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PREFACE

The United Nations General Assembly has declared 2023 as the International Year of Millets, recognizing the crucial role these ancient grains play in food security, nutrition, and sustainable agriculture. This book, **"International Year of Millets 2023,"** serves as a comprehensive guide to understanding the significance of millets in the face of global challenges such as climate change, growing populations, and the need for resilient and diverse food systems.

Millets, a collective term for a group of small-seeded grasses, have been cultivated for thousands of years across the world. These humble grains are known for their adaptability to harsh growing conditions, their high nutritional value, and their potential to support sustainable farming practices. Despite their numerous benefits, millets have often been overshadowed by more popular cereals like wheat, rice, and maize.

This book aims to shed light on the untapped potential of millets and their role in addressing the pressing issues of our time. It explores the various types of millets, their cultural and historical significance, and their agronomic and nutritional properties. The book also delves into the challenges and opportunities in millet production, processing, and market development, highlighting the need for collaborative efforts to promote these underutilized grains.

Through the pages of this book, readers will gain insights into the latest research, innovations, and best practices in millet cultivation, as well as the policies and initiatives supporting the growth of the millet sector. The book features contributions from leading experts, farmers, and stakeholders from around the world, offering a diverse range of perspectives and experiences.

As we celebrate **the International Year of Millets**, this book serves as a timely resource for policymakers, researchers, farmers, and consumers alike. By raising awareness and fostering a deeper understanding of millets, we hope to inspire action towards building a more sustainable, nutritious, and resilient food future for all.

Happy reading and happy gardening!

Editors……

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CHAPTER - 1

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Millets: Ancient Grains for a Sustainable Future

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Abstract

Millets, a group of small-seeded cereal crops, have been cultivated for thousands of years and serve as a staple food for millions of people worldwide. In the face of climate change and the need for sustainable agriculture, millets are gaining renewed attention for their resilience, nutritional value, and potential to support food security. This chapter explores the diverse types of millets, their agronomic advantages, and their role in sustainable farming systems. It also examines the nutritional profile of millets, highlighting their potential health benefits. Furthermore, the chapter discusses the socio-economic importance of millets, particularly for smallholder farmers in developing countries, and the challenges and opportunities for promoting millet cultivation and consumption. Finally, it addresses the need for research and policy interventions to support the development of millet value chains and to realize the full potential of these ancient grains in contributing to a sustainable and resilient food future.

Keywords: Millets, Sustainable Agriculture, Climate Resilience, Nutrition, Food Security

1. Introduction

Millets are a diverse group of small-seeded cereal crops that have been cultivated for thousands of years in many parts of the world, particularly in Asia and Africa [1]. These ancient grains have played a vital role in supporting the livelihoods and nutrition of millions of people, especially in semi-arid and arid regions where other crops may struggle to grow [2]. In recent years, millets have been gaining renewed attention for their potential to contribute to sustainable agriculture, climate resilience, and food security [3].

The United Nations General Assembly declared 2023 as the International Year of Millets, recognizing the importance of these crops in addressing global challenges such as climate change, malnutrition, and poverty [4]. This declaration has brought millets into the spotlight and has created an opportunity to promote their cultivation, consumption, and research.

2. Types of Millets

Millets are a diverse group of cereal crops that belong to different genera and species within the Poaceae family [5]. The most commonly cultivated millets include:

1. Pearl millet (*Pennisetum glaucum*)
2. Finger millet (*Eleusine coracana*)
3. Foxtail millet (*Setaria italica*)
4. Proso millet (*Panicum miliaceum*)
5. Barnyard millet (*Echinochloa spp.*)
6. Kodo millet (*Paspalum scrobiculatum*)
7. Little millet (*Panicum sumatrense*)

Table 1: Characteristics of common millet types

Millet Type	**Scientific Name**	**Cultivation Regions**	**Yield (t/ha)**	**Protein Content (%)**
Pearl millet	*Pennisetum glaucum*	Africa, Asia	0.5-2.0	11-19
Finger millet	*Eleusine coracana*	Africa, South Asia	1.0-3.0	7-14
Foxtail millet	*Setaria italica*	Asia, Europe, North America	1.5-3.0	10-14
Proso millet	*Panicum miliaceum*	Asia, Europe, North America	1.0-2.5	12-14
Barnyard millet	*Echinochloa spp.*	Asia, Africa	0.5-2.0	6-15
Kodo millet	*Paspalum scrobiculatum*	South Asia	0.5-1.5	8-12
Little millet	*Panicum sumatrense*	South and Southeast Asia	0.5-1.0	7-11

These millets vary in their morphological characteristics, adaptability to different agro-ecological conditions, and nutritional composition [6]. Pearl millet and finger millet are the most widely cultivated and consumed millets globally, while others are of regional importance [7].

3. Agronomic Advantages of Millets

Millets possess several agronomic advantages that make them well-suited for cultivation in marginal environments and under changing climatic conditions [8]. These advantages include:

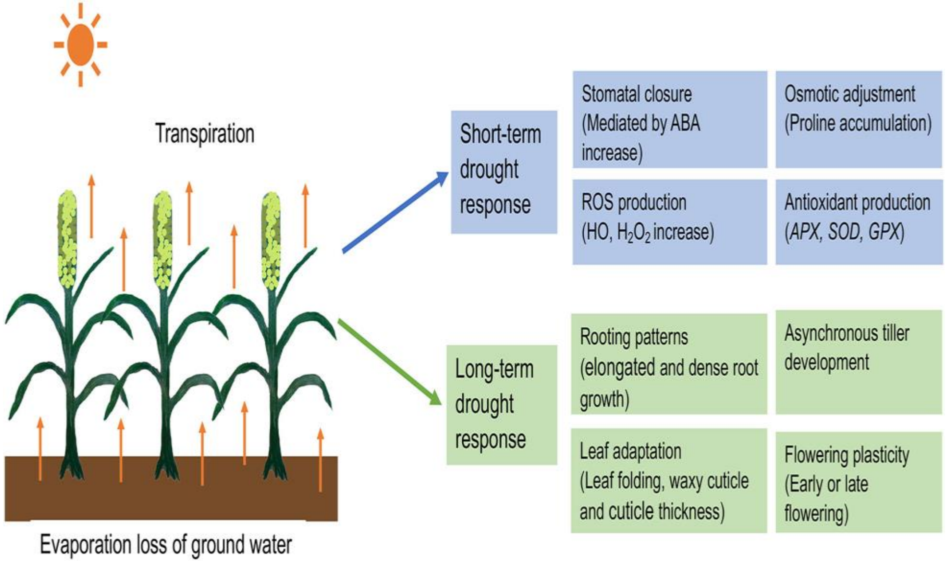
3.1 Drought tolerance

Millets have a high water-use efficiency and can thrive in areas with low and erratic rainfall [9]. They have deep root systems that enable them to access moisture from deeper soil layers [10].

3.2 Short growing season

Most millet crops have a short growing season of 60-90 days, making them suitable for cultivation in regions with short rainy seasons or as a catch crop in between major cropping seasons [11].

Figure 1: Drought tolerance of millets compared to other cereal crops



These agronomic advantages make millets a valuable component of sustainable farming systems, particularly in the context of climate change and the need to promote resilient agriculture [15].

3.3 Low input requirements

Millets can grow in poor soils and require minimal fertilizer and pesticide inputs compared to other cereal crops [12]. This makes them an attractive option for resource-poor farmers and for promoting sustainable agriculture.

3.4 Resilience to pests and diseases

Millets have a natural resistance to many pests and diseases, reducing the need for chemical pest control measures [13].

3.5 Adaptability to diverse agro-ecologies

Millets can be grown in a wide range of agro-ecological conditions, from arid to semi-arid regions, and from sea level to high altitudes [14].

4. Nutritional Profile of Millets

Millets are nutritionally superior to many other cereal crops and are often referred to as "nutri-cereals" [16]. They are rich in several essential nutrients, including:

4.1 Protein

Millets have a higher protein content than most other cereals, with some varieties containing up to 14% protein [17]. They also have a well-balanced amino acid profile, with higher levels of essential amino acids compared to wheat and rice [18].

Table 2: Nutritional composition of common millets (per 100 g)

Millet Type	**Energy (kcal)**	**Protein (g)**	**Fat (g)**	**Carbohydrate (g)**	**Fiber (g)**	**Iron (mg)**	**Zinc (mg)**	**Calcium (mg)**
Pearl millet	361	11.6	5.0	67.5	11.3	8.0	3.1	42
Finger millet	328	7.3	1.3	72.0	11.5	3.9	2.3	350
Foxtail millet	331	12.3	4.3	60.9	8.0	2.8	3.3	31
Proso millet	354	11.0	3.5	70.4	7.2	3.0	1.7	14

4.2 Micronutrients

Millets are a good source of several micronutrients, including iron, zinc, calcium, and phosphorus [19]. For example, finger millet has the highest calcium content among all cereals [20].

4.3 Dietary fiber

Millets are rich in dietary fiber, particularly insoluble fiber, which promotes digestive health and may reduce the risk of chronic diseases such as diabetes and cardiovascular disease [21].

4.4 Phytochemicals

Millets contain various phytochemicals, such as phenolic compounds and flavonoids, which have antioxidant and anti-inflammatory properties [22].The nutritional profile of millets makes them a valuable component of a balanced and healthy diet [23]. Incorporating millets into the diet can help address micronutrient deficiencies, which are prevalent in many developing countries [24].

5. Health Benefits of Millets

The consumption of millets has been associated with several health benefits, largely due to their nutritional composition and bioactive compounds [25]. Some of the potential health benefits of millets include:

5.1 Glycemic control

Millets have a low glycemic index, meaning they release glucose slowly into the bloodstream, helping to control blood sugar levels [26]. This makes them a suitable food for people with diabetes or at risk of developing the condition.

5.2 Cardiovascular health

The high fiber content and phytochemicals in millets may help reduce the risk of cardiovascular diseases by lowering blood cholesterol levels and improving blood pressure [27].

5.3 Digestive health

The high fiber content in millets promotes digestive health by preventing constipation and supporting the growth of beneficial gut bacteria [28].

5.4 Weight management

Millets are high in fiber and protein, which can promote feelings of fullness and reduce overall calorie intake, thus supporting weight management [29].

5.5 Antioxidant properties

The phenolic compounds and flavonoids in millets have antioxidant properties, which may help protect against oxidative stress and related chronic diseases [30].

6. Socio-Economic Importance of Millets

Millets play a crucial role in the livelihoods and food security of millions of people, particularly in developing countries [32]. Some of the socio-economic aspects of millet cultivation and consumption include:

6.1 Importance for smallholder farmers

Millets are primarily grown by smallholder farmers in marginal environments, where they contribute to household food security and income [33]. The low input requirements and resilience of millets make them a suitable crop for resource-poor farmers.

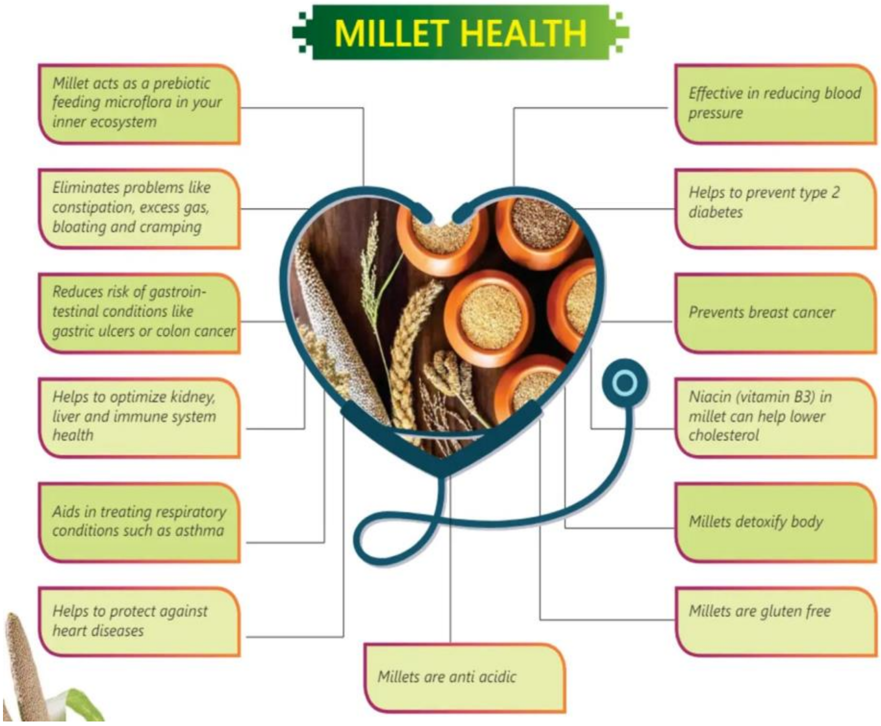


Figure 2: Potential health benefits of millet consumption

While more research is needed to fully understand the health benefits of millets, their nutritional profile and traditional use in many cultures suggest that they can be a valuable component of a healthy diet [31].

6.2 Contribution to rural economy

Millet cultivation and processing provide employment and income opportunities for rural communities, particularly for women who are often involved in post-harvest processing and value addition [34].

6.3 Potential for value chain development

There is a growing interest in developing millet value chains, including improved production, processing, and marketing of millet products [35]. This can create new economic opportunities and contribute to rural development.

6.4 Role in food security

Millets are an important staple food for millions of people in Asia and Africa, and their cultivation can contribute to local and regional food security

[36]. The nutritional quality of millets makes them a valuable component of food security strategies.

Table 3: Millet production and consumption in major producing countries (2020)

Country	Production (million tonnes)	Per capita consumption (kg/year)
India	10.3	7.5
Niger	3.3	78.0
China	1.7	1.2
Mali	1.6	64.0
Nigeria	1.5	7.8
Burkina Faso	1.2	61.0
Sudan	1.1	26.0

Despite their importance, millet cultivation and consumption face several challenges, including low productivity, limited value addition, and changing consumer preferences [37]. Addressing these challenges requires concerted efforts from researchers, policymakers, and development organizations.

7. Challenges for Promoting Millets

While millets have several agronomic and nutritional advantages, their cultivation and consumption face various challenges that need to be addressed to fully realize their potential [38]. Some of these challenges include:

7.1 Low productivity

Millet yields are generally lower than those of other cereal crops due to factors such as limited use of improved varieties, poor soil fertility, and inadequate crop management practices [39].

7.2 Limited value addition

Millet processing and value addition are often limited, resulting in low economic returns for farmers and limited consumer appeal [40].

7.3 Changing consumer preferences

With increasing urbanization and changing dietary habits, the consumption of millets has been declining in many traditional millet-consuming regions [41].

7.4 Inadequate research and policy support

Compared to other major cereal crops, millets have received less attention in terms of research and policy support, which has hindered their development and promotion [42].

8. Opportunities for Promoting Millets

Despite the challenges, there are several opportunities for promoting millet cultivation and consumption, including:

8.1 Developing improved varieties

Breeding efforts focused on developing high-yielding, climate-resilient, and nutrient-dense millet varieties can help increase productivity and make millets more attractive to farmers and consumers [43].

8.2 Promoting value addition

Encouraging the development of millet-based products, such as ready-to-eat snacks, baked goods, and beverages, can create new market opportunities and increase consumer demand for millets [44].

8.3 Supportive policies and programs

Government policies and programs that support millet cultivation, processing, and marketing can help create an enabling environment for the development of millet value chains [45].

8.4 Awareness and education

Increasing awareness about the nutritional and environmental benefits of millets among consumers, policymakers, and development organizations can help promote their cultivation and consumption [46].

9. Research Interventions for Promoting Millets

To support the development of millet value chains and promote their cultivation and consumption, several research interventions are needed [48]. These include:

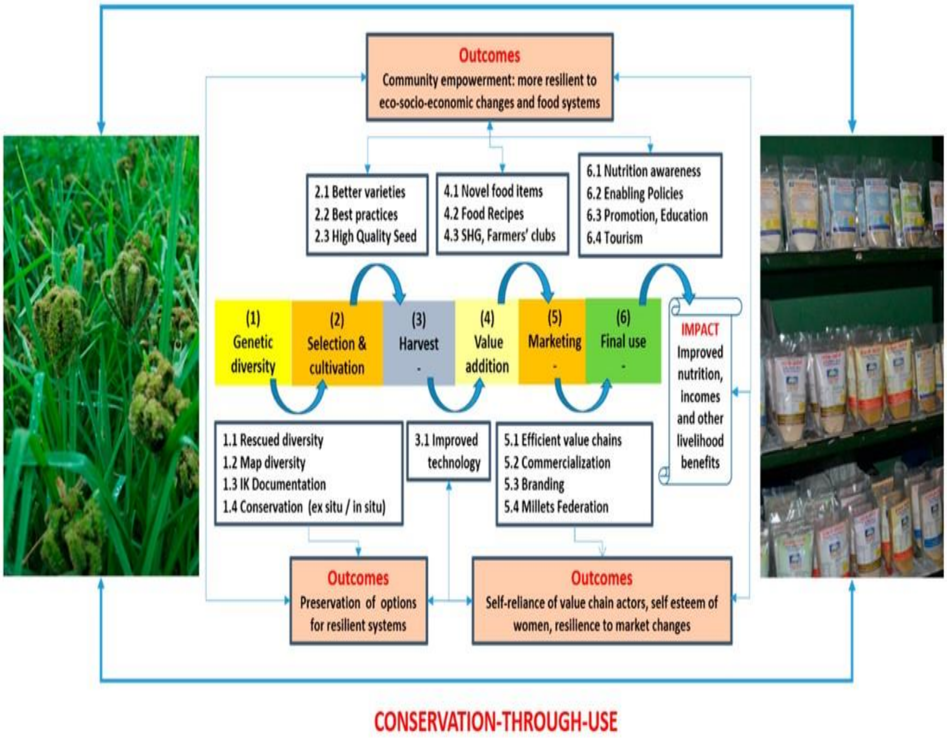
9.1 Varietal development and dissemination

Investing in the development and dissemination of improved millet varieties that are high-yielding, climate-resilient, and nutrient-dense [49]. This requires strengthening the capacity of national and international research organizations working on millets.

9.2 Agronomy and crop management

Conducting research on best agronomic practices for millet cultivation, including soil fertility management, water management, and pest and disease control [50]. Disseminating this knowledge to farmers through extension services and capacity building programs.

Figure 3: Strategies for promoting millet cultivation and consumption



Realizing the full potential of millets in contributing to sustainable food systems requires a multi-stakeholder approach that addresses the challenges and leverages the opportunities for promoting these ancient grains [47].

9.3 Value chain development

Supporting the development of millet value chains through research on post-harvest processing, product development, and market linkages [51]. This also involves building the capacity of small and medium enterprises involved in millet processing and marketing.

10. Policy Interventions for Promoting Millets

In addition to research interventions, policy support is crucial for promoting millet cultivation and consumption. Some key policy interventions include:

10.1 Including millets in public distribution systems

Incorporating millets into public food distribution programs can help create a stable demand for these crops and support their cultivation [52].

10.2 Providing incentives for millet producers and processors

Offering incentives such as subsidies, credit support, and tax benefits can encourage farmers and entrepreneurs to invest in millet production and processing [53].

10.3 Promoting millets in national dietary guidelines

Incorporating millets into national dietary guidelines and nutrition programs can help raise awareness about their health benefits and increase their consumption [54].

Table 4: Examples of research and policy interventions for promoting millets

Intervention Category	Examples
Varietal development	- Breeding for high yield, climate resilience, and nutrient density - Participatory varietal selection involving farmers
Agronomy and crop management	- Research on integrated soil fertility management - Developing decision support tools for millet farmers
Value chain development	- Research on improved millet processing technologies - Capacity building for millet-based enterprises
Policy support	- Including millets in public distribution systems - Providing incentives for millet producers and processors
Awareness and promotion	- Nutrition education campaigns promoting millets - Partnering with the private sector to develop

11. Awareness and Promotion of Millets

Raising awareness about the nutritional and environmental benefits of millets is crucial for promoting their cultivation and consumption. Some strategies for awareness and promotion include:

11.1 Nutrition education campaigns

Conducting nutrition education campaigns that highlight the health benefits of millets can help increase their consumption, particularly among urban consumers [55].

11.2 Partnerships with the private sector

Collaborating with the private sector to develop and promote millet-based products can help create new market opportunities and raise awareness about millets [56].

