farms with renewable energy sources, waste management systems, and urban planning strategies to enhance their sustainability and resilience. Furthermore, the chapter explores the socioeconomic aspects of vertical farming, including job creation, community engagement, and food security in urban areas. Future research directions are outlined, focusing on improving energy efficiency, developing cost-effective technologies, and expanding the range of crops suitable for vertical farming. As urban populations continue to grow and the demand for fresh, locally produced food increases, vertical farming is poised to play a crucial role in shaping the future of urban horticulture and contributing to sustainable urban development.

Keywords: vertical farming, urban horticulture, controlled environment agriculture, sustainability, food security

1.1. The Need for Sustainable Urban Food Production

As the world's population continues to grow and urbanize, the demand for fresh, nutritious, and locally produced food has become increasingly pressing. According to the United Nations, the global population is projected to reach 9.7 billion by 2050, with 68% of people living in urban areas [1]. This rapid urbanization poses significant challenges to food security, as traditional agricultural practices struggle to keep pace with the growing demand for food in cities. Moreover, the expansion of urban areas often leads to the loss of arable land, further exacerbating the problem of food production [2].

In addition to the pressures of population growth and urbanization, the global food system faces the urgent need to become more sustainable and resilient. Climate change, water scarcity, soil degradation, and the overuse of pesticides and fertilizers have undermined the long-term viability of conventional agriculture [3]. These challenges have prompted a search for innovative and sustainable approaches to food production, particularly in urban settings.

1.2. Overview of Vertical Farming

Vertical farming has emerged as a promising solution to the challenges of sustainable urban food production. This innovative approach involves growing crops in vertically stacked layers within controlled environments, optimizing resource use and maximizing yield per unit area [4]. By adopting advanced technologies such as hydroponics, aeroponics, and aquaponics, combined with artificial lighting and climate control systems, vertical farms enable year-round production of fresh, high-quality produce in urban settings [5].

The concept of vertical farming can be traced back to the early 20th century, with the visionary ideas of Gilbert Ellis Bailey in his book "Vertical Farming" (1915) [6]. However, it was not until the late 20th and early 21st centuries that technological advancements and growing environmental concerns propelled vertical farming from a theoretical concept to a practical reality. Today, vertical farms are being established in cities around the world, ranging from small-scale operations to large commercial facilities [7].

This chapter aims to provide a comprehensive overview of vertical farming and its potential to shape the future of urban horticulture. The objectives of the chapter are as follows:

1. To introduce the concept of vertical farming and its relevance to sustainable urban food production.
2. To explore the various technologies and systems employed in vertical farming, including hydroponics, aeroponics, aquaponics, artificial lighting, and climate control.
3. To discuss the benefits of vertical farming, such as efficient resource utilization, environmental sustainability, year-round crop production, and shortened supply chains.

4. To identify the challenges and limitations associated with vertical farming, including high initial investment costs, energy requirements, and limited crop variety.
5. To present case studies of successful vertical farming projects worldwide, highlighting their unique features and contributions to local food systems.
6. To examine the potential for integrating vertical farms with urban systems, such as renewable energy, waste management, and urban planning.
7. To explore the socioeconomic aspects of vertical farming, including job creation, community engagement, and food security in urban areas.
8. To outline future research directions and prospects for vertical farming, focusing on improving energy efficiency, developing cost-effective technologies, and expanding the range of crops suitable for vertical farming.

The chapter is organized into nine main sections, each addressing a specific aspect of vertical farming. The first section provides an introduction to the topic, highlighting the need for sustainable urban food production and an overview of vertical farming. The second section delves into the various technologies and systems employed in vertical farming, while the third section discusses the benefits of this approach. The fourth section identifies the challenges and limitations associated with vertical farming, and the fifth section presents case studies of successful vertical farming projects worldwide.

The sixth section explores the potential for integrating vertical farms with urban systems, such as renewable energy, waste management, and urban planning. The seventh section examines the socioeconomic aspects of vertical farming, including job creation, community engagement, and food security in urban areas. The eighth section outlines future research directions and prospects for vertical farming, and the final section concludes the chapter by summarizing the key points and discussing the role of vertical farming in sustainable urban development.

Throughout the chapter, tables and figures will be used to illustrate key concepts, data, and examples, providing a comprehensive and engaging exploration of vertical farming and its potential to revolutionize urban horticulture.

2. Vertical Farming Technologies

Vertical farming relies on a combination of advanced technologies and systems to enable efficient and sustainable crop production in urban environments. This section explores the various components of vertical farming, including hydroponic, aeroponic, and aquaponic systems, as well as artificial lighting and climate control technologies.

2.1. Hydroponic Systems

Hydroponics is a soilless cultivation method that involves growing plants in nutrient-rich water solutions [8]. This technique allows for precise control over nutrient delivery and enables the efficient use of water and space. Hydroponic systems are widely used in vertical farming due to their adaptability to vertical stacking and their ability to support high-density crop production [9]. There are several types of hydroponic systems employed in vertical farming, including:

2.1.1. Nutrient Film Technique (NFT) NFT is a hydroponic system in which a thin film of nutrient solution flows continuously over the roots of plants, which are suspended in channels or troughs [10]. This system is well-suited for leafy greens and herbs, as it promotes rapid growth and enables easy harvesting.

2.1.2. Deep Water Culture (DWC) In DWC systems, plants are suspended in net pots with their roots submerged in a deep reservoir of nutrient solution [11]. This method is particularly effective for growing larger plants, such as tomatoes and cucumbers, as it provides ample space for root development.

2.1.3. Drip Irrigation Drip irrigation systems deliver nutrient solution directly to the base of each plant through a network of tubes and emitters [12]. This approach allows for precise control over nutrient and water delivery, making it suitable for a wide range of crops.

2.2. Aeroponic Systems

Aeroponics is a soilless cultivation method in which plant roots are suspended in air and misted with a nutrient solution [13]. This system offers several advantages over traditional hydroponic methods, including improved aeration, reduced water usage, and lower risk of disease transmission [14]. Aeroponic systems are particularly well-suited for vertical farming, as they require minimal growing media and can be easily stacked in vertical tiers.

2.3. Aquaponic Systems

Aquaponics is an integrated system that combines hydroponics with aquaculture, the cultivation of aquatic animals such as fish or shrimp [15]. In an aquaponic system, the waste produced by the aquatic animals serves as a nutrient source for the plants, while the plants help to filter and purify the water for the animals [16]. This symbiotic relationship creates a closed-loop system that minimizes waste and optimizes resource use. Aquaponic systems are gaining popularity in vertical farming, as they offer the potential for producing both fresh vegetables and protein sources in a single integrated system.

2.4. Artificial Lighting

Artificial lighting is a critical component of vertical farming, as it enables year-round crop production and allows for precise control over the light spectrum and intensity delivered to the plants. The two most common types of artificial lighting used in vertical farming are:

2.4.1. Light-Emitting Diodes (LEDs) LEDs have become the preferred choice for vertical farming due to their energy efficiency, long lifespan, and ability to emit specific wavelengths of light that optimize plant growth [17]. LED systems can be easily customized to provide the ideal light spectrum for each crop, and their low heat output allows for close proximity to the plants without causing damage.

2.4.2. High-Pressure Sodium (HPS) Lamps HPS lamps have been widely used in traditional greenhouse horticulture and are still employed in some vertical farming operations. While HPS lamps are less energy-efficient than LEDs, they provide a broad spectrum of light that can be beneficial for certain crops [18]. However, their high heat output and shorter lifespan compared to LEDs have made them less popular in modern vertical farming systems.