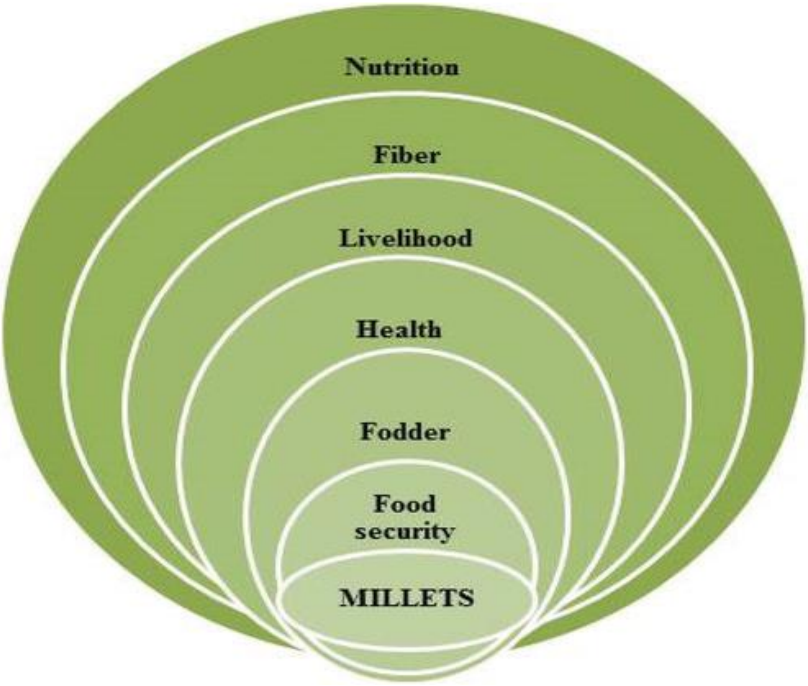
11.3 Leveraging social media and digital platforms

Using social media and digital platforms to share information about millets, their benefits, and recipes can help reach a wider audience and promote their consumption [57].

11.4 Celebrating the International Year of Millets

Leveraging the International Year of Millets 2023 to organize events, conferences, and campaigns that showcase the potential of millets and build stakeholder partnerships [58].

Figure 4: Awareness and promotion strategies for millets



Implementing these awareness and promotion strategies requires collaboration among various stakeholders, including government agencies, civil society organizations, research institutions, and the private sector [59].

Conclusion

Millets are ancient grains with the potential to contribute to sustainable food systems and address global challenges such as climate change, malnutrition, and poverty. Their agronomic resilience, nutritional quality, and socio-economic importance make them valuable for supporting the livelihoods and food security of millions of people, particularly in developing countries.

However, realizing the full potential of millets requires addressing several challenges, including low productivity, limited value addition, and changing consumer preferences. This calls for concerted efforts in research, policy support, and awareness-raising to promote millet cultivation and consumption.

Research interventions should focus on developing improved millet varieties, optimizing agronomic practices, and strengthening millet value chains. Policy interventions, such as including millets in public distribution systems, providing incentives for millet producers and processors, and promoting millets in national dietary guidelines, can create an enabling environment for the growth of the millet sector.

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CHAPTER - 02

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Global Diversity and Adaptability of Millets

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Abstract

Millets are a diverse group of small-seeded cereal crops that have been cultivated for thousands of years across the globe. They are known for their remarkable adaptability to a wide range of agro-climatic conditions, including drought, heat, and poor soil fertility. This chapter explores the global diversity and adaptability of millets, highlighting their importance as climate-resilient crops and their potential in ensuring food security and nutrition. The chapter discusses the various types of millets, their taxonomic classification, and their distribution across different regions. It also delves into the genetic diversity and variability within millet species, which form the basis for their adaptability. The chapter emphasizes the need for research and development efforts to further enhance the productivity and utilization of millets, and to promote their cultivation as a sustainable and climate-smart agricultural practice. The potential of millets in contributing to the achievement of sustainable development goals, particularly in the face of climate change and increasing food demand, is also discussed.

Keywords: Millets, diversity, adaptability, climate resilience, food security

1. Introduction

1.1. Background on millets

Millets are a group of small-seeded cereal crops that belong to the family Poaceae (grasses) [1]. They are known by various names across different regions, such as sorghum, pearl millet, finger millet, foxtail millet, proso millet, barnyard millet, kodo millet, and little millet [2]. Millets have been cultivated for thousands of years in Asia, Africa, and other parts of the world, and have played a significant role in the food and livelihood security of millions of people [3].

1.2. Significance of millets in global agriculture

Millets are considered as important crops for global agriculture due to their unique characteristics and potential benefits [4]. They are highly adaptable to a wide range of agro-climatic conditions, including drought, heat, and poor soil fertility [5]. Millets require less water and inputs compared to other major cereal crops, making them suitable for cultivation in marginal and rainfed areas [6]. Moreover, millets are nutritionally superior to many other cereals, being rich in protein, fiber, minerals, and bioactive compounds [7].

Component	**Straw (%)**	**Husks (%)**	**Bran (%)**
Cellulose	30-40	25-35	10-20
Hemicellulose	20-30	30-40	30-40
Lignin	15-25	20-30	5-10
Protein	2-5	2-5	10-20
Ash	5-10	2-5	5-10
Other	5-10	5-10	10-20

Table 1. Typical composition of millet waste (adapted from [13])

2. Diversity of Millets

2.1. Taxonomic classification of millets

Millets belong to the family Poaceae, which includes other major cereal crops such as rice, wheat, and maize [8]. The term "millet" is used to describe a diverse group of small-seeded grasses that are cultivated as cereal crops [9]. The taxonomic classification of millets is complex and varies depending on the criteria used, such as morphology, cytology, and molecular markers [10].

2.2. Major types of millets

The major types of millets cultivated worldwide are:

2.2.1. Pearl millet (*Pennisetum glaucum*)

Pearl millet is the most widely cultivated millet crop, grown primarily in the arid and semi-arid regions of Asia and Africa [11]. It is a highly drought-tolerant crop and can grow in soils with low fertility [12]. Pearl millet is used for food, feed, and fodder purposes [13].

2.2.2. Finger millet (*Eleusine coracana*)

Finger millet is an important staple crop in many parts of Asia and Africa, particularly in the hills and tribal regions [14]. It is known for its high nutritional value, being rich in calcium, iron, and other essential minerals [15]. Finger millet is also used in traditional medicine for various health benefits [16].

2.2.3. Foxtail millet (*Setaria italica*)

Foxtail millet is one of the oldest cultivated crops, originating in China and later spreading to other parts of Asia and Europe [17]. It is a short-duration crop with high nutritional value and is used for food and feed purposes [18]. Foxtail millet is also known for its drought tolerance and can grow in marginal soils [19].

2.2.4. Proso millet (*Panicum miliaceum*)

Proso millet is a short-duration crop that is cultivated in many parts of Asia, Europe, and North America [20]. It is a highly nutritious crop, being rich in protein, fiber, and minerals [21]. Proso millet is used for food, feed, and birdseed purposes [22].

2.2.5. Barnyard millet (*Echinochloa* spp.)

Barnyard millet is a group of species belonging to the genus *Echinochloa*, which are cultivated as minor millets in many parts of Asia and Africa [23]. They are known for their high yield potential and adaptability to waterlogged conditions [24]. Barnyard millets are used for food, feed, and fodder purposes [25].

2.2.6. Kodo millet (*Paspalum scrobiculatum*)

Kodo millet is a minor millet crop that is cultivated in parts of India and Africa [26]. It is known for its drought tolerance and can grow in poor soils [27]. Kodo millet is used for food and feed purposes and is also known for its medicinal properties [28].

2.2.7. Little millet (*Panicum sumatrense*)

Little millet is a minor millet crop that is cultivated in parts of India and Southeast Asia [29]. It is a short-duration crop with high nutritional value and is used for food and feed purposes [30]. Little millet is also known for its drought tolerance and can grow in marginal soils [31].

2.3. Minor millets and their importance

Apart from the major types of millets, there are several minor millets that are cultivated in specific regions and have local importance [32]. These include fonio millet (*Digitaria exilis*), Guinea millet (*Brachiaria deflexa*), browntop millet (*Urochloa ramosa*), and teff millet (*Eragrostis tef*), among others [33]. Minor millets are important for their adaptability to specific agro-climatic conditions, their nutritional value, and their role in supporting local food security and livelihoods [34].

Method	**Advantages**	**Disadvantages**
Physical	- Simple and low-cost - No chemicals required	- High energy consumption - Incomplete delignification
Chemical	- High efficiency - Short reaction time	- Corrosive and toxic chemicals - High cost of reagents and equipment
Biological	- Environmentally friendly - Low energy consumption	- Long reaction time - Low efficiency

Table 2. Comparison of pretreatment methods for millet waste (adapted from [29])

2.4. Genetic diversity and variability in millets

Millets exhibit a wide range of genetic diversity and variability, both within and between species [35]. This diversity is a result of the long history of domestication and selection by farmers in different agro-ecological regions [36]. The genetic diversity in millets is a valuable resource for crop improvement programs, as it provides the basis for developing new varieties with desirable traits such as high yield, disease resistance, and abiotic stress tolerance [37].

Studies have shown that there is significant genetic variability in millet germplasm collections for various morphological, physiological, and biochemical traits [38]. For example, a study on pearl millet germplasm from Senegal revealed a wide range of variability in traits such as plant height, panicle length, and grain yield [39]. Similarly, a study on finger millet germplasm from Ethiopia showed significant diversity in traits such as days to maturity, plant height, and grain calcium content [40].

Molecular markers have also been used to assess the genetic diversity and relationships among millet species and cultivars [41]. For instance, a study using SSR markers revealed a high level of genetic diversity in foxtail millet germplasm from China [42]. Another study using AFLP markers showed the genetic relationships among different species of *Pennisetum*, including pearl millet [43].

The genetic diversity in millets is not only important for crop improvement but also for conservation and sustainable use of these resources [44]. Many millet species and landraces are at risk of genetic erosion due to factors such as land use changes, agricultural intensification, and replacement by high-yielding varieties [45]. Therefore, there is a need for systematic collection, characterization, and conservation of millet genetic resources in genebanks and on-farm [46].

Waste type	**Biogas yield (L/kg VS)**	**Methane content (%)**
Straw	200-300	50-60
Bran	400-500	60-70
Husks	100-200	40-50

Table 3. Biogas yields and methane contents of millet waste

3. Adaptability of Millets

3.1. Climatic adaptability

Millets are known for their remarkable adaptability to a wide range of climatic conditions, particularly in arid and semi-arid regions [47]. They have evolved various morphological, physiological, and biochemical mechanisms to cope with abiotic stresses such as drought, heat, and salinity [48].

3.1.1. Drought tolerance

Millets are highly drought-tolerant crops and can grow in areas with low and erratic rainfall [49]. They have a deep and extensive root system that allows them to extract water from deeper soil layers [50]. Millets also have efficient water use efficiency and can maintain high photosynthetic rates under water stress conditions [51].

Studies have shown that millets have higher drought tolerance compared to other cereal crops such as maize and wheat [52]. For example, pearl millet can produce grain yields of 1-2 tons per hectare under rainfall of 200-300 mm, while maize requires 400-500 mm of rainfall for similar yields [53].

3.1.2. Heat tolerance

Millets are also highly heat-tolerant crops and can grow in areas with high temperatures and low humidity [54]. They have a C4 photosynthetic pathway, which allows them to maintain high photosynthetic rates even at high temperatures [55]. Millets also have a short life cycle and can complete their growth and development before the onset of high temperatures [56].

Studies have shown that millets can tolerate temperatures up to 40-45°C during the reproductive stage without significant yield losses [57]. For example, a study on pearl millet showed that it could tolerate temperatures up to 42°C during the grain filling stage without affecting grain yield [58].

3.1.3. Resistance to extreme weather events

Millets are also known for their resistance to extreme weather events such as floods, cyclones, and hailstorms [59]. They have a strong stem and root system that can withstand high winds and water currents [60]. Millets also have a quick recovery ability and can regenerate after damage by extreme weather events [61].

For example, a study on finger millet showed that it could recover quickly after submergence in water for up to 10 days [62]. Another study on barnyard millet showed that it could tolerate waterlogging for up to 15 days without significant yield losses [63].

3.2. Soil adaptability

Millets are highly adaptable to a wide range of soil types and conditions, including marginal and degraded soils [64]. They have a high nutrient use efficiency and can grow in soils with low fertility and organic matter content [65].

3.2.1. Tolerance to poor soil fertility

Millets have a high tolerance to poor soil fertility and can grow in soils with low nitrogen, phosphorus, and potassium levels [66]. They have a strong root system that can extract nutrients from deeper soil layers and can form symbiotic associations with soil microorganisms such as mycorrhizae and nitrogen-fixing bacteria [67].

Studies have shown that millets can produce reasonable yields even in soils with low fertility levels [68]. For example, a study on finger millet showed that it could produce grain yields of 1-2 tons per hectare in soils with low phosphorus levels [69].

3.2.2. Adaptability to marginal lands

Millets are also highly adaptable to marginal lands such as saline, acidic, and alkaline soils [70]. They have a high tolerance to soil salinity and can grow in soils with electrical conductivity up to 8-10 dS/m [71]. Millets also have a high tolerance to soil acidity and can grow in soils with pH levels as low as 4.5-5.0 [72].

Studies have shown that millets can be used for the rehabilitation of degraded and marginal lands [73]. For example, a study on kodo millet showed that it could be used for the reclamation of salt-affected soils in India [74]. Another study on proso millet showed that it could be used for the restoration of abandoned mining sites in China [75].

3.3. Pest and disease resistance

Millets are generally less susceptible to pests and diseases compared to other cereal crops [76]. They have evolved various morphological and biochemical defenses against insect pests and pathogens [77].

For example, pearl millet has a thick and tough seed coat that provides resistance against seed-borne fungi and insects [78]. Finger millet has a high content of phenolic compounds and tannins that provide resistance against fungal diseases such as blast and rust [79].

However, millets are not completely immune to pests and diseases and can be affected by various biotic stresses depending on the region and season [80]. Some of the major pests and diseases of millets include stem borers, aphids, shoot flies, downy mildew, blast, and smut [81].

Integrated pest and disease management strategies, including the use of resistant varieties, cultural practices, and biological control agents, are recommended for the sustainable management of pests and diseases in millets [82].

3.4. Comparative advantages over other crops

Millets have several comparative advantages over other major cereal crops such as rice, wheat, and maize [83]. These include:

1. Higher water use efficiency and drought tolerance
2. Higher heat and salinity tolerance
3. Higher nutrient use efficiency and adaptability to low fertility soils
4. Lower input requirements (water, fertilizers, pesticides)
5. Shorter growth duration and higher crop rotation flexibility
6. Higher nutritional value (protein, fiber, minerals)
7. Lower glycemic index and higher health benefits
8. Higher fodder quality and palatability for livestock
9. Higher ecological and economic sustainability

For example, a study comparing the water use efficiency of different crops found that pearl millet had the highest water use efficiency (4.7 kg/ha/mm), followed by sorghum (3.8 kg/ha/mm), maize (2.5 kg/ha/mm), and wheat (1.5 kg/ha/mm) [84].

Another study comparing the nutritional value of different cereal grains found that finger millet had the highest calcium content (344 mg/100g), followed by pearl millet (42 mg/100g), sorghum (28 mg/100g), and wheat (30 mg/100g) [85].

These comparative advantages make millets a suitable crop for sustainable intensification of agriculture, particularly in marginal and rainfed areas [86].

4. Global Distribution and Production of Millets

4.1. Major millet-producing countries

Millets are cultivated in more than 130 countries across the world, with a total area of about 36 million hectares and a production of about 28 million tons [87]. The major millet-producing countries are:

4.1.1. India

India is the largest producer of millets in the world, accounting for about 40% of the global millet production [88]. The major millet crops grown in India are pearl millet, finger millet, foxtail millet, barnyard millet, and little millet [89]. Millets are grown in the arid and semi-arid regions of India, particularly in the states of Rajasthan, Maharashtra, Gujarat, Uttar Pradesh, and Karnataka [90].

4.1.2. Nigeria

Nigeria is the second-largest producer of millets in the world, accounting for about 15% of the global millet production [91]. The major millet crop grown in Nigeria is pearl millet, which is cultivated in the northern and central regions of the country [92].

4.1.3. China

China is the third-largest producer of millets in the world, accounting for about 10% of the global millet production [93]. The major millet crops grown in China are foxtail millet, proso millet, and finger millet [94]. Millets are cultivated in the northern and western regions of China, particularly in the provinces of Hebei, Shanxi, and Inner Mongolia [95].

4.1.4. Niger

Niger is the fourth-largest producer of millets in the world, accounting for about 5% of the global millet production [96]. The major millet crop grown in

Niger is pearl millet, which is cultivated in the southern and central regions of the country [97].

4.1.5. Mali

Mali is the fifth-largest producer of millets in the world, accounting for about 3% of the global millet production [98]. The major millet crop grown in Mali is pearl millet, which is cultivated in the southern and central regions of the country [99].

4.2. Regional distribution and production trends

Millets are widely distributed across the world, with different regions having specific millet crops and production systems [100]. The major regions of millet cultivation are:

1. **South Asia:** Pearl millet, finger millet, foxtail millet, barnyard millet, and little millet are the major millet crops grown in South Asia, particularly in India, Pakistan, Nepal, and Bangladesh [101]. Millets are grown in the arid and semi-arid regions of these countries, often as a rainfed crop [102].
2. **Sub-Saharan Africa:** Pearl millet, finger millet, and teff millet are the major millet crops grown in sub-Saharan Africa, particularly in Nigeria, Niger, Mali, Burkina Faso, and Ethiopia [103]. Millets are a staple food crop in the dry and marginal regions of these countries, often grown in intercropping or mixed cropping systems [104].
3. **East Asia:** Foxtail millet, proso millet, and finger millet are the major millet crops grown in East Asia, particularly in China, Japan, and Korea [105]. Millets are cultivated in the northern and western regions of these countries, often as a minor crop in rotation with other cereals [106].
4. **North America:** Proso millet is the major millet crop grown in North America, particularly in the United States and Canada [107]. Proso millet is cultivated as a short-season crop in the dryland regions of these countries, often as a rotational crop with wheat or barley [108].

The global production of millets has shown a declining trend in recent decades, from about 40 million tons in the 1960s to about 28 million tons in the 2010s [109]. This decline is attributed to factors such as the replacement of millets by high-yielding cereals like rice and wheat, the low market demand and price for millets, and the lack of policy support and research investment in millet improvement [110].

However, there is a growing interest in promoting millet cultivation and consumption, given their nutritional value, climate resilience, and potential for sustainable agriculture [111]. Several national and international initiatives, such as the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) and the All India Coordinated Research Project on Small Millets (AICRP-Small Millets), are focusing on millet research and development [112].

4.3. Factors influencing millet cultivation

The cultivation of millets is influenced by various agro-climatic, socio-economic, and institutional factors [113]. These include:

4.3.1. Agro-climatic conditions

Millets are generally grown in arid and semi-arid regions with low and erratic rainfall, high temperatures, and poor soil fertility [114]. The specific agro-climatic requirements vary for different millet crops, but in general, millets are adapted to harsh and marginal environments [115].

For example, pearl millet can grow in areas with annual rainfall of 200-800 mm and temperatures up to 40°C [116]. Finger millet can grow in areas with annual rainfall of 500-1000 mm and temperatures up to 35°C [117]. Foxtail millet can grow in areas with annual rainfall of 400-800 mm and temperatures up to 38°C [118].

4.3.2. Socio-economic factors

The cultivation of millets is also influenced by various socio-economic factors such as market demand, price, labor availability, and cultural preferences [119]. In many regions, millets are considered as a low-value crop compared to other cereals like rice and wheat, which have higher market demand and price [120].

Moreover, the cultivation of millets is often associated with small and marginal farmers, who have limited access to resources and technologies [121]. The labor-intensive nature of millet cultivation, particularly for weeding and harvesting, also limits its adoption by farmers [122].

However, there is a growing demand for millets as a healthy and nutritious food, particularly in urban and export markets [123]. The increasing awareness about the health benefits of millets, such as their high fiber, protein, and mineral content, is driving the market demand for millet-based products [124].

4.3.3. Policy support and institutional frameworks

The cultivation of millets is also influenced by the policy support and institutional frameworks at the national and regional levels [125]. In many countries, the agricultural policies and research priorities have focused on the major cereal crops like rice, wheat, and maize, with limited attention to millets [126].

However, there is a growing recognition of the importance of millets for food and nutrition security, particularly in the context of climate change and sustainable agriculture [127]. Several countries have initiated policies and programs to promote millet cultivation and consumption, such as the "Initiative for Nutritional Security through Intensive Millet Promotion (INSIMP)" in India [128].

Moreover, international research and development organizations, such as ICRISAT and the Food and Agriculture Organization (FAO), are supporting millet research and promotion through various projects and partnerships [129].

5. Nutritional and Health Benefits of Millets

5.1. Nutrient composition of millets

Millets are highly nutritious cereals that are rich in various macro- and micronutrients [130]. The nutrient composition of millets varies depending on the type of millet, the growing conditions, and the processing methods [131]. However, in general, millets have a high content of protein, fiber, minerals, and bioactive compounds compared to other cereals [132].

5.1.1. Protein content

Millets have a higher protein content compared to other cereals like rice and wheat [133]. The protein content of millets ranges from 7-12%, with some varieties having up to 18% protein [134]. Millets also have a better amino acid profile compared to other cereals, with higher levels of essential amino acids like lysine and methionine [135].

For example, a study comparing the protein content and quality of different cereals found that finger millet had the highest protein content (11.5%), followed by pearl millet (10.6%), sorghum (10.4%), and wheat (8.6%) [136]. The study also found that finger millet had the highest lysine content (4.1 g/100g protein) and the best amino acid score (0.54) among the cereals [137].

5.1.2. Micronutrients (iron, zinc, calcium)

Millets are also rich in various micronutrients like iron, zinc, and calcium, which are essential for human health [138]. The micronutrient content of millets is higher compared to other cereals, particularly for calcium [139].

For example, a study comparing the mineral content of different cereals found that finger millet had the highest calcium content (344 mg/100g), followed by pearl millet (42 mg/100g), sorghum (25 mg/100g), and wheat (30 mg/100g)

[140]. The study also found that pearl millet had the highest iron content (8 mg/100g) and zinc content (3.1 mg/100g) among the cereals [141].

5.1.3. Dietary fiber

Millets are a good source of dietary fiber, both soluble and insoluble [142]. The fiber content of millets ranges from 7-20%, with some varieties having up to 25% fiber [143]. The high fiber content of millets is beneficial for digestive health, weight management, and blood sugar control [144].

For example, a study comparing the fiber content of different cereals found that barnyard millet had the highest total dietary fiber (13.6%), followed by little millet (12.8%), foxtail millet (11.2%), and proso millet (10.1%) [145]. The study also found that the soluble fiber content of millets ranged from 1.5-3.5%, while the insoluble fiber content ranged from 9-20% [146].

5.2. Gluten-free properties of millets

Millets are naturally gluten-free cereals, making them a suitable option for people with celiac disease or gluten intolerance [147]. Gluten is a protein found in wheat, barley, and rye, which can cause an autoimmune reaction in the small intestine of susceptible individuals [148].

The gluten-free properties of millets have led to their increasing use in the development of gluten-free products, such as bread, pasta, and snacks [149]. Millets can be used as a whole grain or as a flour in these products, providing a nutritious and tasty alternative to wheat-based products [150].

For example, a study on the development of gluten-free bread using millet flour found that the bread had acceptable sensory properties and a higher protein and fiber content compared to rice-based gluten-free bread [151]. Another study on the development of gluten-free pasta using proso millet flour found that the pasta had good cooking quality and a similar texture to wheat-based pasta [152].

5.3. Potential health benefits

Millets have several potential health benefits, due to their unique nutritional and functional properties [153]. Some of the potential health benefits of millets include:

5.3.1. Diabetes management

Millets have a low glycemic index (GI), which means that they release glucose slowly into the bloodstream, preventing sudden spikes in blood sugar levels [154]. The low GI of millets is attributed to their high fiber content and the presence of certain bioactive compounds like polyphenols and phytates [155].

Studies have shown that the consumption of millets can help in the management of diabetes, by improving glucose tolerance, insulin sensitivity, and lipid profile [156]. For example, a study on the effect of finger millet on blood glucose levels in diabetic patients found that the consumption of finger millet for 28 days led to a significant reduction in fasting and post-prandial blood glucose levels [157].

5.3.2. Cardiovascular health

Millets have several properties that can benefit cardiovascular health, such as their high fiber content, low glycemic index, and the presence of bioactive compounds like phytosterols and flavonoids [158]. These properties can help in reducing the risk factors for cardiovascular diseases, such as high blood pressure, high cholesterol, and obesity [159].

Studies have shown that the consumption of millets can have a positive effect on cardiovascular health markers, such as blood lipids, inflammatory markers, and oxidative stress [160]. For example, a study on the effect of foxtail millet on cardiovascular risk factors in adults found that the consumption of foxtail millet for 12 weeks led to a significant reduction in total cholesterol, LDL cholesterol, and triglycerides [161].

5.3.3. Digestive health

Millets are a good source of dietary fiber, both soluble and insoluble, which can benefit digestive health [162]. The high fiber content of millets can help in promoting regular bowel movements, preventing constipation, and maintaining a healthy gut microbiome [163].

Moreover, millets contain resistant starch, a type of carbohydrate that is not digested in the small intestine but fermented in the large intestine, producing short-chain fatty acids (SCFAs) [164]. SCFAs have several beneficial effects on gut health, such as promoting the growth of beneficial bacteria, reducing inflammation, and improving gut barrier function [165].

Studies have shown that the consumption of millets can have a positive effect on digestive health markers, such as stool frequency, stool consistency, and gut microbiota composition [166]. For example, a study on the effect of finger millet on constipation in elderly adults found that the consumption of finger millet for 4 weeks led to a significant increase in stool frequency and a decrease in laxative use [167].

5.4. Millets in traditional and modern diets

Millets have been a part of the traditional diets in many regions of the world, particularly in Asia and Africa [168]. Millets are often consumed as a staple food in the form of porridges, flatbreads, and snacks [169]. In India, for example, millets like finger millet (ragi), pearl millet (bajra), and sorghum (jowar) are used in the preparation of traditional dishes like roti, bhakri, and ambali [170].

However, with the increasing dominance of rice and wheat in the global food system, the consumption of millets has declined in many regions [171]. This shift in dietary patterns has led to a decrease in the dietary diversity and nutritional quality, particularly in developing countries [172].

In recent years, there has been a renewed interest in promoting millets as a healthy and sustainable food, both in traditional and modern diets [173]. Millets are being incorporated into various food products, such as bread, pasta, breakfast cereals, and snacks, to increase their nutritional value and appeal to modern consumers [174].

Moreover, there are efforts to revive the traditional millet-based farming systems and food cultures, through initiatives like the "Millet Mission" in India [175]. These initiatives aim to promote the cultivation, consumption, and marketing of millets, by providing support to farmers, creating awareness among consumers, and developing value-added products [176].

6. Millet Cultivation Practices

6.1. Traditional cultivation methods

Millets have been traditionally cultivated using various methods, depending on the agro-climatic conditions, soil type, and socio-economic factors [177]. Some of the traditional cultivation methods of millets include:

1. **Broadcasting:** In this method, the millet seeds are scattered by hand or machine on the prepared land, and then covered with soil using a plough or harrow [178]. This method is simple and low-cost, but has a lower seed germination rate and crop uniformity compared to other methods [179].

2. **Line sowing**: In this method, the millet seeds are sown in lines or rows, either by hand or using a seed drill [180]. This method allows for better crop management, such as weeding, thinning, and fertilizer application, and results in higher yields compared to broadcasting [181].

3. **Transplanting:** In this method, the millet seedlings are raised in a nursery and then transplanted to the main field [182]. This method is used in areas with high rainfall or irrigation, and helps in optimizing the plant population and reducing the crop duration [183].

4. **Inter-cropping:** In this method, millets are grown along with other crops, such as legumes, oilseeds, or vegetables, in the same field [184]. This method

helps in increasing the land use efficiency, reducing the risk of crop failure, and improving the soil fertility through nitrogen fixation by legumes [185].

5. **Mixed cropping:** In this method, different millet crops or varieties are grown together in the same field [186]. This method helps in increasing the crop diversity, reducing the pest and disease incidence, and providing a buffer against environmental stresses [187].

6.2. Improved cultivation techniques

Over the years, several improved cultivation techniques have been developed to enhance the productivity and sustainability of millet cultivation [188]. Some of these techniques include:

6.2.1. Crop rotation and intercropping

Crop rotation and intercropping are important practices in millet cultivation, as they help in improving the soil fertility, reducing the pest and disease incidence, and increasing the crop diversity [189]. Millets are often rotated with legumes, such as chickpea, pigeon pea, or green gram, which fix atmospheric nitrogen and improve the soil organic matter [190].

Moreover, millets are intercropped with other crops, such as sorghum, cowpea, or sesame, which have different growth habits and resource requirements [191]. Intercropping helps in optimizing the use of land, water, and nutrients, and reducing the risk of crop failure due to environmental stresses [192].

For example, a study on the effect of intercropping pearl millet with cowpea found that the intercropping system had a higher land equivalent ratio (1.3) and net returns compared to sole cropping of either crop [193].

6.2.2. Seed treatment and sowing methods

Seed treatment and sowing methods are important factors in millet cultivation, as they influence the seed germination, crop establishment, and yield [194]. Millet seeds are often treated with fungicides or biocontrol agents to control seed-borne diseases and improve the seed vigor [195].

Moreover, millet seeds are sown using different methods, such as broadcasting, line sowing, or transplanting, depending on the agro-climatic conditions and resource availability [196]. Line sowing is generally recommended for millet cultivation, as it allows for better crop management and results in higher yields compared to broadcasting [197]. For example, a study on the effect of seed treatment and sowing methods on finger millet found that seed treatment with thiram and line sowing at 30 cm spacing resulted in the highest grain yield (2.5 t/ha) and benefit-cost ratio (2.8) [198].

6.2.3. Nutrient management

Nutrient management is an important aspect of millet cultivation, as it influences the crop growth, yield, and quality [199]. Millets have a high nutrient requirement, particularly for nitrogen, phosphorus, and potassium [200]. However, millet farmers often face challenges in accessing and affording the required fertilizers, due to their high cost and limited availability [201].

Therefore, integrated nutrient management approaches, combining organic and inorganic sources of nutrients, are recommended for millet cultivation [202]. Organic sources, such as farmyard manure, compost, and green manure, can improve the soil organic matter, water holding capacity, and microbial activity, while inorganic sources, such as urea, diammonium phosphate, and muriate of potash, can provide readily available nutrients to the crop [203].

For example, a study on the effect of integrated nutrient management on pearl millet found that the application of 50% recommended dose of fertilizer (RDF) along with farmyard manure (5 t/ha) and biofertilizers (Azospirillum and phosphate-solubilizing bacteria) resulted in the highest grain yield (3.2 t/ha) and net returns (Rs. 31,500/ha) [204].

6.2.4. Water management

Water management is a critical factor in millet cultivation, as millets are generally grown in rainfed conditions with limited and erratic rainfall [205]. Millets have a high water use efficiency compared to other cereals, but still require adequate and timely water supply for optimal growth and yield [206]. Water management is a critical factor in millet cultivation, as millets are generally grown in rainfed conditions with limited and erratic rainfall [205]. Millets have a high water use efficiency compared to other cereals, but still require adequate and timely water supply for optimal growth and yield [206].

Therefore, various water conservation and management practices, such as mulching, ridge and furrow system, and micro-irrigation, are recommended for millet cultivation [207]. Mulching with organic materials, such as straw or leaves, can reduce the soil evaporation, regulate the soil temperature, and improve the soil moisture retention [208].

Ridge and furrow system involves the creation of alternate ridges and furrows in the field, which helps in conserving the rainwater and improving the soil moisture availability [209]. Micro-irrigation methods, such as drip or sprinkler irrigation, can provide precise and controlled water application to the crop, reducing the water losses and improving the water productivity [210].

For example, a study on the effect of water management practices on finger millet found that the use of ridge and furrow system along with straw mulching resulted in the highest grain yield (2.8 t/ha) and water use efficiency (5.2 kg/ha/mm) compared to flat bed sowing and no mulching [211].

6.2.5. Weed control

Weed control is an important component of millet cultivation, as weeds can compete with the crop for water, nutrients, and light, reducing the crop yield and quality [212]. Millets are generally slow-growing crops and are sensitive to weed competition, particularly in the early stages of growth [213].

Therefore, various weed control methods, such as manual weeding, mechanical weeding, and chemical weeding, are used in millet cultivation [214]. Manual weeding involves the removal of weeds by hand or using simple tools, and is often done by women and children in smallholder farming systems [215].

Mechanical weeding involves the use of tools, such as hoes, weeders, or cultivators, to remove the weeds between the crop rows [216]. Chemical weeding involves the use of herbicides, such as atrazine, pendimethalin, or glyphosate, to control the weeds before or after the crop emergence [217].

However, the use of herbicides in millet cultivation is limited, due to their high cost, potential environmental and health risks, and the development of herbicide-resistant weeds [218]. Therefore, integrated weed management approaches, combining cultural, mechanical, and biological methods, are recommended for sustainable weed control in millet cultivation [219].

For example, a study on the effect of weed management practices on pearl millet found that the use of hand weeding at 20 and 40 days after sowing along with the intercropping of pearl millet with cowpea resulted in the highest grain yield (2.5 t/ha) and weed control efficiency (80%) compared to sole cropping and no weeding [220].

6.3. Mechanization in millet cultivation

Mechanization is an important aspect of modern agriculture, as it helps in reducing the labor requirements, improving the timeliness and efficiency of farm operations, and increasing the crop productivity [221]. However, the adoption of mechanization in millet cultivation is limited, due to the small and fragmented landholdings, low crop value, and limited access to credit and machinery [222].

Therefore, various efforts are being made to promote the mechanization of millet cultivation, through the development and dissemination of small-scale and affordable machinery, such as seed drills, planters, weeders, and threshers

[223]. These machines are designed to suit the specific requirements of millet crops and the socio-economic conditions of smallholder farmers [224].

For example, the Indian Council of Agricultural Research (ICAR) has developed a multi-crop seed drill for sowing millets and other small-seeded crops, which can reduce the labor requirement by 50% and improve the crop yield by 20% compared to manual sowing [225]. Similarly, the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) has developed a low-cost, hand-operated pearl millet thresher, which can reduce the labor requirement by 75% and improve the grain quality compared to manual threshing [226].

6.4. Post-harvest management and storage

Post-harvest management and storage are critical factors in millet cultivation, as they influence the grain quality, marketability, and profitability [227]. Millets are generally harvested at physiological maturity, when the grains are fully developed and the moisture content is around 20-25% [228].

After harvesting, the millet panicles are dried in the sun for 3-5 days to reduce the moisture content to 12-14%, which is safe for storage [229]. The dried panicles are then threshed using manual or mechanical methods to separate the grains from the panicles [230].

The threshed grains are cleaned using winnowing or sieving to remove the impurities, such as dust, chaff, and broken grains [231]. The cleaned grains are then graded based on their size, color, and damage level, and packed in suitable containers, such as jute bags or metallic bins, for storage [232].

Millet grains are susceptible to various storage pests, such as insects, rodents, and fungi, which can cause significant losses in grain quantity and quality [233]. Therefore, various pest management methods, such as fumigation, irradiation, and hermetic storage, are used to control the storage pests in millets [234].

For example, a study on the effect of storage methods on the quality of finger millet found that the use of hermetic storage bags (PICS bags) could maintain the grain quality and reduce the insect infestation for up to 12 months compared to conventional jute bags [235]. Similarly, a study on the effect of fumigation on the quality of pearl millet found that the use of aluminum phosphide fumigant could effectively control the storage pests and maintain the grain quality for up to 6 months [236].

7. Challenges and Opportunities in Millet Cultivation

7.1. Biotic and abiotic stresses

Millet cultivation faces various biotic and abiotic stresses, which can limit the crop growth, yield, and quality [237]. Biotic stresses refer to the damage caused by living organisms, such as insects, diseases, and weeds, while abiotic stresses refer to the damage caused by non-living factors, such as drought, heat, and soil constraints [238].

7.1.1. Insect pests and diseases

Millets are attacked by various insect pests and diseases, which can cause significant yield losses and economic damages [239]. The major insect pests of millets include stem borers, shoot flies, aphids, and head bugs, which feed on the leaves, stems, and panicles of the crop [240].

The major diseases of millets include downy mildew, blast, rust, and ergot, which are caused by fungal pathogens and can infect the leaves, stems, and panicles of the crop [241]. These pests and diseases can be controlled using various methods, such as resistant varieties, cultural practices, biological control, and chemical control [242].

For example, the use of resistant varieties, such as ICTP 8203 and ICMV 221, can reduce the damage caused by downy mildew in pearl millet by up to 90% [243]. Similarly, the use of cultural practices, such as early sowing, intercropping, and sanitation, can reduce the damage caused by shoot fly in sorghum by up to 50% [244].

7.1.2. Drought and heat stress

Drought and heat stress are major abiotic constraints to millet cultivation, particularly in the semi-arid and arid regions [245]. Millets are generally drought-tolerant crops, but can still suffer yield losses under severe and prolonged drought conditions [246].

Similarly, millets are generally heat-tolerant crops, but can still suffer yield losses under extreme heat conditions, particularly during the reproductive stage [247]. These stresses can be mitigated using various strategies, such as drought-tolerant varieties, water conservation practices, and crop diversification [248].

For example, the use of drought-tolerant varieties, such as ICMV 221 and ICMV 97774, can increase the grain yield of pearl millet by up to 20% under drought conditions [249]. Similarly, the use of water conservation practices, such as mulching and ridge-furrow system, can increase the grain yield of finger millet by up to 30% under drought conditions [250].

7.1.3. Soil fertility constraints

Soil fertility constraints, such as nutrient deficiencies and soil acidity, are major limiting factors for millet cultivation, particularly in the marginal and degraded lands [251]. Millets have a high nutrient requirement, particularly for nitrogen, phosphorus, and potassium, and can suffer yield losses under nutrient-deficient conditions [252].

Similarly, millets are sensitive to soil acidity, and can suffer yield losses under low pH conditions [253]. These constraints can be addressed using various strategies, such as integrated nutrient management, soil amendment, and crop rotation [254].

For example, the use of integrated nutrient management, combining organic and inorganic sources of nutrients, can increase the grain yield of finger millet by up to 40% compared to sole inorganic fertilization [255]. Similarly, the use of soil amendment, such as liming, can increase the grain yield of pearl millet by up to 20% in acidic soils [256].

7.2. Yield gaps and productivity challenges

Despite the high potential of millets for food and nutritional security, the actual yields of millets in farmers' fields are generally low and variable, due to various biophysical, socio-economic, and institutional constraints [257]. The yield gaps, i.e., the difference between the potential and actual yields, of millets are estimated to be 50-70% in most of the millet-growing regions [258].

Some of the major factors contributing to the yield gaps and productivity challenges in millet cultivation include:

1. Low adoption of improved varieties and management practices by farmers, due to lack of awareness, access, and affordability [259].
2. Inadequate and untimely availability of inputs, such as seeds, fertilizers, and pesticides, due to weak input supply chains and market linkages [260].
3. Insufficient and erratic rainfall, due to climate variability and change, leading to drought and crop failures [261].
4. Degradation of soil health and fertility, due to continuous cultivation, erosion, and nutrient mining [262].
5. Damage by biotic stresses, such as insect pests, diseases, and weeds, due to lack of resistance and management options [263].
6. Limited access to credit, insurance, and market opportunities for smallholder farmers, due to weak institutional support and infrastructure [264].

Therefore, various efforts are being made to address these challenges and bridge the yield gaps in millet cultivation, through research, extension, and policy interventions [265]. Some of the key strategies include:

1. Development and dissemination of high-yielding, stress-tolerant, and nutrient-dense millet varieties, through participatory breeding and seed systems [266].
2. Promotion of sustainable intensification practices, such as integrated crop management, conservation agriculture, and agroforestry, through farmer training and capacity building [267].
3. Strengthening of input supply chains and market linkages, through public-private partnerships and collective action by farmer organizations [268].
4. Provision of weather-based agro-advisory services and crop insurance products, through information and communication technologies and financial institutions [269].
5. Investment in research and development of millet value chains, including processing, value addition, and product diversification, through innovation platforms and entrepreneurship [270].

7.3. Research and development efforts

To address the challenges and harness the opportunities in millet cultivation, various research and development efforts are being undertaken by national and international organizations, universities, and private sector [271]. Some of the major areas of research and development in millets include:

7.3.1. Germplasm conservation and utilization

Germplasm conservation and utilization are essential for the sustainable use and improvement of millet genetic resources [272]. Millets have a wide genetic diversity, with thousands of landraces and wild relatives, which are adapted to various agro-ecologies and have unique traits of interest [273].

However, many of these genetic resources are under threat of genetic erosion and loss, due to factors such as land use change, modernization of agriculture, and climate change [274]. Therefore, various efforts are being made to collect, conserve, and characterize millet germplasm, through gene banks, field gene banks, and in situ conservation [275].

For example, the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) has a global collection of over 22,000 pearl millet accessions from 50 countries, which are conserved in its gene bank and used for crop improvement [276]. Similarly, the All India Coordinated Research Project on Small Millets (AICRP-SM) has a network of 14 centers across India, which are involved in the collection, evaluation, and utilization of small millet germplasm [277].

7.3.2. Breeding for improved varieties

Breeding for improved varieties is a key strategy for enhancing the productivity, resilience, and quality of millets [278]. Millet breeding programs aim to develop varieties with high yield potential, resistance to biotic and abiotic stresses, and desirable grain qualities, such as high nutrient content and consumer preference [279].