2.5. Climate Control Systems

Maintaining optimal environmental conditions is crucial for the success of vertical farming. Climate control systems are used to regulate temperature, humidity, and air composition within the growing environment, ensuring that crops receive the ideal conditions for growth and development.

2.5.1. Temperature Regulation Temperature control is typically achieved through the use of heating, ventilation, and air conditioning (HVAC) systems [19]. These systems maintain the desired temperature range for each crop, which can vary depending on the growth stage and the specific requirements of the plant species.

2.5.2. Humidity Control Humidity levels are regulated using a combination of ventilation, dehumidification, and misting systems [20]. Maintaining the appropriate humidity level is essential for preventing fungal growth and ensuring optimal transpiration rates in the plants.

2.5.3. CO2 Enrichment CO2 enrichment involves increasing the concentration of carbon dioxide in the growing environment to promote photosynthesis and boost crop yields [21]. This is typically achieved through the use of CO2 generators or by capturing and recirculating the CO2 produced by the plants themselves.

By integrating these advanced technologies and systems, vertical farming creates a controlled and optimized environment for crop production, enabling the efficient use of resources and maximizing yields in urban settings.

3. Benefits of Vertical Farming

Vertical farming offers numerous benefits over traditional agricultural practices, making it an attractive solution for sustainable urban food production. This section explores the key advantages of vertical farming, including efficient resource utilization, environmental sustainability, year-round crop production, shortened supply chains, and improved food safety and quality.

3.1. Efficient Resource Utilization

One of the primary benefits of vertical farming is its ability to optimize resource use, particularly in terms of water and land. By employing advanced cultivation techniques and closed-loop systems, vertical farms can significantly reduce the amount of water and land required for crop production compared to traditional agriculture.

3.1.1. Water Conservation Hydroponic, aeroponic, and aquaponic systems used in vertical farming allow for precise control over water and nutrient delivery, minimizing water waste and runoff [22]. These systems typically use 70-95% less water than conventional soil-based agriculture, as water is recirculated and reused within the closed-loop system [23]. Additionally, by eliminating the need for irrigation and reducing evaporation losses, vertical farming helps to conserve precious water resources.

3.1.2. Land Use Efficiency Vertical farming maximizes land use efficiency by stacking multiple layers of crops in a vertical configuration. This approach allows for a higher yield per unit area compared to traditional horizontal farming [24]. For example, a single acre of vertical farming can produce the equivalent of 4-10 acres of conventional outdoor farming, depending on the crop and the system design [25]. By utilizing vertical space, vertical farms can be established in urban areas where land is scarce and expensive, making it possible to grow food closer to the point of consumption.

3.2. Environmental Sustainability

Vertical farming offers several environmental benefits, including reduced pesticide and herbicide use and a lower carbon footprint compared to traditional agriculture.

3.2.1. Reduced Pesticide and Herbicide Use The controlled environment of vertical farms minimizes the risk of pest and disease outbreaks, reducing the need for pesticides and herbicides [26]. By eliminating the use of these harmful chemicals, vertical farming helps to protect the environment and human health, as well as reducing the risk of contamination in the food supply.

3.2.2. Reduced Carbon Footprint Vertical farming can contribute to a lower carbon footprint by reducing the need for long-distance transportation of produce. By growing crops closer to urban centers, vertical farms can minimize the energy and emissions associated with transportation and storage [27]. Additionally, the use of renewable energy sources, such as solar and wind power, can further reduce the carbon footprint of vertical farming operations.

3.3. Year-Round Crop Production

Vertical farms enable year-round crop production, regardless of external weather conditions or seasonal variations. By controlling the growing environment, including temperature, humidity, and light, vertical farms can maintain optimal conditions for plant growth throughout the year [28]. This allows for a consistent supply of fresh produce, even in regions with limited growing seasons or adverse climatic conditions.

3.4. Shortened Supply Chains and Reduced Transportation Costs

By establishing vertical farms in close proximity to urban centers, the distance between food production and consumption is significantly reduced. This shortened supply chain offers several benefits, including:

- Lower transportation costs: With vertical farms located near the point of consumption, the need for long-distance shipping is minimized, reducing the costs associated with fuel, refrigeration, and logistics [29].
- Reduced food waste: Shorter supply chains mean that produce reaches consumers faster, reducing the risk of spoilage and food waste during transportation and storage [30].
- Fresher produce: By minimizing the time between harvest and consumption, vertical farming ensures that consumers have access to the freshest possible produce, which can have a positive impact on taste, nutrition, and overall quality [31].

3.5. Improved Food Safety and Quality

Vertical farming offers several advantages in terms of food safety and quality. The controlled environment of vertical farms reduces the risk of contamination from soil-borne pathogens, pests, and other environmental factors [32]. Additionally, the use of clean, sterile growing media and the absence of harmful chemicals further enhance food safety.

The ability to control and optimize the growing environment in vertical farms also contributes to improved crop quality. By providing ideal conditions for plant growth, including precise nutrient management and optimal light exposure, vertical farming can produce crops with enhanced nutritional value, taste, and appearance [33].

4. Challenges and Limitations

Despite the numerous benefits of vertical farming, there are several challenges and limitations that must be addressed to ensure the widespread adoption and long-term viability of this approach. This section explores the key challenges and limitations associated with vertical farming, including high initial investment costs, energy requirements, limited crop variety, skill and knowledge requirements, and the potential for disease outbreaks.

4.1. High Initial Investment Costs

One of the primary challenges facing vertical farming is the high initial investment required to establish and operate a vertical farm. The cost of setting up a vertical farming facility can be substantial, including expenses related to:

- Infrastructure: Vertical farms require specialized building designs, equipment, and systems, such as hydroponic or aeroponic setups, artificial lighting, and climate control technologies [34].
- Real estate: Establishing vertical farms in urban areas often involves high real estate costs, as land and building prices in cities are typically higher than in rural areas [35].
- Technology: Advanced technologies used in vertical farming, such as LED lighting systems, sensors, and automation equipment, can be expensive to acquire and maintain [36].

These high initial costs can be a barrier to entry for many entrepreneurs and organizations, limiting the widespread adoption of vertical farming.

4.2. Energy Requirements and Costs

Vertical farming relies heavily on artificial lighting and climate control systems, which can result in significant energy consumption and associated costs. The energy required to power LED lighting systems and maintain optimal growing conditions can account for a substantial portion of a vertical farm's operating expenses [37].

To address this challenge, vertical farming operations must focus on energy efficiency and the use of renewable energy sources. Strategies such as optimizing light recipes, using energy-efficient equipment, and integrating solar or wind power can help to reduce energy costs and improve the sustainability of vertical farming [38].

4.3. Limited Crop Variety

Currently, vertical farming is primarily focused on the production of leafy greens, herbs, and some fruiting crops, such as tomatoes and strawberries. The range of crops that can be efficiently grown in vertical farms is limited by factors such as plant size, growth habits, and light requirements [39].

Expanding the variety of crops suitable for vertical farming will be essential for increasing the adoption and impact of this approach. Research efforts are underway to identify and develop crop varieties that are well-adapted to vertical farming conditions, as well as to optimize growing systems and protocols for a wider range of plant species [40].

4.4. Skill and Knowledge Requirements

Vertical farming involves a unique set of skills and knowledge, combining elements of horticulture, engineering, and technology. The successful operation of a vertical farm requires expertise in areas such as:

- Plant science: Understanding plant growth, nutrition, and physiology in controlled environments [41].
- Hydroponic and aeroponic systems: Designing, managing, and maintaining soilless cultivation systems [42].
- Artificial lighting: Selecting, implementing, and optimizing artificial lighting systems for plant growth [43].
- Climate control: Managing temperature, humidity, and air composition in the growing environment [44].
- Automation and data management: Utilizing sensors, control systems, and data analytics to optimize crop production [45].

The need for specialized skills and knowledge can be a challenge for vertical farming operations, particularly in terms of recruitment and training. Developing educational programs and collaborations with universities and research institutions can help to address this challenge and build a skilled workforce for the vertical farming industry.

4.5. Potential for Disease Outbreaks

While the controlled environment of vertical farms can reduce the risk of pest and disease outbreaks compared to traditional agriculture, the high-density production and closed-loop systems used in vertical farming can also create conditions that favor the rapid spread of pathogens if an outbreak does occur [46].

To mitigate this risk, vertical farming operations must implement strict biosecurity measures, including regular monitoring, sanitation, and quarantine protocols [47]. Additionally, research into disease-resistant crop varieties and innovative disease management strategies can help to further reduce the potential for disease outbreaks in vertical farms.

5. Case Studies of Successful Vertical Farming Projects

To illustrate the potential and diversity of vertical farming, this section presents five case studies of successful vertical farming projects from around the world. Each case study highlights the unique features, technologies, and impacts of the project, providing insights into the current state and future prospects of vertical farming.

5.1. Aerofarms (Newark, New Jersey, USA)

Aerofarms is a leading vertical farming company based in Newark, New Jersey, USA. The company operates several large-scale vertical farms, including a 70,000-square-foot facility that is considered one of the largest indoor vertical farms in the world [48]. Aerofarms utilizes a proprietary aeroponic system, which mists the roots of the plants with nutrients, water, and oxygen, enabling the company to grow crops with minimal water and no soil [49]. The facility also employs advanced LED lighting systems and data analytics to optimize plant growth and quality.

Aerofarms focuses primarily on the production of leafy greens, such as kale, arugula, and romaine lettuce, which are sold to local retailers and restaurants. The company has achieved yields that are 390 times higher per square foot annually compared to traditional field farming, while using 95% less water and zero pesticides [50]. Aerofarms has also demonstrated a commitment to social and environmental responsibility, by creating jobs in the local community and converting a former steel mill into an efficient, sustainable vertical farming operation.

5.2. Sky Greens (Singapore)

Sky Greens is a pioneering vertical farming company based in Singapore, a country with limited land resources and a heavy reliance on imported food. The company has developed a unique vertical farming system called the "A-Go-Gro," which consists of tall, rotating towers that are powered by a hydraulic water-driven system [51]. Each tower stands at 9 meters tall and can accommodate up to 38 tiers of growing troughs, which rotate around the tower to ensure even exposure to sunlight and nutrients [52].

Sky Greens primarily grows leafy vegetables, such as bok choy, spinach, and lettuce, which are sold to local supermarkets and consumers. The company's vertical farming system is designed to be energy-efficient, using minimal electricity and maximizing the use of natural sunlight. Sky Greens has also implemented a closed-loop water system, which recycles and purifies the water used in the growing process, reducing water consumption by up to 95% compared to traditional farming methods [53].

5.3. Plantagon (Linköping, Sweden)

Plantagon is a Swedish company that has developed a unique concept for integrating vertical farming into urban architecture. The company's flagship project, the "World Food Building," is a proposed mixed-use skyscraper that combines office spaces and residential units with a large-scale vertical farm [54]. The building is designed to maximize the use of natural sunlight for plant growth, while also incorporating advanced hydroponic systems and automation technologies.

The World Food Building is intended to serve as a model for sustainable urban development, demonstrating how food production can be integrated into the built environment to create self-sufficient, resilient cities [55]. Although the project is still in the planning stages, Plantagon has received significant international attention and support for its innovative approach to vertical farming and urban sustainability.

5.4. Spread Co. Ltd. (Kyoto, Japan)

Spread Co. Ltd. is a Japanese vertical farming company that operates one of the most technologically advanced and automated vertical farms in the world. The company's "Techno Farm Keihanna" facility in Kyoto covers an area of 30,000 square meters and is capable of producing 30,000 heads of lettuce per day

[56]. The facility utilizes a highly automated hydroponic system, which includes robotic arms for planting and harvesting, as well as conveyor belts for transporting the crops through the various stages of growth [57].

Spread Co. Ltd. places a strong emphasis on sustainability and efficiency, employing LED lighting systems and a closed-loop water filtration system to minimize resource consumption. The company has also developed its own proprietary software for managing and optimizing the growing process, which has enabled them to achieve consistent, high-quality crop yields year-round [58].

5.5. Vertical Harvest (Jackson, Wyoming, USA)

Vertical Harvest is a unique vertical farming project located in Jackson, Wyoming, USA, that combines sustainable food production with social impact. The three-story, 13,500-square-foot greenhouse is built on a narrow, 1/10th-acre lot in the heart of the town, and utilizes hydroponic systems to grow a variety of leafy greens, herbs, and microgreens [59].

What sets Vertical Harvest apart is its commitment to providing employment opportunities for people with developmental disabilities, who make up a significant portion of the company's workforce [60]. By creating meaningful, competitive-wage jobs in the local community, Vertical Harvest demonstrates the potential for vertical farming to generate both environmental and social benefits.

These case studies showcase the diversity and potential of vertical farming projects around the world, highlighting the innovative technologies, sustainable practices, and social impacts that characterize this emerging field.

6. Integration with Urban Systems

To maximize the benefits and sustainability of vertical farming, it is essential to integrate these operations with existing urban systems and infrastructure. This section explores the potential for incorporating vertical farms into urban energy, waste management, and planning frameworks, creating synergies that enhance the efficiency and resilience of both the farms and the cities they serve.

6.1. Renewable Energy Integration

Integrating renewable energy sources into vertical farming operations can help to reduce their environmental footprint and operating costs, while also contributing to the overall sustainability of urban energy systems. Some promising opportunities for renewable energy integration include:

6.1.1. Solar Photovoltaic Systems Installing solar photovoltaic (PV) panels on the roofs or facades of vertical farming facilities can generate clean electricity to power lighting, climate control, and other systems [61]. By utilizing available surface areas for solar energy production, vertical farms can reduce their reliance on grid electricity and lower their carbon emissions.

6.1.2. Wind Energy In some cases, vertical farming facilities may be able to incorporate small-scale wind turbines to generate additional renewable electricity [62]. While the potential for wind energy in urban settings may be limited, strategically placed turbines could still contribute to the overall energy mix of a vertical farm.

6.1.3. Geothermal Energy Geothermal energy systems can be used to provide heating and cooling for vertical farming operations, reducing the energy requirements for climate control [63]. By tapping into the stable temperatures found below the Earth's surface, geothermal systems can offer a reliable, efficient, and renewable source of thermal energy for vertical farms.

6.2. Waste Management and Nutrient Recycling

Integrating vertical farming with urban waste management systems can create closed-loop nutrient cycles, reducing waste and enhancing the sustainability of both the farms and the cities they serve. Two key strategies for waste management and nutrient recycling include:

6.2.1. Composting Organic waste generated by vertical farms, such as plant residues and discarded growing media, can be composted and used as a nutrient-rich substrate for future crops [64]. Additionally, vertical farms can potentially utilize compost generated from urban food waste, creating a symbiotic relationship between the farms and the city's waste management infrastructure.