Various breeding methods, such as classical breeding, marker-assisted selection, and genetic engineering, are used to develop improved millet varieties [280]. Classical breeding involves the selection and crossing of superior parents to create new genetic combinations, followed by evaluation and selection of the best performing progenies [281].

Marker-assisted selection involves the use of DNA markers to identify and select the desired genes or traits, which can improve the efficiency and precision of breeding [282]. Genetic engineering involves the transfer of genes from other species or organisms to create transgenic varieties with novel traits, such as herbicide tolerance or insect resistance [283].

For example, the pearl millet hybrid HHB 67 Improved, developed by ICRISAT and partners using marker-assisted selection, has a yield potential of 3-4 tons per hectare and resistance to downy mildew disease [284]. Similarly, the finger millet variety GPU 28, developed by the University of Agricultural Sciences, Bangalore, India, using classical breeding, has a yield potential of 3.5-4 tons per hectare and high calcium content [285].

7.3.3. Biotechnological interventions

Biotechnological interventions, such as tissue culture, genetic engineering, and genomics, are emerging as powerful tools for millet improvement and utilization [286]. Tissue culture involves the use of plant cells, tissues, or organs to regenerate whole plants under controlled conditions, which can be used for rapid multiplication, germplasm conservation, and genetic transformation [287].

Genetic engineering involves the transfer of genes from other species or organisms to create transgenic plants with novel traits, such as resistance to pests, diseases, or abiotic stresses [288]. Genomics involves the study of the complete set of genes and their functions in an organism, which can provide insights into the genetic basis of complex traits and guide breeding efforts [289].

For example, researchers at the University of California, Davis, USA, have developed transgenic pearl millet lines expressing the Bt gene from the bacterium Bacillus thuringiensis, which confers resistance to the stem borer pest [290]. Similarly, researchers at the Chinese Academy of Agricultural Sciences, China, have sequenced the genome of foxtail millet, which has provided valuable information on the evolution and domestication of the crop [291].

7.4. Policy support and extension services

Policy support and extension services are critical for the promotion and adoption of improved millet technologies and practices by farmers [292]. Millets have been neglected in agricultural policies and programs in many countries, due to their low economic value and market demand compared to other major cereals [293].

However, there is a growing recognition of the importance of millets for food and nutritional security, particularly in the context of climate change and sustainable development goals [294]. Therefore, various policy measures and initiatives are being taken to support millet cultivation and consumption, such as inclusion in public distribution systems, minimum support prices, and research and development funding [295].

For example, the government of India has launched the "Millet Mission" in 2018, which aims to promote millets as "nutri-cereals" and increase their production, consumption, and marketing [296]. The mission includes various interventions, such as seed distribution, demonstration farms, processing and value addition, and awareness campaigns [297].

Conclusion

The extensive body of research on millets, particularly foxtail millet (*Setaria italica),* demonstrates their significance as model crops for genetic and genomic studies in cereals and bioenergy grasses. The sequencing of the foxtail millet genome has provided valuable insights into grass evolution and biofuel potential. Numerous studies have focused on identifying and characterizing various gene families and transcription factors involved in stress response and other important agronomic traits. The research highlights the adaptability and resilience of millets, making them suitable for cultivation in diverse agro-climatic conditions. Their nutritional value and potential for food security in the face of climate change have also been emphasized. The development of genomic resources, including genetic maps, molecular markers, and transcriptome data, has facilitated the genetic improvement of millets. As climate-smart crops, millets offer promising solutions for sustainable agriculture and global food security. Continued research and development in millet genomics will likely contribute to the improvement of both millet varieties and other important cereal crops.

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CHAPTER - 03

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Nutritional and Health Benefits of Millets

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Abstract

Millets are a diverse group of small-seeded grasses that have been cultivated as staple crops for thousands of years. In recent decades, millets have gained renewed interest due to their nutritional profile, environmental resilience, and potential health benefits. This chapter reviews the current scientific evidence on the nutritional composition of various millet types and their associated health effects. Millets are rich in dietary fiber, minerals like iron, zinc, and magnesium, B-vitamins, and phytochemicals such as phenolic acids and flavonoids. Regular consumption of millets has been linked to reduced risk of type 2 diabetes, cardiovascular disease, certain cancers, and gastrointestinal disorders. The gluten-free status of millets also makes them suitable for celiac patients. As climate-resilient crops, millets offer a sustainable and nutritious alternative to major cereals, aligning with the goals of the International Year of Millets 2023 to promote their cultivation and consumption globally.

Keywords: millets, nutrition, dietary fiber, antioxidants, gluten-free, non-communicable diseases

1. Introduction

Millets are a group of small-seeded grasses belonging to the Poaceae family, which have been cultivated as food crops for over 7000 years [1]. They are widely grown in the arid and semi-arid regions of Asia and Africa as staple grains. The most commonly cultivated millet types include pearl millet (*Pennisetum glaucum*), foxtail millet (*Setaria italica*), finger millet (*Eleusine coracana*), proso millet (*Panicum miliaceum*), barnyard millet (*Echinochloa*spp.), kodo millet (*Paspalum scrobiculatum*), and little millet (*Panicum sumatrense*) [2].

Figure 1. Major millet types:

Despite their historical significance and nutritional advantages, millets have largely been neglected in the latter half of the 20th century with the dominance of rice, wheat, and maize in global food systems [3]. However, in light of the challenges posed by climate change, water scarcity, and malnutrition, millets are regaining attention worldwide. The year 2023 has been declared by the United Nations as the International Year of Millets to raise awareness about their nutritional benefits, climate-resilient properties, and potential to address food security issues [4].

2. Nutritional Composition of Millets

2.1. Macronutrients

Millets are nutritionally comparable or superior to major cereal grains like rice and wheat. They are a good source of energy, carbohydrates, protein, and dietary fiber (Table 1). The protein content of millets ranges from 7-12%, which is higher than rice, wheat, and maize [5]. Millets also have a well-balanced amino acid profile with high contents of methionine and cysteine, which are lacking in legumes [6].

The lipid content of millets varies from 1.5-5%, with a higher proportion of unsaturated fatty acids, particularly linoleic and oleic acids [7]. Millets are rich in non-starchy polysaccharides and dietary fiber, which constitute about 7-20% of the grain [8]. The insoluble fraction of dietary fiber (e.g., cellulose, hemicellulose, lignin) is predominant in millets and associated with several health benefits (Section 4).

Table 1. Macronutrient composition of selected millets (per 100 g edible portion, raw) [9]

Millet Type	**Energy (kcal)**	**Protein (g)**	**Fat (g)**	**Carbohydrate (g)**	**Dietary Fiber (g)**
Pearl millet	361	11.6	4.8	67.0	11.3
Foxtail millet	331	12.3	4.3	60.9	8.0
Finger millet	328	7.3	1.3	72.0	11.5
Proso millet	341	11.0	4.2	70.4	8.5
Kodo millet	309	8.3	1.4	65.9	9.0
Little millet	329	7.7	4.7	67.0	7.6
Barnyard millet	300	11.2	3.9	74.3	14.7

2.2. Micronutrients

Millets are superior to rice and wheat in terms of mineral content. They are rich sources of calcium, iron, zinc, phosphorus, magnesium, and potassium (Table 2). Finger millet, in particular, has the highest calcium content (350 mg/100 g) among cereals [10]. Regular consumption of finger millet is recommended to prevent calcium deficiency and osteoporosis [11]. Millets are also good sources of B-vitamins, including thiamin, riboflavin, niacin, and folic acid [12]. The niacin content of millets (except finger millet) is higher than other cereals and recommended for treating pellagra [13]. However, millets have lower fat-soluble vitamin (A, D, E, K) content than other cereals.

The bioavailability of minerals like iron and zinc in millets is hindered by the presence of anti-nutritional factors such as phytates, phenols, and tannins [14]. Processing methods like decortication, malting, fermentation, and germination can reduce anti-nutrient levels and improve mineral bioaccessibility [15].

Table 2. Mineral composition of selected millets (mg/100 g edible portion, raw) [9]

Millet Type	**Calcium**	**Iron**	**Zinc**	**Phosphorus**	**Magnesium**	**Potassium**
Pearl millet	42	8.0	3.1	296	137	307
Foxtail millet	31	2.8	2.4	290	81	250
Finger millet	350	3.9	2.3	283	137	408
Proso millet	14	2.9	1.7	206	153	113
Kodo millet	27	0.5	0.7	188	133	144
Little millet	17	9.3	3.7	220	133	195
Barnyard millet	22	15.2	3.2	280	82	280

2.3. Phytochemicals

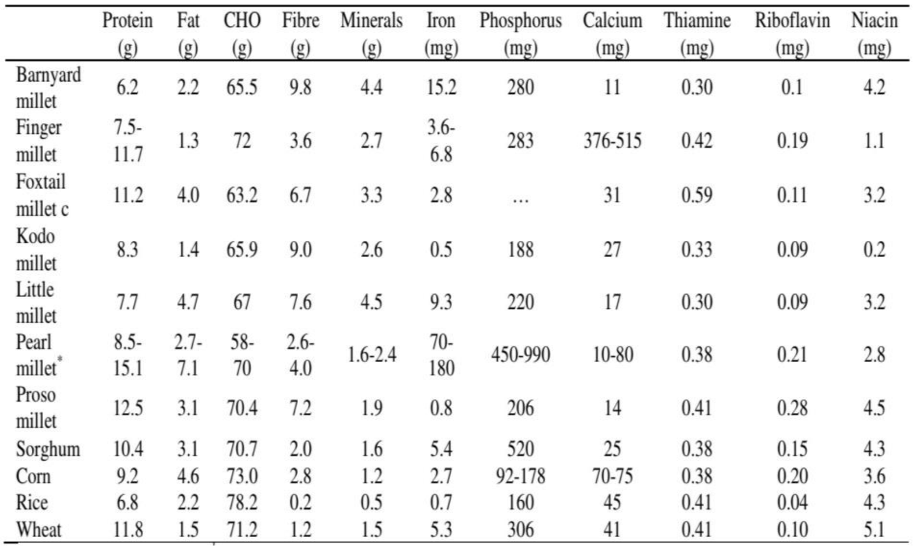
Millets are rich sources of various phytochemicals, including phenolic acids, flavonoids, tannins, and phytosterols [16]. These bioactive compounds are known for their antioxidant, anti-inflammatory, anti-carcinogenic, and cholesterol-lowering properties [17]. The phytochemical content of millets is influenced by genotype, growing conditions, and processing methods.

The most abundant phenolic acids in millets are ferulic acid and *p*-coumaric acid, which are concentrated in the bran layer [18]. Finger and foxtail millets have the highest total phenolic content (TPC) among millets, ranging from 50-250 mg gallic acid equivalent (GAE)/100 g [19]. The most common flavonoids in millets are catechin, quercetin, and apigenin [20].

Millets also contain considerable amounts of phytosterols, particularly β-sitosterol, campesterol, and stigmasterol [21]. The phytosterol content of millets

(80-210 mg/100 g) is comparable to other cereals and associated with cholesterol-lowering effects [22].

Figure 2. Nutrient composition of selected millets compared to other cereals (per 100 g edible portion).



	Protein (g)	Fat (g)	CHO (g)	Fibre (g)	Minerals (g)	Iron (mg)	Phosphorus (mg)	Calcium (mg)	Thiamine (mg)	Riboflavin (mg)	Niacin (mg)
Barnyard millet	6.2	2.2	65.5	9.8	4.4	15.2	280	11	0.30	0.1	4.2
Finger millet	7.5-11.7	1.3	72	3.6	2.7	3.6-6.8	283	376-515	0.42	0.19	1.1
Foxtail millet c	11.2	4.0	63.2	6.7	3.3	2.8	…	31	0.59	0.11	3.2
Kodo millet	8.3	1.4	65.9	9.0	2.6	0.5	188	27	0.33	0.09	0.2
Little millet	7.7	4.7	67	7.6	4.5	9.3	220	17	0.30	0.09	3.2
Pearl millet*	8.5-15.1	2.7-7.1	58-70	2.6-4.0	1.6-2.4	70-180	450-990	10-80	0.38	0.21	2.8
Proso millet	12.5	3.1	70.4	7.2	1.9	0.8	206	14	0.41	0.28	4.5
Sorghum	10.4	3.1	70.7	2.0	1.6	5.4	520	25	0.38	0.15	4.3
Corn	9.2	4.6	73.0	2.8	1.2	2.7	92-178	70-75	0.38	0.20	3.6
Rice	6.8	2.2	78.2	0.2	0.5	0.7	160	45	0.41	0.04	4.3
Wheat	11.8	1.5	71.2	1.2	1.5	5.3	306	41	0.41	0.10	5.1

Anti-nutritional factors like phytates, oxalates, and tannins are also present in millets, which can reduce the bioavailability of nutrients [23]. However, these compounds also exhibit beneficial antioxidant and prebiotic effects at lower concentrations [24]. Appropriate processing and cooking methods can optimize the health benefits of millet phytochemicals.

3. Health Benefits of Millets

3.1. Glycemic Control and Diabetes Prevention

Millets have a low to medium glycemic index (GI) due to their high fiber, resistant starch, and protein content [25]. Consumption of low-GI foods is associated with improved blood sugar control and reduced risk of developing type 2 diabetes [26]. Several studies have shown the beneficial effects of millet-based diets on glycemic status.

A randomized controlled trial by Ugare et al. [27] found that daily consumption of foxtail millet for 90 days significantly reduced fasting and postprandial blood glucose levels in type 2 diabetes patients compared to a rice-based diet. Another study by Thathola et al. [28] reported that a finger millet-based diet improved glycemic control and reduced insulin resistance in adult diabetic patients.

The potential mechanisms behind the anti-diabetic properties of millets include inhibition of α-glucosidase and pancreatic amylase enzymes, modulation of glucose transporters, and increased insulin sensitivity [29]. The phenolic compounds and dietary fiber in millets also contribute to their hypoglycemic effects [30].

Figure 3. Potential health benefits of millet consumption.

3.2. Cardiovascular Health

The high dietary fiber, phytosterols, and antioxidants in millets can help reduce the risk factors for cardiovascular diseases (CVDs) such as dyslipidemia, hypertension, and chronic inflammation [31]. Regular consumption of millets has been shown to lower blood cholesterol levels and improve lipid profiles.

A meta-analysis by Anitha et al. [32] concluded that millet consumption significantly reduced total cholesterol and low-density lipoprotein (LDL) cholesterol levels compared to non-millet controls. The soluble fiber and phytosterols in millets can inhibit cholesterol absorption and synthesis, while the insoluble fiber aids in fecal excretion of bile acids [33].

Millet proteins, particularly the prolamin fraction, have shown ACE inhibitory and antihypertensive effects in vitro and animal studies [34]. The potassium and magnesium content of millets may also help regulate blood pressure [35]. Additionally, the antioxidant-rich phenolic compounds in millets can mitigate oxidative stress and inflammation, which are key factors in the pathogenesis of CVDs [36].

3.3. Gastrointestinal Health

The high dietary fiber content of millets promotes gastrointestinal health by improving bowel movement, preventing constipation, and maintaining a healthy gut microbiome [37]. The insoluble fiber in millets increases fecal bulk and transit time, while the soluble fiber acts as a prebiotic, supporting the growth of beneficial gut bacteria [38].

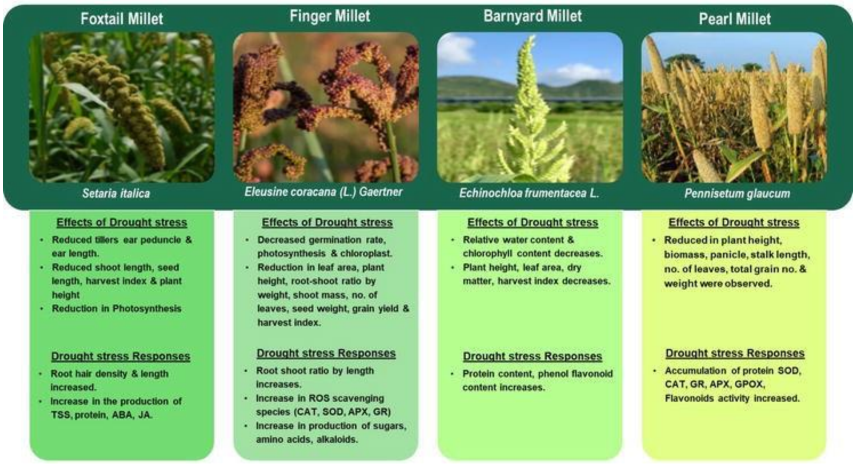
Fermented millet foods like porridges and beverages are rich sources of probiotics, which can further enhance gut health [39]. The short-chain fatty acids (SCFAs) produced by microbial fermentation of millet fiber have anti-inflammatory and immunomodulatory effects on the colonic mucosa [40].

Millet consumption has also been associated with reduced risk of gastrointestinal disorders like colorectal cancer, diverticulitis, and inflammatory bowel disease [41]. The antiproliferative and apoptosis-inducing effects of millet phenolics on colon cancer cells have been demonstrated in vitro [42].

3.4. Gluten-Free Diet and Celiac Disease

Millets are naturally gluten-free and thus suitable for individuals with celiac disease or gluten sensitivity [43]. Gluten is a protein complex found in wheat, barley, and rye that triggers an autoimmune response in the small intestine of celiac patients, leading to malabsorption and gastrointestinal symptoms [44].

Figure 4. Millet cultivation in drought-prone areas of India.



Foxtail Millet

Effects of Drought stress

- Reduced tillers ear peduncle & ear length.
- Reduced shoot length, seed length, harvest index & plant height
- Reduction in Photosynthesis

Drought stress Responses

- Root hair density & length increased.
- Increase in the production of TSS, protein, ABA, JA.

Finger Millet

Effects of Drought stress

- Decreased germination rate, photosynthesis & chloroplast.
- Reduction in leaf area, plant height, root-shoot ratio by weight, shoot mass, no. of leaves, seed weight, grain yield & harvest index.

Drought stress Responses

- Root shoot ratio by length increases.
- Increase in ROS scavenging species (CAT, SOD, APX, GR)
- Increase in production of sugars, amino acids, alkaloids.

Barnyard Millet

Effects of Drought stress

- Relative water content & chlorophyll content decreases.
- Plant height, leaf area, dry matter, harvest index decreases.

Drought stress Responses

- Protein content, phenol flavonoid content increases.

Pearl Millet

Effects of Drought stress

- Reduced in plant height, biomass, panicle, stalk length, no. of leaves, total grain no. & weight were observed.

Drought stress Responses

- Accumulation of protein SOD, CAT, GR, APX, GPOX, Flavonoids activity increased.

Millet grains and flours can be used as functional ingredients to formulate gluten-free products with improved nutritional quality and sensory attributes [45]. Studies have shown that millet-based gluten-free breads, cookies, and pasta have comparable or better texture, flavor, and consumer acceptability than their wheat-based counterparts [46, 47].

The diverse nutrient profile of millets can help prevent the nutritional deficiencies commonly associated with strict gluten-free diets, such as low intake of fiber, iron, zinc, and B-vitamins [48]. However, care must be taken to avoid cross-contamination with gluten-containing grains during millet processing and preparation [49].

3.5. Other Potential Health Benefits

Apart from the aforementioned health benefits, millet consumption has been linked to several other positive outcomes based on preliminary research:

- **Antioxidant and Anti-inflammatory Effects**: The phenolic compounds, carotenoids, and tocopherols in millets exhibit strong antioxidant and free radical scavenging activities [50]. These bioactive compounds can help reduce oxidative stress and chronic inflammation, which are implicated in various degenerative diseases [51].
- **Cancer Prevention**: In vitro and animal studies suggest that millet phenolics and phytosterols may have chemopreventive effects against breast, liver, and colon cancers by modulating cell signaling pathways and inducing apoptosis in tumor cells [52, 53]. However, more human interventional studies are needed to confirm these findings.
- **Immunomodulation**: Millet peptides and polysaccharides have shown immunostimulatory effects in animal models by enhancing the phagocytic activity of macrophages and increasing the production of cytokines and antibodies [54]. These immunomodulatory properties may contribute to the overall health benefits of millet consumption.
- **Metabolic Syndrome**: The synergistic effects of millet nutrients and bioactive compounds on glycemic control, lipid profile, and antioxidant status may help prevent and manage metabolic syndrome, a cluster of risk factors for CVDs and diabetes [55].
- **Weight Management**: The high fiber and protein content of millets can promote satiety and reduce overall calorie intake, making them beneficial for weight management [56]. However, the effects of millet consumption on body weight and composition need to be further investigated in long-term human trials.

4. Millets and Sustainable Food Systems

4.1. Climate Resilience and Adaptability

Millets are highly resilient to climate change and can grow under marginal conditions with minimal inputs [57]. They have a short growing season (60-90 days), require less water than major cereals, and can tolerate high temperatures, drought, and poor soil fertility [58]. These attributes make millets a climate-smart crop choice for resource-constrained farmers in arid and semi-arid regions.