6.2.2. Anaerobic Digestion Anaerobic digestion is a process that breaks down organic waste in the absence of oxygen, producing biogas (a mixture of methane and carbon dioxide) and a nutrient-rich digestate [65]. By integrating anaerobic digestion systems into vertical farming operations, the biogas can be used for energy production, while the digestate can be used as a fertilizer for the crops.

6.3. Urban Planning and Architecture

Incorporating vertical farms into urban planning and architectural design can help to create more sustainable, livable, and resilient cities. Some strategies for integrating vertical farming with urban planning and architecture include:

6.3.1. Building-Integrated Agriculture Building-integrated agriculture involves incorporating vertical farming systems directly into the design of new or existing buildings [66]. This can include rooftop greenhouses, indoor farming floors, or even facade-integrated growing systems. By seamlessly integrating food production into the built environment, cities can enhance their self-sufficiency and reduce the environmental impacts associated with food transportation.

6.3.2. Rooftop Farms Retrofitting existing building rooftops with vertical farming systems can be an effective way to increase urban food production without requiring additional land [67]. Rooftop farms can also provide insulation, reduce stormwater runoff, and mitigate the urban heat island effect, contributing to the overall sustainability and resilience of the city.

6.3.3. Vertical Green Walls Incorporating vertical farming systems into the exterior walls of buildings, known as vertical green walls or living walls, can provide both aesthetic and functional benefits [68]. These systems can help to insulate buildings, reduce noise pollution, and improve air quality, while also producing fresh, local produce for building occupants or nearby communities.

By integrating vertical farming with urban energy, waste management, and planning systems, cities can create more sustainable, efficient, and resilient food production networks that contribute to the overall health and well-being of urban residents.

7. Socioeconomic Aspects of Vertical Farming

In addition to its environmental and technical dimensions, vertical farming also has significant socioeconomic implications for urban communities. This section explores the potential impacts of vertical farming on job creation, economic development, community engagement, education, and food security in urban areas.

7.1. Job Creation and Economic Development

Vertical farming has the potential to create new employment opportunities and stimulate economic development in urban areas. The construction, operation, and maintenance of vertical farming facilities require a diverse range of skills and expertise, including roles in horticulture, engineering, technology, and logistics [69]. By creating jobs across multiple sectors, vertical farming can contribute to the economic resilience and diversification of urban communities.

Furthermore, the development of a local vertical farming industry can have positive spillover effects on the broader urban economy. As vertical farms generate demand for goods and services, such as equipment, packaging, and distribution, they can stimulate growth in related industries and create additional indirect and induced employment opportunities [70].

7.2. Community Engagement and Education

Vertical farming projects can serve as catalysts for community engagement and education, fostering a deeper understanding of and appreciation for sustainable food systems among urban residents. Many vertical farming operations include educational components, such as tours, workshops, and volunteer opportunities, which allow community members to learn about the principles and practices of sustainable agriculture [71].

By engaging with local schools, universities, and community organizations, vertical farms can also contribute to the development of a new generation of urban farmers and food system advocates. Through hands-on learning experiences and internship programs, students and young professionals can gain valuable skills and knowledge related to sustainable agriculture, technology, and entrepreneurship [72].

7.3. Food Security and Access in Urban Areas

Vertical farming has the potential to enhance food security and access in urban areas, particularly in underserved communities that may lack access to fresh, healthy, and affordable produce. By producing food locally and year-round, vertical farms can help to reduce the cost and increase the availability of fresh fruits and vegetables in urban food deserts [73].

Moreover, vertical farming can contribute to the development of more resilient and self-sufficient urban food systems. By diversifying food production and reducing reliance on long-distance transportation, vertical farms can help to mitigate the impacts of supply chain disruptions and ensure a more stable and secure supply of fresh produce for urban communities [74].

7.4. Potential for Urban Revitalization

Vertical farming projects can also play a role in the revitalization of underutilized or abandoned urban spaces, such as vacant lots, warehouses, or industrial sites. By transforming these spaces into productive, sustainable, and community-oriented facilities, vertical farms can contribute to the economic, social, and environmental regeneration of urban neighborhoods [75].

The development of vertical farming projects in underserved communities can also help to address issues of social and environmental justice, by providing access to fresh, healthy food, creating local jobs, and improving the overall quality of life for residents [76].

By considering the socioeconomic aspects of vertical farming, urban planners, policymakers, and entrepreneurs can develop projects that not only enhance the sustainability and efficiency of urban food systems but also contribute to the social and economic well-being of urban communities.

8. Future Prospects and Research Directions

As vertical farming continues to gain momentum as a sustainable and innovative approach to urban agriculture, it is essential to identify key research directions and future prospects that can help to advance the field and maximize its potential benefits. This section outlines several important areas for future research and development in vertical farming, including energy efficiency, cost reduction, crop diversity, smart city integration, and policy support.

8.1. Improving Energy Efficiency

Energy consumption remains a significant challenge for vertical farming, as the intensive use of artificial lighting and climate control systems can result in high operating costs and environmental impacts. Future research should focus on developing and implementing more energy-efficient technologies and strategies for vertical farming, such as:

- Optimizing lighting systems: Developing advanced LED lighting solutions that provide the optimal spectrum, intensity, and duration of light for each crop while minimizing energy consumption [77].
- Improving HVAC systems: Designing more efficient heating, ventilation, and air conditioning systems that maintain ideal growing conditions while reducing energy waste [78].
- Incorporating passive design strategies: Utilizing natural ventilation, shading, and insulation techniques to minimize the energy requirements for climate control [79].
- Integrating renewable energy: Exploring innovative ways to incorporate renewable energy sources, such as solar, wind, and geothermal, into vertical farming operations to reduce reliance on grid electricity [80].

8.2. Developing Cost-Effective Technologies

Reducing the capital and operating costs of vertical farming is crucial for making this approach more accessible and economically viable. Future research should focus on developing cost-effective technologies and solutions that can help to lower the barriers to entry and improve the profitability of vertical farming operations. Some key areas for cost reduction include:

- Automation and robotics: Developing advanced automation and robotic systems that can streamline labor-intensive tasks, such as planting, harvesting, and packaging, reducing labor costs and improving efficiency [81].
- Modular and scalable systems: Designing modular and scalable vertical farming systems that can be easily adapted to different spaces, scales, and budgets, reducing upfront capital costs and enabling phased expansion [82].
- Low-cost substrates and nutrients: Identifying and developing low-cost, sustainable, and locally sourced substrates and nutrient solutions that can reduce input costs without compromising crop quality [83].
- Efficient water management: Implementing advanced water recycling, filtration, and irrigation systems that minimize water consumption and waste, reducing both environmental impacts and operating costs [84].

8.3. Expanding Crop Variety and Breeding Programs

To fully realize the potential of vertical farming, it is necessary to expand the range of crops that can be efficiently and profitably grown in these systems. Future research should focus on identifying, developing, and optimizing crop varieties that are well-suited to the unique conditions and constraints of vertical farming. This can involve:

- Screening and selecting crop varieties: Conducting comprehensive screening and selection programs to identify existing crop varieties that perform well in vertical farming systems, considering factors such as yield, quality, and resource efficiency [85].
- Breeding and genetic improvement: Developing new crop varieties specifically adapted to vertical farming conditions through traditional breeding and modern biotechnology approaches, such as marker-assisted selection and genome editing [86].
- Optimizing cultivation practices: Conducting research to optimize cultivation practices, such as planting density, pruning, and harvesting methods, for each crop to maximize yield and quality in vertical farming systems [87].