Pearl millet, for instance, can grow in areas receiving annual rainfall as low as 200-250 mm and withstand temperatures up to 42°C [59]. Finger millet is known for its drought tolerance and can be cultivated at altitudes ranging from sea level to 2,400 m [60]. Foxtail millet is one of the oldest cultivated crops and adapted to a wide range of ecological conditions [61].

The climate resilience of millets is attributed to their efficient root system, quick ground coverage, and C4 photosynthetic pathway [62]. Millets also have a high water use efficiency and can produce more grains per unit of water compared to rice and wheat [63]. As water scarcity becomes a major challenge for agriculture, millets offer a sustainable solution for food production in drought-prone areas.

4.2. Agrobiodiversity and Nutrition Security

Millets encompass a diverse range of species and cultivars adapted to various agro-climatic conditions [64]. This agrobiodiversity is crucial for maintaining genetic resources, enhancing resilience to biotic and abiotic stresses, and providing diverse nutrient sources [65]. However, the cultivation of millets has declined in recent decades due to factors like urbanization, changing consumer preferences, and lack of policy support [66].

Promoting the cultivation and consumption of millets can help conserve this valuable agrobiodiversity and improve nutrition security in developing countries [67]. Millets are often grown as mixed crops with legumes and vegetables, which enhances dietary diversity and nutrient complementarity [68]. Including millets in crop rotations can also improve soil fertility, reduce pest and disease pressure, and increase overall farm productivity [69]. Millet-based biofortification strategies, such as developing high-iron and high-zinc varieties, can further address micronutrient deficiencies in populations heavily reliant on cereal-based diets [70]. For example, the development and dissemination of biofortified pearl millet varieties in India have shown promising results in improving iron and zinc intake among children and women [71].

4.3. Economic and Social Benefits

Millets are often grown by smallholder farmers in marginal environments, where they contribute to local food security and livelihoods [72]. Enhancing millet production and value chains can create economic opportunities for these farmers, particularly women who are traditionally involved in millet cultivation and processing [73].

Millet processing and value addition activities, such as making flour, snacks, and beverages, can generate employment and income for rural communities [74]. The development of millet-based products also caters to the growing demand for healthy, gluten-free, and functional foods in urban markets [75]. This can lead to increased millet consumption and create a more diversified and resilient food system.

Promoting millets as a nutrient-dense and climate-resilient crop can also have social benefits by improving the health and well-being of vulnerable populations [76]. Millet-based school feeding programs and public distribution systems can help combat malnutrition and ensure food security in regions where millets are traditionally consumed [77].

5. Challenges and Future Prospects

5.1. Research and Development

Despite the numerous benefits of millets, there are still knowledge gaps and research challenges that need to be addressed. More studies are required to understand the genetic diversity, nutritional profile, and bioactive compounds of different millet species and cultivars [78]. This can help in selecting and breeding millet varieties with enhanced nutritional quality, yield, and resilience to climate change.

Research on millet processing technologies and product development is also crucial to increase the utilization and consumer acceptability of millets [79]. Innovations in millet milling, fortification, and packaging can improve the shelf life, safety, and nutritional value of millet products [80]. Collaborative research efforts between agricultural scientists, nutritionists, and food technologists are essential to harness the full potential of millets.

5.2. Policy Support and Awareness

Supportive policies and programs are necessary to promote millet cultivation, consumption, and trade at the national and international levels [81]. This includes providing incentives for millet farmers, investing in millet research and extension services, and including millets in public procurement and distribution systems [82].

Creating awareness about the nutritional and environmental benefits of millets among consumers, policymakers, and other stakeholders is also crucial [83]. This can be achieved through information campaigns, food festivals, and nutrition education programs highlighting the importance of dietary diversity and the role of millets in sustainable food systems [84].

The declaration of 2023 as the International Year of Millets by the United Nations is a significant step towards raising global awareness and support for these underutilized crops [85]. This initiative aims to promote millet production, research, and consumption worldwide and contribute to the achievement of the Sustainable Development Goals (SDGs) related to zero hunger, good health, and climate action [86].

5.3. Market Development and Value Chains

Developing efficient and inclusive millet value chains is essential to ensure the availability, affordability, and profitability of millet products [87]. This involves strengthening linkages between millet producers, processors, traders, and consumers, and creating an enabling environment for millet entrepreneurship and innovation [88].

Market research and consumer studies are needed to understand the demand, preferences, and willingness to pay for millet products in different segments and regions [89]. This information can guide the development of targeted marketing strategies and value-added products that meet the needs of diverse consumers [90].

Promoting the integration of millets into formal food systems, such as supermarkets, restaurants, and institutional cafeterias, can increase their visibility and consumption in urban areas [91]. Public-private partnerships and multi-stakeholder collaborations can play a key role in developing sustainable and equitable millet value chains [92].

Conclusion

Millets are nutrient-dense, climate-resilient, and gluten-free grains with immense potential to address food and nutrition security challenges in the face of climate change. This chapter highlighted the nutritional composition and health benefits of various millet types, including their role in managing chronic diseases, promoting gut health, and providing a gluten-free alternative. The cultivation and consumption of millets can also contribute to sustainable food systems by promoting agrobiodiversity, climate resilience, and local livelihoods. However, realizing the full potential of millets requires concerted efforts in research, policy support, awareness creation, and market development. The International Year of Millets 2023 serves as a catalyst for global action to harness the nutritional and environmental benefits of these ancient grains for a healthier and more sustainable future.

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CHAPTER - 4

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Millet Cultivation Practices: Traditional and Modern Approaches

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Abstract

Millets are a diverse group of small-seeded cereal crops that play a vital role in food security, nutrition, and sustainable agriculture, particularly in arid and semi-arid regions. This chapter provides a comprehensive overview of millet cultivation practices, encompassing both traditional methods and modern approaches. It explores the historical significance of millets, their adaptability to various agro-climatic conditions, and their potential to address challenges posed by climate change. The chapter delves into the agronomic aspects of millet production, including land preparation, sowing, nutrient management, weed control, and pest and disease management. It also highlights the importance of integrating traditional knowledge with modern scientific advancements to enhance millet productivity and sustainability. Furthermore, the chapter discusses post-harvest practices, value addition, and the socio-economic dimensions of millet cultivation. By presenting a holistic view of millet cultivation practices,

this chapter aims to promote the adoption of sustainable and resilient farming systems that can contribute to food and nutritional security while conserving agro-biodiversity and supporting rural livelihoods.

Keywords: Millets, traditional practices, modern approaches, sustainable agriculture, food security

Introduction

Millets are a group of small-seeded cereal crops that have been cultivated for thousands of years in various parts of the world, particularly in Asia and Africa. These crops are known for their resilience, adaptability to diverse agro-climatic conditions, and nutritional value. In recent years, there has been a renewed interest in millets due to their potential to address food security challenges, enhance nutrition, and promote sustainable agriculture practices. The United Nations General Assembly has declared 2023 as the International Year of Millets, recognizing their importance in achieving the Sustainable Development Goals (SDGs) [1]. India is the largest producer of millets globally, with a rich history of millet cultivation and consumption [2]. Traditional millet cultivation practices in India have evolved over centuries, adapting to local conditions and incorporating indigenous knowledge. However, with the advent of modern agriculture, there has been a shift towards high-yielding varieties and input-intensive cultivation practices. This chapter aims to provide a comprehensive overview of millet cultivation practices in India, encompassing both traditional methods and modern approaches. Historical Significance and Diversity of Millets Millets have been an integral part of Indian agriculture and culinary traditions for millennia. Archaeological evidence suggests that millets were domesticated in the Indian subcontinent as early as 3000 BCE [3]. The term "millet" encompasses a diverse group of crops, including pearl millet (Pennisetum glaucum), finger millet (Eleusine coracana), foxtail millet (Setaria italica), barnyard millet Echinochloa frumentacea, kodo millet (Paspalum scrobiculatum), little millet (Panicum sumatrense), and proso millet (Panicum miliaceum) [4]. Each type of millet has its unique characteristics, adaptability, and nutritional profile. For instance, pearl millet is known for its drought tolerance and high protein content, while finger millet is rich in calcium and has excellent storage properties [5]. The diversity of millets enables farmers to choose crops that are best suited to their local agro-climatic conditions and dietary preferences.

Table 1: Major Millet Crops Cultivated in India

Millet Type	Scientific Name	Area (Million ha)	Production (Million Tonnes)
Pearl Millet	Pennisetum glaucum	7.12	10.28

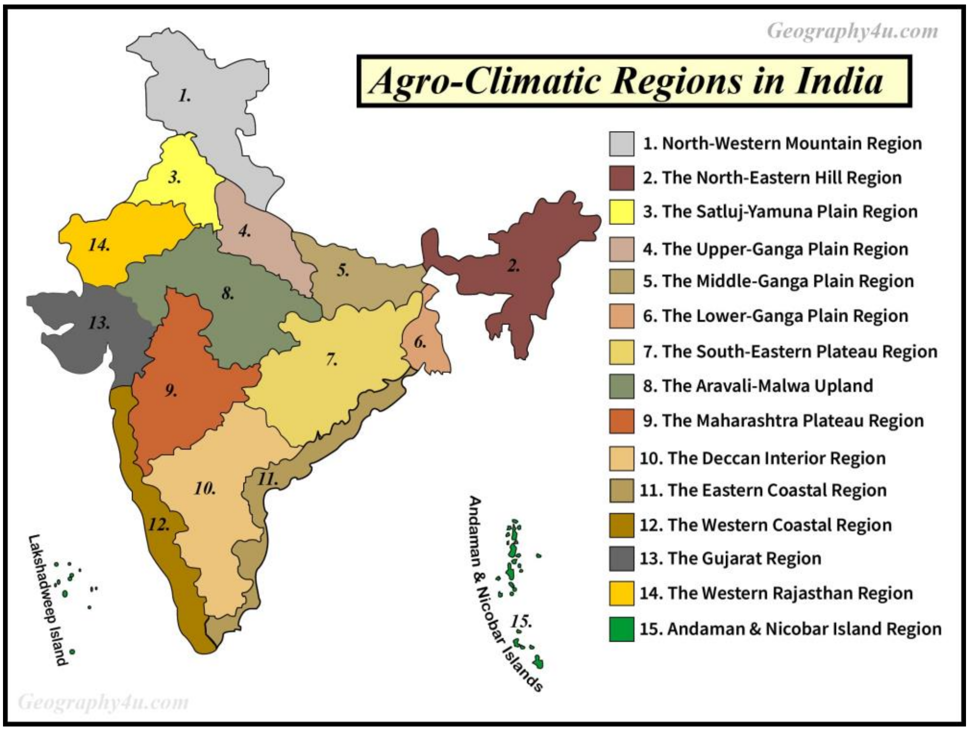
Finger Millet	Eleusine coracana	1.19	1.98
Foxtail Millet	Setaria italica	0.50	0.40
Barnyard Millet	Echinochloa frumentacea	0.15	0.13
Kodo Millet	Paspalum scrobiculatum	0.25	0.07
Little Millet	Panicum sumatrense	0.26	0.08
Proso Millet	Panicum miliaceum	0.02	0.01

Source: Ministry of Agriculture & Farmers Welfare, Government of India (2019-20) [6]

Adaptability to Diverse Agro-Climatic Conditions

One of the key features of millets is their adaptability to a wide range of agro-climatic conditions. Millets can thrive in arid and semi-arid regions, where water scarcity and high temperatures limit the cultivation of other crops [7]. They have a short growing season, requiring less water compared to major cereal crops like rice and wheat. This makes millets an ideal choice for rainfed farming systems and regions prone to drought.

Figure 1: Agro-Climatic Zones Suitable for Millet Cultivation in India



Moreover, millets exhibit remarkable tolerance to various abiotic stresses, such as heat, salinity, and poor soil fertility [8]. Their deep root systems enable them to access moisture and nutrients from deeper soil layers, making them resilient to adverse conditions. This adaptability is crucial in the context of climate change, as millets can contribute to building resilient farming systems and ensuring food security in vulnerable regions.

Traditional Millet Cultivation Practices

Traditional millet cultivation practices in India have evolved over generations, incorporating local knowledge and adapting to specific agro-ecological conditions. These practices often involve low-input, sustainable methods that prioritize the conservation of natural resources and the maintenance of soil health.

Land Preparation and Sowing

In traditional millet cultivation, land preparation typically involves plowing the field with bullock-drawn implements or manual labor. Farmers often follow mixed cropping or intercropping systems, where millets are grown alongside other crops like pulses, oilseeds, or vegetables [9]. This practice helps in optimizing resource utilization, enhancing soil fertility, and reducing the risk of crop failure.

Sowing is usually done by broadcasting the seeds or using a seed drill. The seed rate varies depending on the type of millet and the local practices. For example, in pearl millet cultivation, the recommended seed rate is 4-5 kg/ha for rainfed conditions and 8-10 kg/ha for irrigated conditions [10].

Nutrient Management

Traditional nutrient management in millet cultivation relies on organic sources such as farmyard manure, compost, and green manure. Farmers incorporate crop residues and leguminous plants into the soil to improve soil organic matter content and fertility [11]. The use of biofertilizers, such as Azospirillum and phosphate-solubilizing bacteria, is also common in some regions.

Table 2: Traditional Nutrient Management Practices in Millet Cultivation

Nutrient Source	Application Rate	Timing of Application
Farmyard Manure	10-15 t/ha	Before sowing
Compost	5-7 t/ha	Before sowing
Green Manure (Leguminous crops)	Incorporated into the soil	Before sowing
Biofertilizers (Azospirillum, PSB)	Seed treatment	At the time of sowing

However, the nutrient requirements of millets vary depending on the soil type, cropping system, and targeted yield. In general, millets respond well to the application of nitrogen, phosphorus, and potassium [12]. The recommended fertilizer dose for pearl millet is 60-80 kg N, 30-40 kg P_2O_5, and 20-30 kg K_2O per hectare [13].

Weed Management.

Weed management is a critical aspect of millet cultivation, as weeds can significantly reduce crop yields. Traditional weed control methods include manual weeding, intercropping, and mulching. Hand weeding is commonly practiced by smallholder farmers, especially during the early stages of crop growth [14].

Intercropping millets with legumes or other crops can help suppress weed growth by providing ground cover and competing with weeds for resources [15]. Mulching with crop residues or organic materials can also be effective in controlling weeds and conserving soil moisture.

Figure 2: Manual Weeding in a Millet Field

Pest and Disease Management

Millets are generally less susceptible to pests and diseases compared to other cereal crops. However, some common pests that affect millets include stem borers, earhead caterpillars, and aphids [16]. Traditional pest management practices involve the use of botanical pesticides, such as neem extract, and the promotion of natural enemies through intercropping and habitat management.

Diseases like downy mildew, blast, and rust can also impact millet production [17]. Farmers traditionally rely on crop rotation, the use of resistant varieties, and the removal of infected plants to manage these diseases. The application of fungicides is limited in traditional millet cultivation.

Table 3: Common Pests and Diseases of Millets and their Management

Pest/Disease	Affected Millet Types	Traditional Management Practices
Stem Borer	Pearl Millet, Finger Millet	Removal of infected plants, use of botanical pesticides
Earhead Caterpillar	Pearl Millet	Handpicking, use of bird perches
Aphids	All Millets	Intercropping, use of botanical pesticides
Downy Mildew	Pearl Millet, Finger Millet	Use of resistant varieties, crop rotation
Blast	Finger Millet	Removal of infected plants, use of resistant varieties
Rust	Pearl Millet, Foxtail Millet	Crop rotation, removal of infected plants

Modern Approaches to Millet Cultivation

While traditional millet cultivation practices have sustained farmers for centuries, modern approaches aim to enhance productivity, resource use efficiency, and resilience. These approaches integrate scientific advancements, improved varieties, and precision agriculture techniques to address the challenges faced by millet farmers.

High-Yielding Varieties and Hybrids1: The development of high-yielding varieties (HYVs) and hybrids has been a significant breakthrough in millet cultivation. These improved varieties offer higher yield potential, better resistance to pests and diseases, and enhanced nutritional quality [18]. For instance, the introduction of pearl millet hybrids in India has led to a significant increase in productivity, with yields reaching up to 4-5 t/ha under favorable conditions [19].

Table 4: Popular High-Yielding Varieties and Hybrids of Millets in India

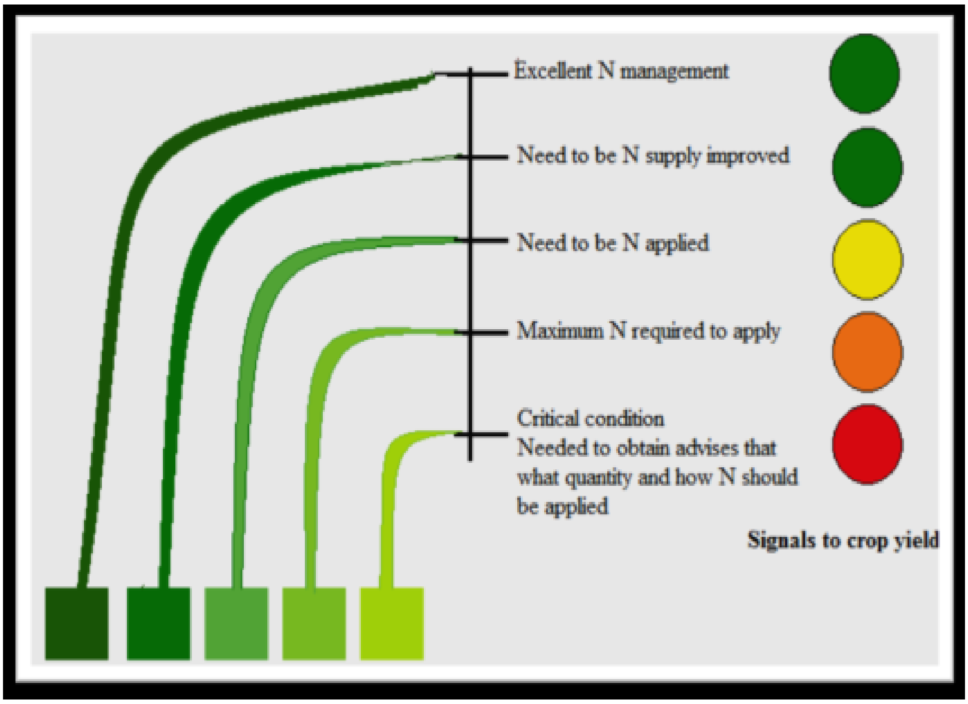
Millet Type	Variety/Hybrid	Yield Potential (t/ha)	Special Features
Pearl Millet	HHB 67 Improved	3.5-4.0	Drought tolerant, downy mildew resistant
Pearl Millet	Pro Agro 9444	4.0-4.5	High yield, suitable for irrigated conditions

Finger Millet	GPU 28	3.0-3.5	Blast resistant, high calcium content
Finger Millet	PR 202	3.5-4.0	Early maturing, suitable for rainfed conditions
Foxtail Millet	SiA 3085	2.5-3.0	High iron and zinc content

However, the adoption of HYVs and hybrids requires access to quality seeds, proper management practices, and adequate inputs. Extension services and farmer training programs play a crucial role in promoting the adoption of these improved varieties among millet farmers.

Precision Nutrient Management`Precision nutrient management involves the application of nutrients based on the specific requirements of the crop and the soil conditions. This approach optimizes nutrient use efficiency, reduces environmental impacts, and improves crop yields [20]. Techniques such as soil testing, leaf color charts, and sensor-based nutrient management can help farmers make informed decisions about fertilizer application.

Figure 3: Leaf Color Chart for Nitrogen Management in Millets



The use of slow-release fertilizers and fertigation (applying fertilizers through irrigation systems) can further enhance nutrient use efficiency and reduce nutrient losses [21]. Integrating organic and inorganic nutrient sources, such as vermicompost, biofertilizers, and mineral fertilizers, can also improve soil health and fertility in millet cultivation.