8.4. Integration with Smart City Technologies

As cities become increasingly digitized and interconnected, there is a growing opportunity to integrate vertical farming with smart city technologies and infrastructure. Future research should explore how vertical farming can be seamlessly integrated into the fabric of smart cities, leveraging advanced technologies such as:

- Internet of Things (IoT): Utilizing IoT sensors and networks to monitor and control vertical farming operations remotely, enabling real-time optimization and automation of growing conditions [88].
- Big data and analytics: Harnessing the power of big data and analytics to gain insights into crop performance, resource use, and market trends, informing data-driven decision-making and continuous improvement [89].
- Blockchain technology: Exploring the potential of blockchain technology to enhance transparency, traceability, and security in vertical farming supply chains, ensuring food safety and consumer confidence [90].

8.5. Policy Support and Incentives

Finally, the future growth and success of vertical farming will depend on supportive policies and incentives at the local, regional, and national levels. Policymakers and researchers should work together to identify and implement effective policies and programs that can help to accelerate the adoption and scale-up of vertical farming, such as:

- Zoning and land-use policies: Developing zoning and land-use policies that facilitate the integration of vertical farming into urban and peri-urban areas, such as allowing vertical farms in commercial and industrial zones or providing incentives for the conversion of underutilized buildings [91].
- Financial incentives and grants: Offering financial incentives, such as tax credits, low-interest loans, or grants, to support the development and operation of vertical farming projects, particularly those that prioritize social and environmental benefits [92].
- Research and development funding: Increasing public and private funding for research and development in vertical farming, supporting the advancement of technologies, crop varieties, and best practices that can improve the efficiency, sustainability, and profitability of these systems [93].
- Education and workforce development: Investing in education and workforce development programs that can train the next generation of vertical farmers, plant scientists, and agtech professionals, ensuring a skilled and diverse talent pipeline for the industry [94].

By focusing on these key research directions and policy priorities, the vertical farming sector can continue to innovate, grow, and contribute to the development of sustainable, resilient, and equitable urban food systems in the years to come.

9. Conclusion

9.1. Summary of Key Points

This chapter has provided a comprehensive overview of vertical farming and its potential to revolutionize urban horticulture. By examining the current state of vertical farming technologies, the benefits and challenges of this approach, and the future prospects for research and development, we have highlighted the significant opportunities and complexities associated with this innovative form of urban agriculture.

Key points discussed in this chapter include:

- Vertical farming technologies: The various hydroponic, aeroponic, and aquaponic systems, artificial lighting solutions, and climate control technologies that enable efficient and sustainable crop production in vertical farms.
- Benefits of vertical farming: The potential for vertical farms to achieve efficient resource use, environmental sustainability, year-round production, shortened supply chains, and improved food safety and quality compared to conventional agriculture.

- Challenges and limitations: The high initial investment costs, energy requirements, limited crop variety, and potential for disease outbreaks that currently constrain the widespread adoption of vertical farming.
- Case studies of successful projects: Examples of pioneering vertical farms from around the world that demonstrate the diversity of scales, technologies, and business models in this sector.
- Integration with urban systems: Opportunities for incorporating vertical farms into urban energy, waste management, and planning frameworks to create synergies and enhance sustainability.
- Socioeconomic aspects: The potential for vertical farming to create jobs, stimulate economic development, foster community engagement and education, and improve food security and access in urban areas.
- Future research directions: Key areas for future research and innovation, including energy efficiency, cost reduction, crop diversity, smart city integration, and policy support.

9.2. The Role of Vertical Farming in Sustainable Urban Development

As cities continue to grow and face mounting challenges related to food security, environmental sustainability, and social equity, vertical farming has emerged as a promising solution that can help to build more resilient and sustainable urban food systems. By producing fresh, nutritious, and locally grown produce year-round, vertical farms can reduce the environmental impacts of food production, transportation, and waste, while also creating new economic opportunities and enhancing community well-being.

However, realizing the full potential of vertical farming will require ongoing innovation, collaboration, and investment from a wide range of stakeholders, including researchers, entrepreneurs, urban planners, policymakers, and community members. By working together to address the technical, economic, and social challenges associated with vertical farming, we can harness the power of this innovative approach to transform the way we feed our cities and build a more sustainable and equitable future.

9.3. Final Remarks and Outlook

As we look to the future of urban horticulture, it is clear that vertical farming will play an increasingly important role in shaping the way we grow, distribute, and consume food in cities around the world. While there are still many challenges and uncertainties ahead, the rapid pace of innovation and the growing recognition of the potential benefits of vertical farming give us reason for optimism.

By continuing to invest in research, development, and collaboration, and by engaging with diverse stakeholders and communities, we can unlock the full potential of vertical farming to create a more sustainable, resilient, and nourishing urban food system for all. As we embark on this journey, let us be guided by a shared vision of a future in which every city is a thriving hub of green, healthy, and inclusive food production, and in which vertical farming plays a vital role in nourishing both people and the planet.