Integrated Pest and Disease Management

Integrated pest and disease management (IPDM) combines various strategies to minimize crop damage while promoting ecological balance and reducing reliance on chemical pesticides. IPDM practices in millet cultivation include [22]:

- Regular monitoring and surveillance of pests and diseases
- Use of resistant varieties and certified seeds
- Promotion of natural enemies through conservation biocontrol
- Judicious use of chemical pesticides based on economic thresholds
- Adoption of cultural practices like crop rotation and intercropping

Table 5: Integrated Pest and Disease Management Strategies for Millets

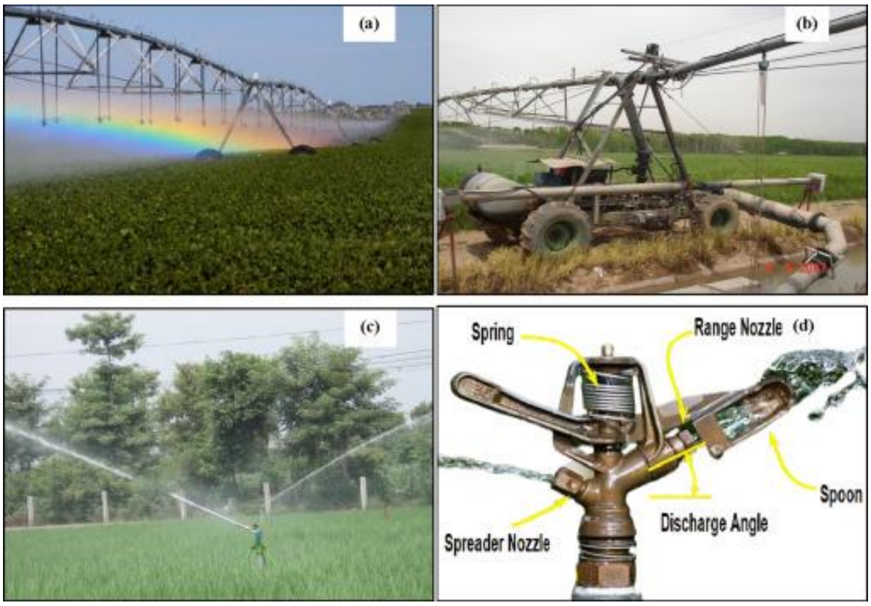
IPDM Component	Practices
Monitoring and Surveillance	Regular field scouting, use of pheromone traps
Resistant Varieties	Use of varieties with genetic resistance to pests and diseases
Biological Control	Conservation of natural enemies, release of parasitoids and predators
Chemical Control	Targeted application of pesticides based on economic thresholds
Cultural Practices	Crop rotation, intercropping, removal of infected plants

The adoption of IPDM practices can help reduce the environmental and health risks associated with excessive pesticide use while ensuring effective pest and disease control in millet cultivation.

Water Management and Conservation

Efficient water management is crucial for sustainable millet cultivation, particularly in rainfed and water-scarce regions. Modern approaches to water conservation include the adoption of micro-irrigation systems, such as drip irrigation and sprinklers, which can significantly reduce water consumption compared to traditional flood irrigation [23].

Figure 4: Drip Irrigation System in a Millet Field



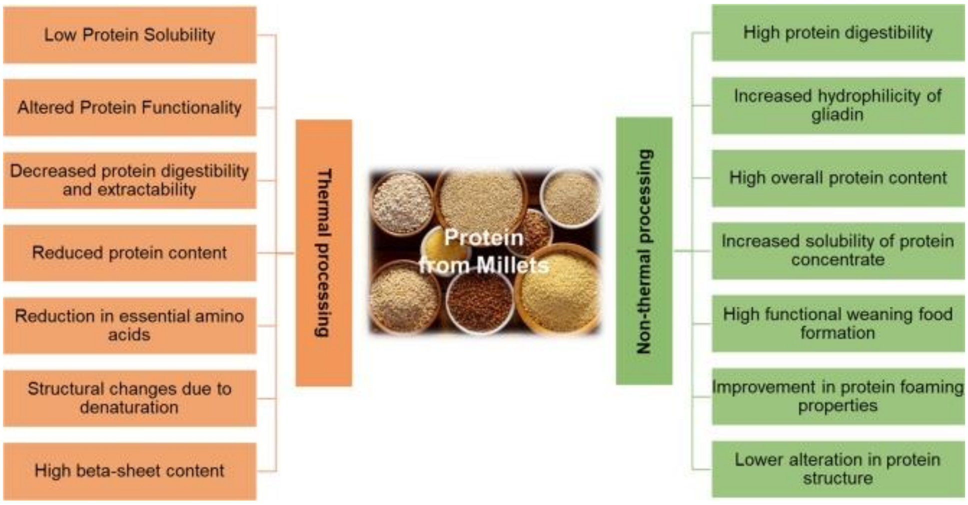
Other water conservation practices include mulching, rainwater harvesting, and the use of drought-tolerant varieties. Mulching with organic materials helps reduce evaporation losses, conserve soil moisture, and suppress weed growth [24]. Rainwater harvesting techniques, such as farm ponds and check dams, can help capture and store excess rainwater for supplemental irrigation during dry spells.

Post-Harvest Practices and Value Addition

Post-harvest practices play a vital role in ensuring the quality and marketability of millet grains. Proper drying, cleaning, grading, and storage of millets can reduce post-harvest losses and enhance their shelf life [25]. Modern post-harvest technologies, such as mechanical threshers, solar dryers, and hermetic storage bags, can improve the efficiency and effectiveness of these processes.

Value addition through the development of millet-based products is another avenue for enhancing the economic returns for farmers. Millets can be processed into various value-added products, such as flour, semolina, flakes, and ready-to-eat snacks [26]. The development of millet-based functional foods and nutraceuticals is also gaining attention due to the nutritional and health benefits of millets.

Figure 5: Value-Added Millet Products



Socio-Economic Dimensions of Millet

Cultivation Millet cultivation plays a significant role in the socio-economic fabric of rural communities, particularly in the semi-arid regions of India. Millets are often referred to as "poor man's crops" due to their association with smallholder farmers and marginalized communities [27]. However, millets have the potential to contribute to poverty alleviation, nutritional security, and women's empowerment.

`Millets are nutrient-dense crops, rich in proteins, minerals, and dietary fiber [28]. The promotion of millet consumption can help address malnutrition and dietary deficiencies, especially among women and children in rural areas. Moreover, millet cultivation is often carried out by women farmers, providing them with an opportunity to generate income and enhance their decision-making power within households [29].

The commercialization of millets and the development of value chains can create new market opportunities for smallholder farmers and rural entrepreneurs. Strengthening the linkages between farmers, processors, and markets can help ensure fair prices for millet producers and encourage the adoption of sustainable cultivation practices [30].

Challenges and Future Prospects

Despite the numerous benefits of millets, their cultivation faces several challenges. One of the major challenges is the declining area under millet cultivation due to the competition from other crops, such as maize and soybean [31]. The lack of policy support, inadequate research and development efforts, and the limited availability of improved varieties and hybrids have also contributed to the neglect of millets.

Moreover, the low productivity of millets compared to other cereal crops has made them less attractive to farmers. The average yield of millets in India is around 1.0-1.5 t/ha, which is significantly lower than that of rice (2.6 t/ha) and wheat (3.5 t/ha) [32]. Improving the yield potential of millets through breeding efforts and agronomic interventions is crucial for enhancing their competitiveness and adoption.

Climate change poses another challenge to millet cultivation. While millets are generally resilient to climate variability, extreme weather events such as prolonged droughts, heat waves, and erratic rainfall patterns can negatively impact their productivity [33]. Developing climate-resilient millet varieties and promoting climate-smart agricultural practices are essential for ensuring the sustainability of millet cultivation in the face of changing climatic conditions.

Despite these challenges, the future prospects of millets are promising. The growing recognition of the nutritional and ecological benefits of millets has led to increased consumer demand and policy support. The Government of India has launched several initiatives, such as the National Food Security Mission (NFSM) and the Millet Mission, to promote millet cultivation and consumption [34].

Research institutions and universities are also focusing on developing improved millet varieties, agronomic practices, and value-added products. For instance, the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) has been working on breeding high-yielding and nutrient-dense millet varieties, as well as promoting millet-based farming systems [35].

Conclusion

Millet cultivation practices in India encompass a rich tapestry of traditional knowledge and modern approaches. While traditional practices have sustained millet production for centuries, the integration of scientific advancements and technological innovations is crucial for enhancing productivity, resilience, and profitability. The adoption of high-yielding varieties, precision nutrient management, integrated pest and disease management, and efficient water conservation practices can help address the challenges faced by millet farmers. Moreover, the development of value-added millet products and the strengthening of market linkages can create new opportunities for smallholder farmers and rural communities. As we celebrate the International Year of Millets in 2023, it is imperative to recognize the potential of these nutrient-dense crops in achieving food and nutritional security, while promoting sustainable and resilient agricultural systems.

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CHAPTER - 5

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Climate Change Resilience: The Role of Millets in Food Security

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Abstract

Climate change poses significant challenges to global food security, particularly in developing nations like India. Droughts, floods, and rising temperatures threaten crop yields and livelihoods. In this context, neglected and underutilized species like millets offer a promising solution. Millets are hardy, climate-resilient crops well-suited to marginal environments. They require minimal inputs, tolerate poor soils, and withstand temperature and precipitation extremes. Millets are also nutritious, providing protein, fiber, minerals, and slow-releasing carbohydrates important for combating hunger and malnutrition. This chapter explores the role of millets in climate change adaptation and food security, with a focus on India. It reviews the impacts of climate change on Indian agriculture, the beneficial attributes of various millet species, and the cultural and culinary significance of millets. Challenges and opportunities around millet cultivation, processing, and marketing are discussed. The chapter recommends greater investment in millet research and development, integration into climate-smart agricultural policies, and awareness-raising to enhance the climate change resilience of food systems and ensure food and nutrition security.

Keywords: Climate Change, Food Security, Millets, Resilience, Nutrition

1. Introduction

Climate change is one of the greatest challenges facing humanity in the 21st century. Rising temperatures, altered precipitation patterns, and more frequent extreme weather events are already impacting food production systems worldwide [1]. In India, climate change threatens the livelihoods of millions of small-scale farmers and poses serious risks to food security [2]. With a population of over 1.3 billion to feed, building resilience in agricultural systems is paramount.

Historically, a diverse range of crops were cultivated in India, adapted to various agro-climatic conditions. However, the Green Revolution of the 1960s emphasised high-yielding varieties of major cereals like rice and wheat, leading to a decline in minor millet cultivation [3]. In light of climate change, there is renewed interest in these neglected and underutilised species (NUS). Millets are now recognised for their potential to enhance the climate resilience of food production while addressing malnutrition [4].

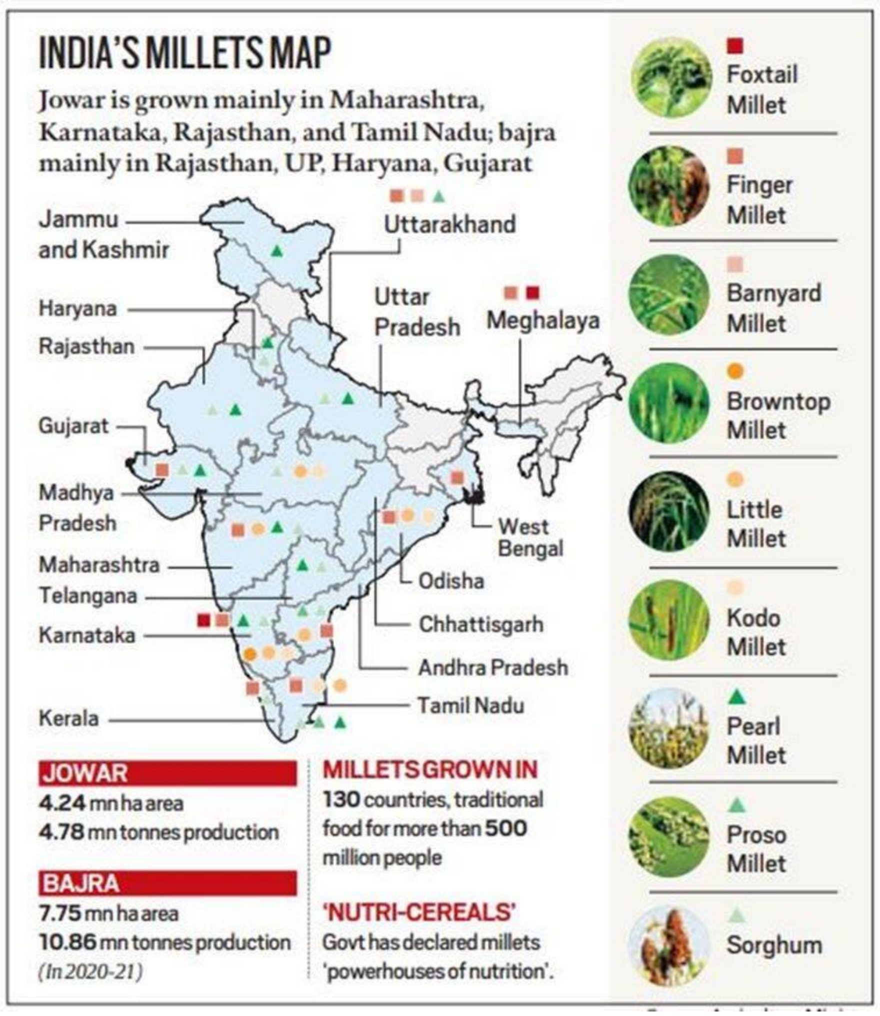

Figure 1: Global distribution of major millet-growing regions

2. Climate Change Impacts on Indian Agriculture

Climate change is already affecting agricultural production across India. Between 1901 and 2018, average temperatures increased by 0.7°C, a trend that is projected to continue [5]. Heatwaves have become more frequent and intense, with severe consequences for crop yields.

A recent study estimates that climate change may reduce wheat yields by 6-23% and rice yields by 4-14% in the absence of adaptation [6].

Rainfall patterns have also shifted, with more intense downpours interspersed by longer dry spells [7]. The summer monsoon, critical for rainfed agriculture, has become more erratic.

Both floods and droughts have increased in frequency over recent decades [8]. These changes in precipitation adversely impact agricultural production and rural livelihoods.

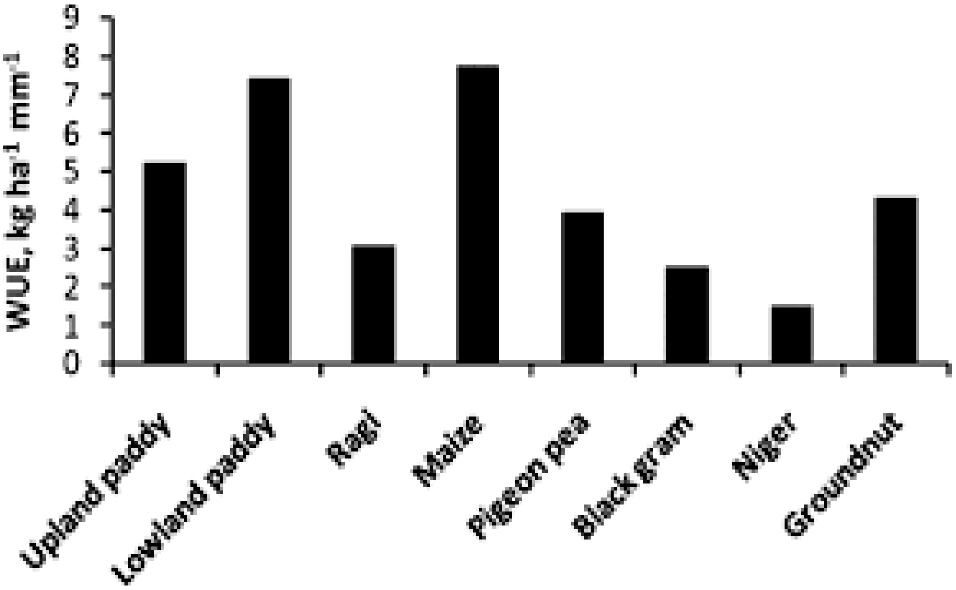

Figure 2: Comparison of millet water use efficiency vs other cereals

The cumulative impacts of climate change make food production more difficult and unpredictable. Small-scale farmers with limited resources are especially vulnerable. Adapting food systems to enhance their resilience is critical for protecting lives and livelihoods in the face of climate change.

Table 1: **Water Requirements of Millets vs Other Cereals**

Crop	**Water Requirement (mm)**	**Growing Period (days)**	**Water Use Efficiency (kg/ha/mm)**
Pearl Millet	200-300	60-70	8-10
Finger Millet	350-450	90-120	5-7
Sorghum	450-650	100-140	5-8
Maize	500-800	95-110	4-6
Rice	1200-1400	120-150	2-4

Wheat	450-650	120-150	4-6

Rising sea levels pose another threat, particularly in low-lying coastal regions. Saltwater intrusion degrades agricultural land and freshwater resources [9]. Coastal flooding and storm surges also wreak havoc on farming communities and infrastructure.

3. Millet Attributes and Climate Resilience

Millets are a diverse group of small-seeded cereal crops belonging to the Poaceae family. The most important millet species cultivated in India include:

- Pearl millet (*Pennisetum glaucum*)
- Finger millet (*Eleusine coracana*)
- Foxtail millet (*Setaria italica*)
- Proso millet (*Panicum miliaceum*)
- Barnyard millet (*Echinochloa* spp.)
- Kodo millet (*Paspalum scrobiculatum*)
- Little millet (*Panicum sumatrense*)

These millet species have several attributes that make them well-suited for cultivation under climate change conditions. Firstly, they are hardy and drought-tolerant, with low water requirements compared to major cereals [10].

Pearl millet, for example, requires 30% less water than maize [11]. Millets have deep root systems that enable them to efficiently access soil moisture and nutrients.

Secondly, millets can grow on marginal lands where other crops may fail. They tolerate poor soil fertility and can thrive in sandy or acidic soils [12]. Finger millet is known for its ability to grow at high elevations and on steep slopes [13].

Table 2: **Climate Resilience Traits of Major Millet Species**

Millet Species	Drought Tolerance	Heat Tolerance	Salinity Tolerance	Pest Resistance	Disease Resistance
Pearl Millet	High	High	Moderate	High	Moderate
Finger Millet	Moderate	High	Low	High	High
Foxtail Millet	High	Moderate	Moderate	Moderate	High
Proso Millet	High	High	Low	Moderate	Moderate
Barnyard Millet	Moderate	Moderate	High	High	High
Little Millet	High	High	Moderate	High	Moderate

Kodo Millet	Very High	Very High	High	High	High

Thirdly, millets have a short growing period, maturing in as little as 65 days depending on the species and variety [14]. This characteristic makes them suitable for cultivation in areas with erratic rainfall and short rainy seasons. Their fast growth also allows for multiple cropping cycles within a year.

Moreover, millets exhibit high photosynthetic efficiency and can withstand temperatures up to 64°C [15]. They show resistance to pests and diseases, reducing the need for chemical inputs [16].

The inherent resilience of millets offers a pathway for climate change adaptation. Cultivating these crops can help farmers cope with abiotic and biotic stresses, reducing their vulnerability to crop losses. Millets enable more efficient use of scarce resources like water and nutrients, while allowing production on marginal lands to expand food supplies.

3.1 Pearl Millet

Pearl millet is the most widely cultivated millet globally and in India, with grain used for food and stalks as fodder [17]. It is mainly grown in the arid and semi-arid regions of Rajasthan, Maharashtra, Gujarat, Uttar Pradesh and Haryana.

Pearl millet is highly drought-tolerant, with some varieties requiring as little as 200-250 mm of rainfall [18]. It is well-adapted to high temperatures, low soil fertility, and acidic soils. Pearl millet has a high tillering capacity and continues to produce tillers and flower under stress conditions [19].

Compared to other cereals, pearl millet grain has higher protein content, ranging from 8-24% [20]. It is a good source of energy, carbohydrates, protein, and important minerals like iron and zinc.

3.2 Finger Millet

Finger millet is an important staple crop cultivated in the hilly regions of India, particularly in Karnataka, Uttarakhand, Maharashtra, Tamil Nadu, and Odisha [21]. Also known as ragi, it thrives at higher elevations than most other millet species. With deep fibrous roots, finger millet can efficiently extract moisture from the soil, requiring only 350-400 mm of rainfall [22]. It tolerates a wide range of temperatures and can be cultivated on marginal lands with poor soil fertility.

Finger millet grain is rich in protein, fiber, calcium, and other minerals [23]. The high calcium content makes it an important food for bone health.

Finger millet has anti-diabetic properties with a low glycemic index, beneficial for managing blood sugar levels [24].

3.3 Foxtail Millet

Foxtail millet is among the oldest cultivated millets, grown in semi-arid regions throughout India [25]. It is most prominent in Andhra Pradesh, Karnataka, and Tamil Nadu.

Foxtail millet is known for its drought tolerance and can be cultivated in areas receiving 250-500 mm of annual rainfall [26]. It quickly establishes with a shallow root system and exhibits rapid growth, maturing in as little as 80-85 days [27]. The nutritional profile of foxtail millet includes high levels of protein, minerals like iron and zinc, and health-promoting phenolic compounds [28]. Regular consumption of foxtail millet is associated with reduced risk of cardiovascular disease and type 2 diabetes [29].

3.4 Other Millet Species

Several other millet species are cultivated to a lesser extent in India, adapted to specific agro-ecologies:

- Proso millet grows rapidly and has very low water requirements, making it ideal for short growing seasons [30].
- Barnyard millet can be cultivated in waterlogged, marginal lands and tolerates flooding [31].
- Kodo millet is resistant to smut and blast diseases that affect other crops [32]. [33].