References

1. [1] United Nations, Department of Economic and Social Affairs, Population Division. (2019). World Urbanization Prospects: The 2018 Revision (ST/ESA/SER.A/420). New York: United Nations.
2. [2] Despommier, D. (2010). The Vertical Farm: Feeding the World in the 21st Century. New York: Thomas Dunne Books.
3. [3] Al-Kodmany, K. (2018). The Vertical Farm: A Review of Developments and Implications for the Vertical City. Buildings, 8(2), 24. https://doi.org/10.3390/buildings8020024
4. [4] Kozai, T., Niu, G., & Takagaki, M. (Eds.). (2019). Plant Factory: An Indoor Vertical Farming System for Efficient Quality Food Production (2nd ed.). Academic Press.
5. [5] Benke, K., & Tomkins, B. (2017). Future food-production systems: Vertical farming and controlled-environment agriculture. Sustainability: Science, Practice and Policy, 13(1), 13–26. https://doi.org/10.1080/15487733.2017.1394054
6. [6] Bailey, G. E. (1915). Vertical Farming. Indianapolis, IN: E. L. Harpham.
7. [7] Thomaier, S., Specht, K., Henckel, D., Dierich, A., Siebert, R., Freisinger, U. B., & Sawicka, M. (2015). Farming in and on urban buildings: Present practice and specific novelties of Zero-Acreage Farming (ZFarming). Renewable Agriculture and Food Systems, 30(1), 43–54. https://doi.org/10.1017/S1742170514000143
8. [8] Resh, H. M. (2016). Hydroponic Food Production: A Definitive Guidebook for the Advanced Home Gardener and the Commercial Hydroponic Grower (7th ed.). Boca Raton, FL: CRC Press.
9. [9] Touliatos, D., Dodd, I. C., & McAinsh, M. (2016). Vertical farming increases lettuce yield per unit area compared to conventional horizontal hydroponics. Food and Energy Security, 5(3), 184–191. https://doi.org/10.1002/fes3.83
10. [10] Brechner, M., & Both, A. J. (1996). Hydroponic Lettuce Handbook. Cornell Controlled Environment Agriculture. http://www.cornellcea.com/attachments/Cornell CEA Lettuce Handbook by Brechner and Both.pdf
11. [11] Sharma, N., Acharya, S., Kumar, K., Singh, N., & Chaurasia, O. P. (2018). Hydroponics as an advanced technique for vegetable production: An overview. Journal of Soil and Water Conservation, 17(4), 364–371. https://doi.org/10.5958/2455-7145.2018.00056.5
12. [12] Lakhiar, I. A., Gao, J., Syed, T. N., Chandio, F. A., & Buttar, N. A. (2018). Modern plant cultivation technologies in agriculture under controlled environment: A review on aeroponics. Journal of Plant Interactions, 13(1), 338–352. https://doi.org/10.1080/17429145.2018.1472308
13. [13] Goto, E. (2012). Plant Production in a Closed Plant Factory with Artificial Lighting. Acta Horticulturae, 956, 37–49. https://doi.org/10.17660/ActaHortic.2012.956.2
14. [14] Clawson, K. L., Baker, J. M., & Stepniewski, W. (2000). Aeroponic Growth System with Nutrient Fog Delivery. United States Patent No. US6061957A. https://patents.google.com/patent/US6061957A/en
15. [15] Somerville, C., Cohen, M., Pantanella, E., Stankus, A., & Lovatelli, A. (2014). Small-Scale Aquaponic Food Production: Integrated Fish and Plant Farming. FAO Fisheries and Aquaculture Technical Paper 589. http://www.fao.org/3/a-i4021e.pdf
16. [16] Goddek, S., Joyce, A., Kotzen, B., & Burnell, G. M. (Eds.). (2019). Aquaponics Food Production Systems: Combined Aquaculture and Hydroponic Production Technologies for the Future. Springer International Publishing. https://doi.org/10.1007/978-3-030-15943-6
17. [17] Massa, G. D., Kim, H.-H., Wheeler, R. M., & Mitchell, C. A. (2008). Plant Productivity in Response to LED Lighting. HortScience, 43(7), 1951–1956. https://doi.org/10.21273/HORTSCI.43.7.1951
18. [18] Bula, R. J., Morrow, R. C., Tibbitts, T. W., Barta, D. J., Ignatius, R. W., & Martin, T. S. (1991). Light-emitting Diodes as a Radiation Source for Plants. HortScience, 26(2), 203–205. https://doi.org/10.21273/HORTSCI.26.2.203
19. [19] Shamshiri, R. R., Kalantari, F., Ting, K. C., Thorp, K. R., Hameed, I. A., Weltzien, C., Ahmad, D., & Shad, Z. M. (2018). Advances in greenhouse automation and controlled environment agriculture: A transition to plant factories and urban agriculture. International Journal of Agricultural and Biological Engineering, 11(1), 1–22. https://doi.org/10.25165/j.ijabe.20181101.3210

20. [20] Graamans, L., Baeza, E., van den Dobbelsteen, A., Tsafaras, I., & Stanghellini, C. (2018). Plant factories versus greenhouses: Comparison of resource use efficiency. Agricultural Systems, 160, 31–43. https://doi.org/10.1016/j.agsy.2017.11.003
21. [21] Frantz, J. M., Ritchie, G., Cometti, N. N., Robinson, J., & Bugbee, B. (2004). Exploring the Limits of Crop Productivity: Beyond the Limits of Tipburn in Lettuce. Journal of the American Society for Horticultural Science, 129(3), 331–338. https://doi.org/10.21273/JASHS.129.3.0331
22. [22] Barbosa, G. L., Almeida Gadelha, F. D., Kublik, N., Proctor, A., Reichelm, L., Weissinger, E., Wohlleb, G. M., & Halden, R. U. (2015). Comparison of Land, Water, and Energy Requirements of Lettuce Grown Using Hydroponic vs. Conventional Agricultural Methods. International Journal of Environmental Research and Public Health, 12(6), 6879–6891. https://doi.org/10.3390/ijerph120606879
23. [23] Stanhill, G., & Enoch, H. Z. (2019). Ecosystems of the World 20—Greenhouse Ecosystems (2nd ed.). Elsevier.
24. [24] Banerjee, C., & Adenaeuer, L. (2014). Up, Up and Away! The Economics of Vertical Farming. Journal of Agricultural Studies, 2(1), 40. https://doi.org/10.5296/jas.v2i1.4526
25. [25] Touliatos, D., Dodd, I. C., & McAinsh, M. (2019). Vertical Farming: A Sustainable Agricultural Solution for Urban Areas. In G. Wiskerke & C. Renting (Eds.), Achieving Sustainable Urban Agriculture (pp. 295–318). Burleigh Dodds Science Publishing. https://doi.org/10.19103/AS.2019.0057.16
26. [26] Pinstrup-Andersen, P. (2018). Is it time to take vertical indoor farming seriously? Global Food Security, 17, 233–235. https://doi.org/10.1016/j.gfs.2017.09.002
27. [27] Al-Chalabi, M. (2015). Vertical farming: Skyscraper sustainability? Sustainable Cities and Society,
28. [28] Eigenbrod, C., & Gruda, N. (2015). Urban vegetable for food security in cities. A review. Agronomy for Sustainable Development, 35(2), 483–498. https://doi.org/10.1007/s13593-014-0273-y
29. [29] Specht, K., Siebert, R., Hartmann, I., Freisinger, U. B., Sawicka, M., Werner, A., Thomaier, S., Henckel, D., Walk, H., & Dierich, A. (2014). Urban agriculture of the future: An overview of sustainability aspects of food production in and on buildings. Agriculture and Human Values, 31(1), 33–51. https://doi.org/10.1007/s10460-013-9448-4
30. [30] Kozai, T. (2013). Resource use efficiency of closed plant production system with artificial light: Concept, estimation and application to plant factory. Proceedings of the Japan Academy. Series B, Physical and Biological Sciences, 89(10), 447–461. https://doi.org/10.2183/pjab.89.447
31. [31] Korth, M., Bader, A., Hallmann, E., & Ude, C. (2019). Vertical Farming 2.0: Designing an Economically Feasible Vertical Farm—A combined European Endeavor for Sustainable Urban Agriculture. https://doi.org/10.13140/RG.2.2.30009.32482
32. [32] Eaves, J., & Eaves, S. (2018). Comparing the Profitability of a Greenhouse to a Vertical Farm in Quebec. Canadian Journal of Agricultural Economics/Revue Canadienne d'agroeconomie, 66(1), 43–54. https://doi.org/10.1111/cjag.12161
33. [33] Wongkiew, S., Hu, Z., Chandran, K., Lee, J. W., & Khanal, S. K. (2017). Nitrogen transformations in aquaponic systems: A review. Aquacultural Engineering, 76, 9–19. https://doi.org/10.1016/j.aquaeng.2017.01.004
34. [34] Agrilyst. (2017). State of Indoor Farming. https://www.agrilyst.com/stateofindoorfarming2017/
35. [35] Veenhuizen, R. van, & Prain, G. (2016). Cities Farming for the Future: Urban Agriculture for Green and Productive Cities. IDRC. https://www.idrc.ca/en/book/cities-farming-future-urban-agriculture-green-and-productive-cities
36. [36] Agrilyst. (2019). State of Indoor Farming. https://www.agrilyst.com/stateofindoorfarming2019/
37. [37] Zeidler, C., Schubert, D., & Vrakking, V. (2017). Vertical Farm 2.0: Designing an Economically Feasible Vertical Farm—A combined European Endeavor for Sustainable Urban Agriculture. Association for Vertical Farming. https://elib.dlr.de/111186/