These minor millets contribute to agricultural biodiversity and provide options for farmers in marginal environments affected by climate change. Further research is needed to fully utilise the potential of these crops.

Table 3: Nutritional Composition of Major Millet Varieties (per 100g) ***[35,36]***

Millet Type	**Protein (g)**	**Carbohydrates (g)**	**Fiber (g)**	**Iron (mg)**	**Calcium (mg)**	**Zinc (mg)**
Pearl Millet	10.6	67.5	1.2	8.0	42	3.1
Finger Millet	7.3	72.0	3.6	3.9	344	2.3
Foxtail Millet	12.3	60.9	8.0	2.8	31	2.4
Proso Millet	12.5	70.4	2.2	0.8	14	1.7
Barnyard Millet	11.2	65.5	9.8	15.2	11	3.0
Little Millet	7.7	67.0	7.6	9.3	17	3.7
Kodo Millet	8.3	65.9	9.0	0.5	27	0.7

4. Nutritional Significance of Millets

Beyond their climate resilience, millets offer important nutritional benefits. Millet grains are a rich source of energy, protein, fiber, vitamins, and minerals critical for human health [34]. Table 1 compares the nutritional content of major millet species to rice and wheat.

Millets contain higher levels of protein compared to rice, with some varieties having up to 12.5 g/100g. They are also superior sources of important micronutrients like iron, calcium and zinc. Finger millet, in particular, has calcium content 5-30 times higher than other cereals [37]. Pearl millet is high in iron, with some varieties providing up to 8 mg/100g [38].

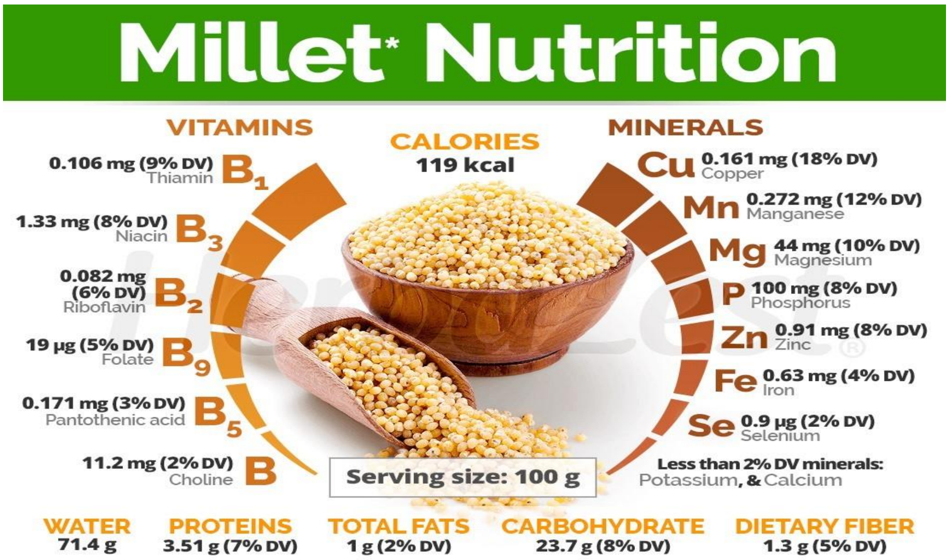

Figure 3: Nutritional profile of millets compared to other staple grains

Millets are rich in dietary fiber, both soluble and insoluble, which promotes digestion, prevents constipation, and reduces the risk of heart disease and diabetes [39].

The fiber content ranges from 7-20% in different millet species [40]. Additionally, millets contain health-benefiting phytochemicals such as polyphenols, tannins, and phytate [41].

These bioactive compounds have antioxidant, antimicrobial, and anticarcinogenic properties [42]. Regular consumption of millets can help alleviate micronutrient deficiencies prevalent in the Indian population, particularly among women and children [43]. Millets thus offer an accessible and affordable means of enhancing nutrition security in the face of climate change.

5. Cultural and Culinary Significance

Millets have been an integral part of Indian diets and cultural heritage for millennia. They are deeply rooted in the food traditions of various regions, particularly in arid and semi-arid areas where they are well-adapted [44].

In Rajasthan, pearl millet (bajra) is a staple food, consumed in the form of rotis (flatbread), khichdi (porridge), and rabdi (a sweet dish).

Rajasthani cuisine features several millet-based delicacies like bajre ki raab (a warming millet drink), bajra kheer (a dessert), and churma (a sweet made from millet flour and ghee) [45].

The Kandha tribal community in Odisha considers finger millet (mandia) as sacred and uses it in various rituals and festivals. Mandia is consumed as roti, porridge, and a fermented drink called handia [46].

Similarly, in Karnataka and Tamil Nadu, finger millet (ragi) is a key part of local diets, used to make mudde (steamed balls), roti, dosa, and porridge [47]. In the Himalayan states of Uttarakhand and Himachal Pradesh, various minor millets like barnyard millet (jhangora), foxtail millet (kangni), and proso millet (cheena) are consumed.

Traditional dishes include jhangore ki kheer, a sweet porridge, and madua ki roti, a flatbread made from finger millet [48]. Millets also have uses in traditional medicine. For instance, kodo millet is considered an antidiabetic and anti-inflammatory food in Ayurveda [49]. Foxtail millet is used to treat asthma, migraine, and heart attack [50].

Table 4: Potential Climate Change Impacts on Millet Production

Climate Factor	**Potential Impact**	**Millet Adaptation Strategy**
Increased Temperature	Accelerated growth, reduced yield	Heat-tolerant varieties, adjusted planting dates
Erratic Rainfall	Water stress, reduced productivity	Drought-resistant varieties, water harvesting
Extreme Weather Events	Crop damage, yield loss	Improved agronomic practices, crop insurance
Elevated CO2 Levels	Increased biomass, altered grain quality	Nutrient management, breeding for quality traits
Soil Degradation	Reduced fertility, lower yields	Conservation agriculture, crop rotation
Pest and Disease Pressure	Increased crop damage	Integrated pest management, resistant varieties

Shortened Growing Season	Reduced yield potential	Early-maturing varieties, cropping system adaptation

The cultivation, processing, and consumption of millets are thus embedded in the cultural fabric of many Indian communities. Preserving and promoting these traditional practices can foster cultural resilience while contributing to food and nutrition security in a changing climate.

6. Challenges and Opportunities

Despite the multiple benefits offered by millets, their cultivation has declined in recent decades. Several challenges constrain efforts to scale up millet production and utilisation, which must be addressed through targeted interventions and policies.

6.1 Limited Research and Development

Compared to major cereals, millets have received significantly less attention from researchers and policymakers [51]. Public expenditure on millet improvement is much lower than for rice, wheat, and maize [52]. Consequently, there are gaps in our understanding of millet genetics, physiology, and agronomy that hinder their full utilisation.

Increased investment in millet research and development is necessary to enhance yields, climate resilience, and nutritional quality. This includes breeding efforts to develop high-yielding, stress-tolerant varieties, as well as agronomic research to optimise millet-based cropping systems. Participatory research approaches involving farmers can help tailor solutions to local contexts [53].

6.2 Low Yields and Drudgery

Millets generally have lower grain yields compared to major cereals, though they are often grown in marginal environments with minimal inputs [54]. The drudgery involved in traditional methods of millet cultivation and processing is another challenge, particularly for women farmers [55].

Mechanisation and improved post-harvest technologies can help reduce drudgery and improve millet processing efficiency [56]. For example, millet dehullers and threshers can significantly reduce labour requirements. Extension services to promote best agronomic practices and improved varieties can close yield gaps.

6.3 Insufficient Value Addition

Millet value chains in India are currently underdeveloped, with limited processing and value addition [57]. Most millet farmers sell their produce as raw grains, missing out on opportunities to enhance their incomes.

Developing millet processing infrastructure and value-added products is crucial for driving demand and improving farmer livelihoods. This includes millet-based flours, snacks, baked goods, and ready-to-eat products that cater to urban consumers [58]. Entrepreneurs and food businesses have a key role in innovating millet products and markets.

6.4 Policy Support

Historically, agricultural policies in India have focussed on rice and wheat, with subsidies and procurement support that inadvertently discouraged millet cultivation [59]. Recognising this, some states have begun promoting millets through various schemes and initiatives.

In 2018, the Government of India declared millets as "Nutri-Cereals" and allowed their inclusion in the Public Distribution System (PDS) [60]. The United Nations General Assembly recently adopted a resolution sponsored by India to declare 2023 as the International Year of Millets [61]. Such policy support is a positive step.

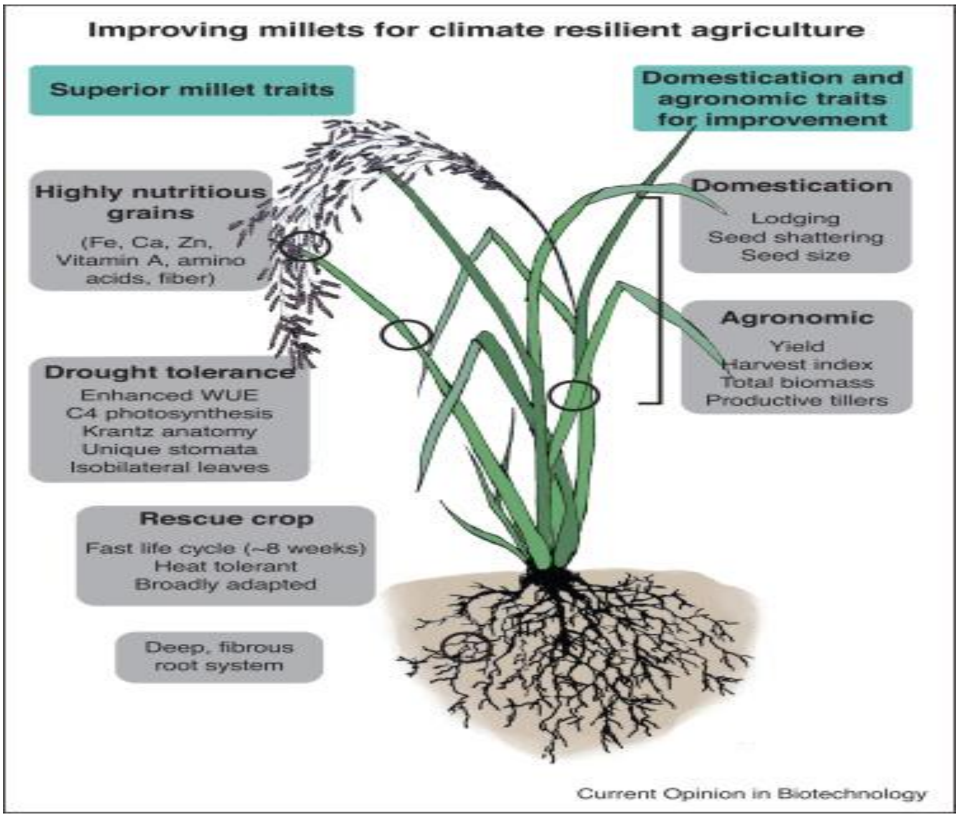

Figure 4: Projected changes in millet yield under different climate scenarios

Further integrating millets into nutrition and food security programmes, like the Mid-Day Meal Scheme and the Integrated Child Development Services, can stimulate demand [62]. Procurement of millets at Minimum Support Prices (MSPs) can incentivise farmers to expand production. Investments in millet seed systems, extension services, and market linkages are also vital.

Table 5: Global Millet Production and Major Producers

Country	Production (Million Tonnes)	Area Harvested (Million Hectares)	Yield (Tonnes/Hectare)
India	11.5	9.2	1.25
Niger	3.9	7.2	0.54
China	1.6	0.7	2.29
Mali	1.8	1.9	0.95
Nigeria	1.5	1.8	0.83
Burkina Faso	1.1	1.3	0.85
Sudan	1.0	2.4	0.42
Ethiopia	0.8	0.4	2.00

Conclusion

Climate change poses grave threats to food security in India, exacerbating the vulnerabilities of small-scale farmers. Enhancing the resilience of food production systems is imperative for achieving the Sustainable Development Goals of zero hunger and climate action. In this context, the mainstreaming of nutrient-dense, climate-resilient crops like millets offers a promising solution. The diverse millet species cultivated in India are well-adapted to marginal environments, with low water requirements, short growing periods, and tolerance to various stresses. Millets are also rich in micronutrients and health-promoting compounds, making them valuable for nutrition security. Moreover, millets are deeply embedded in Indian culinary traditions and cultural heritage.

Realising the full potential of millets necessitates increased research investments, policy support, and the development of value chains. Efforts to improve millet yields, processing efficiency, and market demand can drive adoption while benefitting farmers and consumers. Millet cultivation can be expanded on degraded lands, integrated into resilient farming systems, and used to diversify diets.

In conclusion, scaling up millet production and consumption offers a multi-pronged approach to address the challenges of climate change, food insecurity, and malnutrition in India. With strategic interventions and an enabling policy environment, millets can significantly contribute to the resilience and sustainability of food systems, ensuring food and nutrition security for current and future generations.

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CHAPTER - 06

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Processing and Value Addition Techniques for Millets

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Abstract

Millets are highly nutritious ancient grains that have been cultivated for thousands of years. In recent times, there has been renewed interest in millets due to their numerous health benefits, sustainability, and resilience to climate change. India is one of the largest producers of millets globally, with a rich tradition of millet cultivation and consumption. This chapter provides an in-depth analysis of the various processing and value addition techniques used for millets in India. The primary processing methods covered include cleaning, grading, dehulling, and milling. Secondary processing techniques such as malting, fermentation, extrusion, and baking are also discussed in detail. Value addition through fortification, product development, and by-product utilization is explored. The chapter highlights the potential of millets as functional foods and their role in enhancing food and nutritional security. Challenges and opportunities in the millet value chain are examined, along with strategies for promoting millet processing and value addition. The chapter concludes by emphasizing the need

for collaborative efforts among stakeholders to harness the full potential of millets and create a sustainable and resilient food system.

Keywords: Millets, processing, value addition, fortification, sustainability

1. Introduction

Millets are a group of small-seeded grasses that have been cultivated for food and fodder for thousands of years. They are highly nutritious, climate-resilient, and sustainable crops that can grow in diverse agro-climatic conditions [1]. Millets are rich in protein, dietary fiber, minerals, and bioactive compounds, making them an excellent choice for healthy diets [2]. In recent years, there has been a renewed interest in millets due to their potential to address food and nutritional security challenges, particularly in developing countries.

India is one of the largest producers of millets globally, with a long history of millet cultivation and consumption. Millets are an integral part of the traditional diets in many regions of India, particularly in the semi-arid and arid regions where they are well-adapted to the local conditions [3]. However, over the past few decades, the consumption of millets has declined due to changing dietary preferences and the dominance of wheat and rice in the food system.

To revive the cultivation and consumption of millets, the Government of India has taken several initiatives, including the declaration of 2018 as the National Year of Millets and 2023 as the International Year of Millets [4]. These initiatives aim to promote millets as a nutritious and sustainable food option, enhance their production and productivity, and create new market opportunities for millet-based products.

Processing and value addition are crucial for increasing the utilization and consumption of millets. Primary processing techniques such as cleaning, grading, dehulling, and milling are essential for improving the quality and shelf life of millet grains [5]. Secondary processing methods like malting, fermentation, extrusion, and baking can enhance the nutritional value, sensory attributes, and convenience of millet-based products [6]. Value addition through fortification, product development, and by-product utilization can create new market opportunities and improve the profitability of the millet value chain [7].

2. Primary Processing of Millets

Primary processing of millets involves the basic steps required to convert the raw grains into a form suitable for consumption or further processing. These steps include cleaning, grading, dehulling, and milling, which are essential for improving the quality, shelf life, and acceptability of millet grains [8]. This section discusses the various primary processing techniques used for millets in India.

2.1. Cleaning and grading

Cleaning and grading are the first steps in the primary processing of millets. The harvested grains often contain various impurities such as dust, dirt, stones, and other foreign matter that need to be removed before further processing [9]. Cleaning is usually done using mechanical methods such as sieving, winnowing, or aspiration, which separate the grains from the unwanted materials based on their size, shape, and density [10].

Grading is the process of separating the cleaned grains into different categories based on their size, color, and quality. Grading helps to ensure uniformity in the processed products and facilitates the efficient use of the grains for various applications [11]. Grading is usually done using mechanical sieves or optical sorting machines that can separate the grains based on their physical properties.

The cleaning and grading of millets are essential for maintaining the quality and safety of the processed products. The presence of impurities and contaminants can affect the nutritional value, sensory attributes, and shelf life of the millet-based products [12]. Therefore, it is crucial to follow proper cleaning and grading procedures to ensure the production of high-quality millet products.

2.2. Dehulling

Dehulling is the process of removing the outer husk or hull of the millet grains to obtain the edible portion. Most millet grains have a hard and inedible outer layer that needs to be removed before consumption or further processing [13].

Dehulling is usually done using mechanical methods such as abrasive dehulling, roller milling, or disc milling, which apply pressure or friction to the grains to separate the husk from the endosperm [14].

Traditional dehulling methods such as hand pounding or stone grinding are still used in some parts of India, particularly in rural areas. However, these methods are labor-intensive and time-consuming and often result in high losses and low efficiency [15]. Modern dehulling machines such as abrasive dehullers or rubber roll dehullers are more efficient and can handle larger volumes of grains with minimal losses [16].

The efficiency of dehulling depends on several factors, such as the type and variety of the millet, the moisture content of the grains, and the dehulling method used [17]. Proper dehulling is essential for improving the digestibility, palatability, and nutritional value of the millet grains. Dehulled millets have a higher protein and mineral content compared to whole grains and are easier to cook and consume [18].

2.3. Milling

Milling is the process of reducing the size of the dehulled millet grains into smaller particles such as flour, semolina, or grits. Milling is usually done using mechanical methods such as hammer milling, stone grinding, or roller milling, which apply force or pressure to the grains to break them down into smaller particles [19].

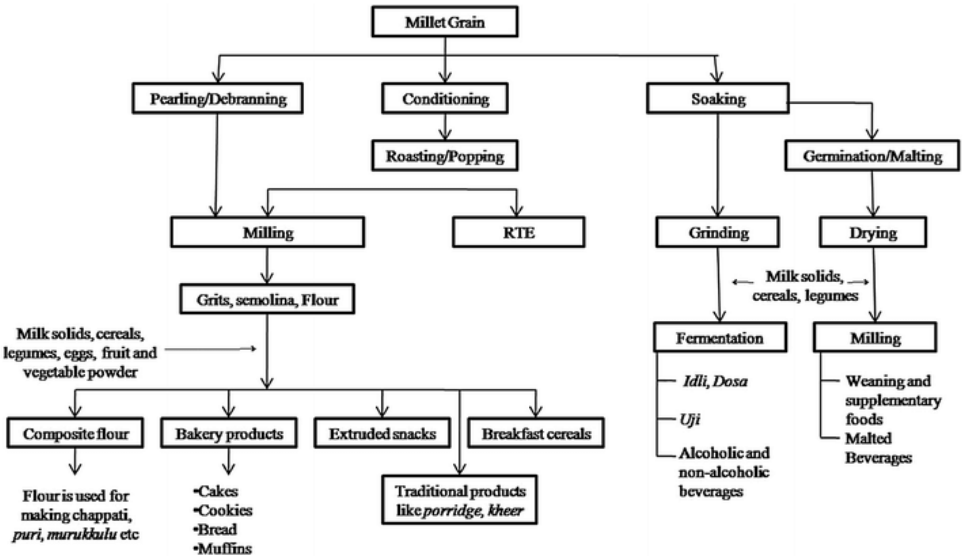
The type of milling method used depends on the desired end product and the quality requirements. Hammer milling is the most common method used for producing millet flour, as it is efficient and can handle large volumes of grains [20].

Stone grinding is often used for producing traditional millet-based products such as roti or dosa, as it retains the natural flavor and texture of the grains [21]. Roller milling is used for producing millet semolina or grits, which are used in the preparation of porridges or snack foods [22]. The milling process can have a significant impact on the nutritional quality of the millet products. Excessive milling can lead to the loss of important nutrients such as dietary fiber, minerals, and vitamins, which are concentrated in the outer layers of the grains [23]. Therefore, it is important to optimize the milling process to retain the maximum nutritional value of the millets while achieving the desired product quality.

Table 1. Nutritional composition of major millet types (per 100 g)

Millet Type	Energy (kcal)	Protein (g)	Fat (g)	Carbohydrates (g)	Fiber (g)	Iron (mg)	Calcium (mg)
Pearl millet	361	11.6	4.8	67.5	1.3	8.0	42
Finger millet	328	7.3	1.3	72.0	3.6	3.9	344
Foxtail millet	331	12.3	4.3	60.9	8.0	2.8	31
Proso millet	354	11.0	1.9	70.4	2.2	3.2	8
Kodo millet	309	8.3	1.4	65.9	9.0	0.5	27
Little millet	329	7.7	4.7	67.0	7.6	9.3	17
Barnyard millet	300	6.2	2.2	65.5	9.8	5.0	20

Figure 1. Schematic representation of the millet processing value chain



3. Secondary Processing Techniques

Secondary processing techniques are used to transform the primary processed millets into value-added products with enhanced nutritional, sensory, and functional properties. These techniques include malting, fermentation, extrusion, and baking, which can improve the digestibility, shelf life, and consumer acceptability of the millet-based products [24]. This section discusses the various secondary processing techniques used for millets in India.