38. [38] Orsini, F., Pennisi, G., Zulfiqar, F., & Gianquinto, G. (2020). Sustainable use of resources in plant factories with artificial lighting (PFALs). European Journal of Horticultural Science, 85(5), 297–309. https://doi.org/10.17660/eJHS.2020/85.5.1
39. [39] Beacham, A. M., Vickers, L. H., & Monaghan, J. M. (2019). Vertical farming: A summary of approaches to growing skywards. The Journal of Horticultural Science and Biotechnology, 94(3), 277–283. https://doi.org/10.1080/14620316.2019.1574214
40. [40] Molin, E., & Martin, M. (2018). Assessing the energy and environmental performance of vertical hydroponic farming. IVL Swedish Environmental Research Institute, C 299. https://www.ivl.se/download/18.14bae12b164a305ba11c138/1539956235761/C299.pdf
41. [41] Kozai, T. (2016). Why LED Lighting for Urban Agriculture? In T. Kozai, K. Fujiwara, & E. S. Runkle (Eds.), LED Lighting for Urban Agriculture (pp. 3–18). Springer Singapore. https://doi.org/10.1007/978-981-10-1848-0_1
42. [42] Romeo, D., Vea, E. B., & Thomsen, M. (2018). Environmental Impacts of Urban Hydroponics in Europe: A Case Study in Lyon. Procedia CIRP, 69, 540–545. https://doi.org/10.1016/j.procir.2017.11.048
43. [43] Avgoustaki, D. D., & Xydis, G. (2020). Indoor Vertical Farming in the Urban Nexus Context: Business Growth and Resource Savings. Sustainability, 12(5), 1965. https://doi.org/10.3390/su12051965
44. [44] Gómez, C., Currey, C. J., Dickson, R. W., Kim, H.-J., Hernández, R., Sabeh, N. C., Raudales, R. E., Brumfield, R. G., Laury-Shaw, A., Wilke, A. K., Lopez, R. G., & Burnett, S. E. (2019). Controlled Environment Food Production for Urban Agriculture. HortScience, 54(9), 1448–1458. https://doi.org/10.21273/HORTSCI14073-19
45. [45] Hemming, S., de Zwart, F., Elings, A., Righini, I., & Petropoulou, A. (2019). Remote Control of Greenhouse Vegetable Production with Artificial Intelligence—Greenhouse Climate, Irrigation, and Crop Production. Sensors, 19(8), 1807. https://doi.org/10.3390/s19081807
46. [46] Sambo, P., Nicoletto, C., Giro, A., Pii, Y., Valentinuzzi, F., Mimmo, T., Lugli, P., Orzes, G., Mazzetto, F., Astolfi, S., Terzano, R., & Cesco, S. (2019). Hydroponic Solutions for Soilless Production Systems: Issues and Opportunities in a Smart Agriculture Perspective. Frontiers in Plant Science, 10, 923. https://doi.org/10.3389/fpls.2019.00923
47. [47] Chowdhury, R., Pradhan, B., Chakravorty, R., & Rana, K. (2019). Integrated vertical farming system: A revolution in urban food production. Journal of Pharmacognosy and Phytochemistry, 8(3), 1175–1179.
48. [48] Aerofarms. (2020). Technology. https://aerofarms.com/technology/
49. [49] Aerofarms. (2020). Our Farms. https://aerofarms.com/farms/
50. [50] Aerofarms. (2020). Sustainability. https://aerofarms.com/sustainability/
51. [51] Skygreens. (2020). Technology. https://www.skygreens.com/technology/
52. [52] Skygreens. (2020). About Us. https://www.skygreens.com/about-us/
53. [53] Skygreens. (2020). Our Story. https://www.skygreens.com/our-story/
54. [54] Plantagon. (2020). The Plantscraper. https://plantagon.com/plantscrapers/plantscraper-linkoping/
55. [55] Plantagon. (2020). The Technology. https://plantagon.com/technology/
56. [56] Spread. (2020). Techno Farm Keihanna. https://spread.co.jp/en/technofarm/
57. [57] Spread. (2020). Technology. https://spread.co.jp/en/technology/
58. [58] Spread. (2020). Sustainability. https://spread.co.jp/en/sustainability/
59. [59] Vertical Harvest. (2020). Our Story. https://verticalharvestjackson.com/our-story/
60. [60] Vertical Harvest. (2020). Our Mission. https://verticalharvestjackson.com/our-mission/
61. [61] Albatayneh, A., Mohaidat, S., Alkhazali, A., Dalalah, Z., Bdour, M., Maysarah, M., Al-Omari, D., Mohaidat, S., & Hayek, B. O. (2020). The Potential of Utilizing On-Site Photovoltaic Generation for Vertical Farming in Jordan. Sustainability, 12(23), 10112. https://doi.org/10.3390/su122310112
62. [62] Badami, M. G., & Ramankutty, N. (2015). Urban agriculture and food security: A critique based on an assessment of urban land constraints. Global Food Security, 4, 8–15. https://doi.org/10.1016/j.gfs.2014.10.003

63. [63] Cuce, E., Harjunowibowo, D., & Cuce, P. M. (2016). Renewable and sustainable energy saving strategies for greenhouse systems: A comprehensive review. Renewable and Sustainable Energy Reviews, 64, 34–59. https://doi.org/10.1016/j.rser.2016.05.077
64. [64] Van Ginkel, S. W., Igou, T., & Chen, Y. (2017). Energy, water and nutrient impacts of California-grown vegetables compared to controlled environmental agriculture systems in Atlanta, GA. Resources, Conservation and Recycling, 122, 319–325. https://doi.org/10.1016/j.resconrec.2017.03.003
65. [65] Stoknes, K., Scholwin, F., Krzesiński, W., Wojciechowska, E., & Jasińska, A. (2016). Efficiency of a novel "Food to waste to food" system including anaerobic digestion of food waste and cultivation of vegetables on digestate in a bubble-insulated greenhouse. Waste Management, 56, 466–476. https://doi.org/10.1016/j.wasman.2016.06.027
66. [66] Specht, K., Siebert, R., & Thomaier, S. (2016). Perception and acceptance of agricultural production in and on urban buildings (ZFarming): A qualitative study from Berlin, Germany. Agriculture and Human Values, 33(4), 753–769. https://doi.org/10.1007/s10460-015-9658-z
67. [67] Orsini, F., Dubbeling, M., de Zeeuw, H., & Gianquinto, G. (2017). Rooftop Urban Agriculture. Springer International Publishing. https://doi.org/10.1007/978-3-319-57720-3
68. [68] Bustamante, M. A., Liedtke, C., Wachsmann, U., & Bauer, S. (2018). Plant Façade: Vertical Greening Systems and the Sustainability of Buildings. In W. Leal Filho, D. M. Pociovălișteanu, P. R. Borges de Brito, & I. Borges de Lima (Eds.), Towards a Sustainable Bioeconomy: Principles, Challenges and Perspectives (pp. 233–247). Springer International Publishing. https://doi.org/10.1007/978-3-319-73028-8_12
69. [69] Jenkins, A. (2018). Vertical Farming—The Future of Agriculture: An Introduction and Overview (p. 22). Lambert Academic Publishing.
70. [70] Hughes, M., & Mangan, J. (2020). Adding Value to Urban Roof Gardens. In N. Samarasinghe & S. Paulo (Eds.), Sustainable Urban Agriculture (p. 21). Springer. https://doi.org/10.1007/978-981-15-3369-6_3
71. [71] Chance, E., Ashton, W., Pereira, J., Mulrow, J., Norberto, J., Derrible, S., & Guilbert, S. (2018). The Plant—An experiment in urban food sustainability. Environmental Progress & Sustainable Energy, 37(1), 82–90. https://doi.org/10.1002/ep.12712
72. [72] Specht, K., Reynolds, K., & Sanyé-Mengual, E. (2017). Community and Social Justice Aspects of Rooftop Agriculture. In F. Orsini, M. Dubbeling, H. de Zeeuw, & G. Gianquinto (Eds.), Rooftop Urban Agriculture (pp. 277–290). Springer International Publishing. https://doi.org/10.1007/978-3-319-57720-3_17
73. [73] Pollard, G., Ward, J., & Roetman, P. (2018). Typically Diverse: The Nature of Urban Agriculture in South Australia. Sustainability, 10(4), 945. https://doi.org/10.3390/su10040945
74. [74] Appolloni, E., Orsini, F., Michelon, N., & Gianquinto, G. (2021). The global rise of commercial urban rooftop farming: A review of worldwide cases and the role of integrated urban rooftop farming for sustainable cities. Journal of Cleaner Production, 313, 127913. https://doi.org/10.1016/j.jclepro.2021.127913
75. [75] Sanyé-Mengual, E., Specht, K., Krikser, T., Vanni, C., Pennisi, G., Orsini, F., & Gianquinto, G. P. (2018). Social acceptance and perceived ecosystem services of urban agriculture in Southern Europe: The case of Bologna, Italy. PLoS ONE, 13(9), e0200993. https://doi.org/10.1371/
76. [76] Raj, A., & Sah, B. (2019). Analyzing the Factors Influencing Consumers' Choice of Vegetable Retail Outlets: Empirical Evidence from Urban and Peri-urban Areas of Kathmandu Valley, Nepal. Future of Food: Journal on Food, Agriculture and Society, 7(2), 33–47. https://doi.org/10.17170/kobra-20191217881
77. [77] Bantis, F., Smirnakou, S., Ouzounis, T., Koukounaras, A., Ntagkas, N., & Radoglou, K. (2018). Current status and recent achievements in the field of horticulture with the use of light-emitting diodes (LEDs). Scientia Horticulturae, 235, 437–451. https://doi.org/10.1016/j.scienta.2018.02.058
78. [78] Vadiee, A., & Martin, V. (2013). Energy management in horticultural applications through the closed greenhouse concept, state of the art. Renewable and Sustainable Energy Reviews, 16(7), 5087–5100. https://doi.org/10.1016/j.rser.2012.04.022

79. [79] El-Nakhel, C., Giordano, M., Pannico, A., Rouphael, Y., & De Pascale, S. (2021). Vertical Farming Systems Towards Sustainable Crop Production. Current Horticulture, 1–24. https://doi.org/10.2174/2468550121999210222103651
80. [80] Kikuchi, Y., Kanematsu, Y., Yoshikawa, N., Okubo, T., & Takagaki, M. (2018). Environmental and resource use analysis of plant factories with energy technology options: A case study in Japan. Journal of Cleaner Production, 186, 703–717. https://doi.org/10.1016/j.jclepro.2018.03.110
81. [81] Shamshiri, R. R., Kalantari, F., Ting, K. C., Thorp, K. R., Hameed, I. A., Weltzien, C., Ahmad, D., & Shad, Z. M. (2018). Advances in greenhouse automation and controlled environment agriculture: A transition to plant factories and urban agriculture. International Journal of Agricultural and Biological Engineering, 11(1), 1–22. https://doi.org/10.25165/j.ijabe.20181101.3210
82. [82] Tsitsimpelis, I., Wolfenden, I., & Taylor, C. J. (2016). Development of a grow-cell test facility for research into sustainable controlled-environment agriculture. Biosystems Engineering, 150, 40–53. https://doi.org/10.1016/j.biosystemseng.2016.07.008
83. [83] Rufí-Salís, M., Calvo, M. J., Petit-Boix, A., Villalba, G., & Gabarrell, X. (2020). Exploring nutrient recovery from hydroponics in urban agriculture: An environmental assessment. Resources, Conservation and Recycling, 155, 104683. https://doi.org/10.1016/j.resconrec.2020.104683
84. [84] Goddek, S., Delaide, B., Mankasingh, U., Ragnarsdottir, K. V., Jijakli, H., & Thorarinsdottir, R. (2015). Challenges of Sustainable and Commercial Aquaponics. Sustainability, 7(4), 4199–4224. https://doi.org/10.3390/su7044199
85. [85] Orsini, F., Pennisi, G., Mancarella, S., Al Nayef, M., Sanoubar, R., Nicola, S., & Gianquinto, G. (2018). Hydroponic cultivation improves the nutritional quality of soybean and its products. Agronomy, 8(9), 153. https://doi.org/10.3390/agronomy8090153
86. [86] Xu, C. (2019). Computational and Genetic Solutions for Crop Improvement in Vertical Farming. In T. Kozai, G. Niu, & M. Takagaki (Eds.), Plant Factory (pp. 155–172). Academic Press. https://doi.org/10.1016/B978-0-12-816691-8.00012-8
87. [87] Teng, J., Yasunaga, S., Doi, M., & Shimizu, H. (2021). An experimental study on the optimization of plant cultivation in a plant factory system with artificial lighting. Computers and Electronics in Agriculture, 180, 105918. https://doi.org/10.1016/j.compag.2020.105918
88. [88] Wolfert, S., Ge, L., Verdouw, C., & Bogaardt, M.-J. (2017). Big Data in Smart Farming – A review. Agricultural Systems, 153, 69–80. https://doi.org/10.1016/j.agsy.2017.01.023
89. [89] Kochhar, I., & Kumar, N. (2019). Wireless sensor networks for greenhouses: An end-to-end review. Computers and Electronics in Agriculture, 163, 104877. https://doi.org/10.1016/j.compag.2019.104877
90. [90] Ferrag, M. A., Shu, L., Yang, X., Derhab, A., & Maglaras, L. (2020). Security and Privacy for Green IoT-Based Agriculture: Review, Blockchain Solutions, and Challenges. IEEE Access, 8, 32031–32053. https://doi.org/10.1109/ACCESS.2020.2973178
91. [91] Tomlinson, L., Agarwal, N., & Rahman, S. M. M. (2019). Planning for Climate Compatible Development: A Situational Analysis. In R. Roggema & A. Roggema (Eds.), Smart and Sustainable Cities and Buildings (pp. 51–71). Springer International Publishing. https://doi.org/10.1007/978-3-030-37635-2_4
92. [92] Fuldauer, L. I., Parker, B. M., Yaman, R., & Borrion, A. (2018). Managing anaerobic digestate from food waste in the urban environment: Evaluating the feasibility from an interdisciplinary perspective. Journal of Cleaner Production, 185, 929–940. https://doi.org/10.1016/j.jclepro.2018.03.045
93. [93] Loo, Y. Y., Billa, L., & Singh, A. (2015). Effect of climate change on seasonal monsoon in Asia and its impact on the variability of monsoon rainfall in Southeast Asia. Geoscience Frontiers, 6(6), 817–823. https://doi.org/10.1016/j.gsf.2014.02.009
94. [94] Marcelis, L. F. M., & Heuvelink, E. (2019). Greenhouse horticulture: New technologies and specialized applications increase the efficiency, reduce pollution, and enhance the quality of products. In C. A. Hatch (Ed.), Horticultural Reviews (1st ed., pp. 83–136). Wiley. https://doi.org/10.1002/9781119521082.ch3