3.1. Malting

Malting is the process of germinating the millet grains under controlled conditions to activate the enzymes and modify the nutritional and functional properties of the grains. Malting is usually done by soaking the grains in water for a specific period, followed by germination and drying [25]. During germination, the enzymes such as amylases and proteases break down the complex carbohydrates and proteins into simpler and more digestible forms [26].

Malting can enhance the nutritional value of the millets by increasing the bioavailability of minerals such as iron and zinc and reducing the levels of antinutritional factors such as phytates and tannins [27]. Malted millets have a higher content of vitamins, especially B vitamins, and a lower glycemic index compared to unmalted grains [28]. Malting can also improve the sensory attributes of the millet-based products by developing desirable flavors and aromas [29].

Malted millets are used in the preparation of various traditional and modern food products such as weaning foods, beverages, and baked goods. Malted millet flour is often used as a nutritious and digestible ingredient in the formulation of complementary foods for infants and young children [30]. Malted millet beverages such as ragi malt or jowar malt are popular health drinks in India, known for their refreshing taste and nutritional benefits [31].

Figure 2. Traditional dehulling equipment: (a) Mortar and pestle, (b) Chakki stone grinder

3.2. Fermentation

Fermentation is a processing technique that involves the use of microorganisms such as bacteria or yeast to transform the millet grains into value-added products with enhanced nutritional, sensory, and functional properties. Fermentation is a traditional method of food preservation and processing that has been used for centuries in India and other parts of the world [32].

Fermentation can improve the nutritional value of the millets by increasing the bioavailability of minerals, reducing the levels of antinutritional factors, and enhancing the protein and vitamin content [33]. Fermented millets have a higher content of B vitamins, especially thiamine and riboflavin, and a lower glycemic index compared to unfermented grains [34]. Fermentation can also develop desirable flavors, aromas, and textures in the millet-based products, making them more palatable and appealing to consumers [35]. Traditional fermented millet products such as idli, dosa, and dhokla are popular breakfast and snack items in India, known for their nutritional and sensory qualities [36]. These products are prepared by fermenting a batter made from millet flour and other ingredients such as legumes or spices, using natural or starter cultures [37]. Fermented millet beverages such as ambali or marwa are also consumed in some parts of India, known for their probiotic and health-promoting properties [38].

Modern fermentation techniques such as solid-state fermentation or submerged fermentation are being explored for the production of value-added millet products such as bioactive compounds, enzymes, and organic acids [39]. These techniques can enhance the functional properties of the millets and create new opportunities for their utilization in the food and pharmaceutical industries [40].

Figure 3. Modern millet milling equipment: (a) Hammer mill, (b) Disc mill, (c) Pin mill

3.3. Extrusion

Extrusion is a processing technique that involves the application of high temperature, pressure, and shear to the millet flour or grit to produce expanded or texturized products such as snacks, breakfast cereals, or pasta [41]. Extrusion is a versatile and efficient method of food processing that can handle a wide range of raw materials and produce a variety of products with different shapes, sizes, and textures [42]. Extrusion can modify the nutritional and functional properties of the millets by gelatinizing the starch, denaturing the proteins, and inactivating the enzymes and antinutritional factors [43]. Extruded millet products have a higher protein and starch digestibility, a lower glycemic index, and a higher content of resistant starch compared to non-extruded products [44]. Extrusion can also improve the sensory attributes of the millet-based products by developing desirable flavors, colors, and textures [45].

Extruded millet snacks such as puffed or expanded snacks are gaining popularity in India as healthy and convenient food options [46]. These snacks are prepared by extruding a mixture of millet flour, water, and other ingredients such as salt, spices, or flavorings, using a single or twin-screw extruder [47]. Extruded millet breakfast cereals such as flakes or loops are also being developed as nutritious and ready-to-eat alternatives to traditional breakfast items [48]. Extrusion technology is also being used for the production of millet-based functional ingredients such as pregelatinized flours, modified starches, or protein concentrates [49][50].

Table 2. Traditional millet-based products in India

Product Name	**Millet Type**	**Description**
Roti	Pearl millet	Flatbread made from pearl millet flour
Idli	Finger millet	Steamed cake made from fermented finger millet and rice batter
Dosa	Finger millet	Thin, crispy pancake made from fermented finger millet and rice batter
Porridge	Foxtail millet	Thin, savory porridge made from foxtail millet flour
Kheer	Barnyard millet	Sweet pudding made from barnyard millet and milk
Laddoo	Pearl millet	Sweet ball-shaped snack made from pearl millet flour and jaggery
Upma	Little millet	Savory breakfast dish made from little millet semolina

3.4. Baking

Baking is a processing technique that involves the use of dry heat to transform the millet flour or other ingredients into value-added products such as bread, biscuits, cakes, or pastries [51]. Baking is a popular method of food processing that can produce a wide range of products with different flavors, textures, and nutritional qualities [52].

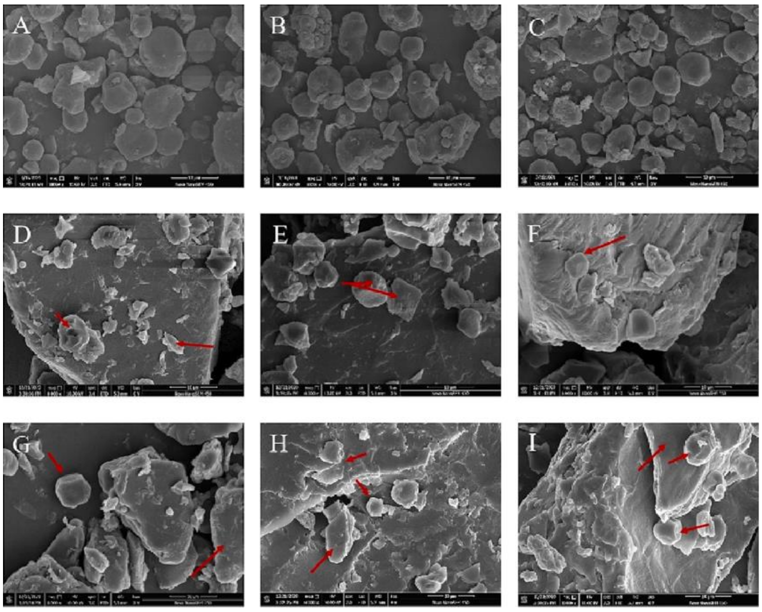
Millet-based bakery products are gaining popularity in India as healthier and gluten-free alternatives to wheat-based products [53]. Millet flour can be used as a partial or complete substitute for wheat flour in the formulation of various bakery products, depending on the type and quality of the millet flour and the desired product characteristics [54].

However, the use of millet flour in baking presents some challenges such as lower gluten content, higher water absorption, and slower dough development, which can affect the quality and acceptability of the products [55]. To overcome these challenges, various strategies such as the use of hydrocolloids, enzymes, or sourdough fermentation are being explored to improve the baking performance and sensory attributes of the millet-based bakery products [56]. These strategies can help to enhance the gluten network, increase the loaf volume, and develop desirable flavors and textures in the products [57].

The use of composite flours or blends of millet and wheat flours is also being investigated as a way to balance the nutritional and sensory qualities of the bakery products [58]. Millet-based gluten-free bakery products such as bread, biscuits, or cakes are being developed for people with celiac disease or gluten intolerance [59]. These products are prepared using millet flour or other gluten-free ingredients such as starch, gums, or proteins, and are formulated to meet the nutritional and sensory requirements of the target consumers [60].

The development of millet-based gluten-free bakery products requires careful selection and optimization of the ingredients and processing conditions to ensure the quality, safety, and acceptability of the products [61].

Figure 4. Scanning electron microscopy images of (a) Raw millet grains, (b) Malted millet grains



4. Value Addition in Millets

Value addition is the process of transforming the primary or secondary processed millets into high-value products with enhanced nutritional, sensory, and functional properties. Value addition can create new market opportunities, increase the profitability, and improve the sustainability of the millet value chain [62]. This section discusses the various value addition strategies used for millets in India, including fortification, product development, and by-product utilization.

4.1. Fortification

Fortification is the practice of adding essential micronutrients such as vitamins or minerals to the millet-based products to enhance their nutritional value and address specific deficiencies in the target population [63]. Fortification is a cost-effective and sustainable strategy to improve the micronutrient status of the population, especially in developing countries where malnutrition is a major public health problem [64].

Millets are naturally rich in several micronutrients such as iron, zinc, calcium, and B vitamins, which can be further enhanced through fortification [65]. The fortification of millet-based products with iron and folic acid is being explored as a strategy to prevent and control anemia, which is a common nutritional disorder in India, especially among women and children [66]. The fortification of millet-based complementary foods with multiple micronutrients is also being investigated as a way to improve the growth and development of infants and young children [67].

The fortification of millet-based products requires careful selection and optimization of the fortificants and the fortification process to ensure the stability, bioavailability, and acceptability of the products [68]. The fortificants should be compatible with the food matrix, stable during processing and storage, and bioavailable for absorption and utilization by the body [69]. The fortification process should not adversely affect the sensory attributes or the shelf life of the products [70].

The development of fortified millet-based products requires collaboration among different stakeholders such as researchers, food processors, policymakers, and consumers to ensure the success and sustainability of the fortification programs [71]. The government of India has launched several initiatives such as the National Nutritional Anemia Control Program and the National Food Security Mission to promote the fortification of staple foods, including millets, with essential micronutrients [72].

4.2. Product development

Product development is the process of creating new or improved millet-based products that meet the changing needs and preferences of the consumers. Product development is a key strategy to diversify the utilization of millets, create value-added products, and increase the market demand for millet-based products [73].

Traditional millet-based products such as roti, idli, or dosa have been consumed in India for centuries and are an integral part of the local food culture and traditions [74]. These products are prepared using simple ingredients and processing methods and are known for their nutritional and sensory qualities. However, the consumption of traditional millet-based products has declined in recent years due to changing lifestyles, urbanization, and the availability of alternative food options [75].

To revive the consumption of millets and create new market opportunities, innovative millet-based products are being developed using modern processing technologies and ingredients [76]. These products include ready-to-eat or ready-to-cook products such as snacks, breakfast cereals, energy bars, or instant mixes, which offer convenience, variety, and nutritional benefits to the consumers [77]. The development of millet-based functional foods or nutraceuticals is also gaining attention as a way to target specific health benefits such as diabetes management, weight control, or gut health [78].

The development of millet-based products requires a thorough understanding of the consumer needs, preferences, and perceptions, as well as the technical and regulatory requirements for the products [79]. The products should be formulated using appropriate ingredients and processing methods to ensure the desired nutritional, sensory, and shelf-life characteristics [80]. The packaging and labeling of the products should also be designed to attract and inform the consumers about the benefits and qualities of the products [81].

The commercialization of millet-based products requires effective marketing and distribution strategies to reach the target consumers and create a sustainable demand for the products [82]. Collaborative efforts among different stakeholders such as farmers, processors, researchers, and policymakers are essential to develop and promote innovative millet-based products and create a vibrant millet value chain [83].

Table 3. Innovative millet-based product formulations

Product Category	Millet Type	Innovative Formulation
Bakery products	Finger millet	Gluten-free bread with finger millet and quinoa flour
Snacks	Foxtail millet	Extruded snacks with foxtail millet and vegetable powder
Beverages	Pearl millet	Probiotic fermented beverage with pearl millet and fruit juice
Ready-to-cook	Kodo millet	Instant kodo millet dosa mix with added herbs and spices
Pasta and noodles	Little millet	Millet-based pasta with enhanced protein content
Functional foods	Barnyard millet	Millet-based energy bars with added nuts and dried fruits
Infant foods	Finger millet	Millet-based complementary food with fortified vitamins and minerals

4.3. By-product utilization

By-product utilization is the process of converting the waste or low-value materials generated during the processing of millets into value-added products or ingredients. By-product utilization is a sustainable strategy to reduce the environmental impact, increase the profitability, and improve the resource efficiency of the millet value chain [84].

Millets generate various by-products during their cultivation, harvesting, and processing, such as straw, husk, bran, or germ, which are often discarded or used as low-value animal feed [85]. These by-products are rich in several nutrients, bioactive compounds, and functional properties that can be extracted and utilized for various food and non-food applications [86].

Millet straw is a major by-product of millet cultivation and is traditionally used as fodder for livestock or as a fuel for cooking [87]. However, millet straw can also be used as a raw material for the production of value-added products such as bioethanol, biogas, or biodegradable packaging materials [88]. The use of millet straw for bioethanol production is being explored as a way to reduce the dependence on fossil fuels and promote sustainable energy production [89]. Millet husk is another major by-product of millet processing and is usually discarded as waste or used as a low-value fuel [90]. However, millet husk is rich in several bioactive compounds such as phenolics, flavonoids, and antioxidants, which can be extracted and used as functional ingredients or nutraceuticals [91]. The use of millet husk as a source of natural antioxidants is being investigated as a way to improve the shelf life and quality of various food products [92].

Millet bran and germ are the nutrient-rich fractions of the millet grains that are often removed during the milling process and used as animal feed [93]. However, millet bran and germ are rich in several essential nutrients such as proteins, lipids, minerals, and vitamins, which can be extracted and used as functional ingredients or food supplements [94]. The use of millet bran and germ as a source of protein and bioactive peptides is being explored as a way to develop novel functional foods or nutraceuticals [95]. The utilization of millet by-products requires the development of appropriate technologies and processes for their collection, processing, and value addition [96]. The by-products should be characterized for their nutritional and functional properties and evaluated for their safety and regulatory compliance [97]. The economic and environmental feasibility of the by-product utilization should also be assessed to ensure the sustainability and viability of the millet value chain [98].

5. Millets as Functional Foods

Functional foods are foods that provide health benefits beyond their basic nutritional value and can help in the prevention or management of certain diseases or health conditions [99]. Millets are considered as potential functional foods due to their unique nutritional and bioactive profiles and their associated health benefits [100]. This section discusses the nutritional and functional properties of millets and their potential as functional foods.

Figure 5. Flowchart of the millet malting process

5.1. Nutritional profile of millets

Millets are nutrient-dense grains that are rich in several essential nutrients such as proteins, carbohydrates, lipids, minerals, and vitamins [101]. The nutritional composition of millets varies depending on the type of millet, the growing conditions, and the processing methods used [102]. Table 1 shows the nutritional composition of some common types of millets. Millets are a good source of proteins, with a protein content ranging from 7 to 12% [103]. The proteins in millets are of good quality and contain essential amino acids such as lysine, methionine, and tryptophan, which are often limiting in other cereals [104]. Millets are also rich in carbohydrates, with a carbohydrate content ranging from 60 to 70% [105]. The carbohydrates in millets consist of both digestible and resistant starches, which can provide sustained energy and promote gut health [106].

Millets are low in fat, with a fat content ranging from 1 to 5% [107]. The lipids in millets are mostly unsaturated and contain essential fatty acids such as linoleic and linolenic acids [108]. Millets are also rich in several essential minerals such as iron, zinc, calcium, and magnesium, which are often deficient in the diets of many populations [109]. The mineral content of millets is higher than that of most other cereals and can help in the prevention of mineral deficiencies [110]. Millets are a good source of several vitamins, especially B vitamins such as thiamine, riboflavin, niacin, and folic acid [111]. The vitamin content of millets is higher than that of most other cereals and can help in the prevention of vitamin deficiencies [112]. Millets are also rich in dietary fiber, with a fiber content ranging from 7 to 12% [113]. The fiber in millets consists of both soluble and insoluble fractions, which can promote satiety, reduce cholesterol absorption, and improve bowel function [114].

5.2. Bioactive compounds in millets

Millets are a rich source of several bioactive compounds that can provide health benefits beyond their basic nutritional value [115]. The bioactive compounds in millets include phenolic acids, flavonoids, tannins, phytosterols, and policosanols, which have antioxidant, anti-inflammatory, antimicrobial, and anticancer properties [116]. Phenolic acids are the most abundant bioactive compounds in millets and include ferulic acid, p-coumaric acid, and caffeic acid [117]. These compounds have strong antioxidant and anti-inflammatory activities and can help in the prevention of several chronic diseases such as cardiovascular diseases, diabetes, and cancer [118]. Flavonoids are another class of bioactive compounds found in millets and include catechin, quercetin, and luteolin [119]. These compounds have antioxidant, antimicrobial, and anticancer properties and can help in the prevention of several diseases [120]. Tannins are polyphenolic compounds found in the outer layers of millet grains and include condensed and hydrolysable tannins [121]. These compounds have antioxidant, antimicrobial, and antinutritional properties and can affect the digestibility and bioavailability of nutrients [122]. However, the tannins in millets can also provide health benefits such as reducing the risk of cardiovascular diseases and cancer [123].

Phytosterols are plant sterols that are found in small amounts in millets and include sitosterol, stigmasterol, and campesterol [124]. These compounds have cholesterol-lowering properties and can help in the prevention of cardiovascular diseases [125]. Policosanols are long-chain alcohols found in the wax layer of millet grains and include octacosanol and triacontanol [126]. These compounds have antioxidant and anti-inflammatory properties and can help in the prevention of several diseases [127]. The bioactive compounds in millets are affected by several factors such as the type of millet, the growing conditions, the processing methods, and the storage conditions [128]. The processing of millets can lead to the degradation or loss of some bioactive compounds, while it can also enhance the bioavailability or formation of others [129]. Therefore, the processing of millets should be optimized to retain or enhance the bioactive compounds and their associated health benefits [130].

5.3. Health benefits of millet consumption

The consumption of millets has been associated with several health benefits due to their unique nutritional and bioactive profiles [131]. Table 5 summarizes some of the potential health benefits of millet consumption and their associated nutrients and bioactive compounds.

Millets have a low glycemic index and can help in the management of diabetes by reducing the postprandial glucose and insulin responses [132]. The consumption of millets has been shown to improve the glycemic control, reduce the oxidative stress, and prevent the complications of diabetes [133]. The resistant starch, dietary fiber, and polyphenols in millets are the main components responsible for their antidiabetic properties [134]. Millets are gluten-free and can be safely consumed by people with celiac disease or gluten intolerance [135]. The consumption of millets can help in the management of celiac disease by providing a nutritious and diversified diet and preventing the nutrient deficiencies associated with the disease [136]. The proteins, minerals, and vitamins in millets can contribute to the nutritional adequacy of the gluten-free diet [137].

Millets are rich in several nutrients and bioactive compounds that can help in the prevention of cardiovascular diseases [138]. The consumption of millets has been shown to reduce the risk factors of cardiovascular diseases such as high blood pressure, high cholesterol, and oxidative stress [139]. The dietary fiber, phytosterols, and polyphenols in millets are the main components responsible for their cardioprotective properties [140]. Millets are rich in antioxidants and can help in the prevention of several types of cancer [141]. The consumption of millets has been shown to reduce the risk of several types of cancer such as breast, colon, and liver cancer [142]. The polyphenols, flavonoids, and tannins in millets are the main components responsible for their anticancer properties [143].

Millets are rich in several nutrients that are essential for the growth and development of children [144]. The consumption of millets has been shown to improve the nutritional status, cognitive performance, and immune function of children [145]. The proteins, minerals, and vitamins in millets can contribute to the nutritional requirements of children and prevent the deficiencies associated with malnutrition [146].

5.4. Millet-based functional food products

The development of millet-based functional food products is gaining attention as a way to promote the consumption of millets and provide health benefits to the consumers [147]. Millet-based functional food products are formulated using millet grains, flours, or fractions as the main ingredients and are enriched with bioactive compounds or nutrients to provide specific health benefits [148].

Some examples of millet-based functional food products include:

1. **Millet-based probiotic beverages:** Fermented millet beverages containing probiotic bacteria such as Lactobacillus or Bifidobacterium can provide gut health benefits and improve the immune function [149].
2. **Millet-based gluten-free products:** Gluten-free products such as bread, pasta, or cookies made using millet flours can provide a nutritious and safe alternative for people with celiac disease or gluten intolerance [150].
3. **Millet-based fortified products:** Millet-based products fortified with essential nutrients such as iron, zinc, or vitamin A can help in the prevention of micronutrient deficiencies and improve the nutritional status of the population [151].
4. **Millet-based functional snacks:** Millet-based snacks such as energy bars, crackers, or chips enriched with bioactive compounds such as polyphenols or dietary fiber can provide health benefits and satisfy the consumer demand for healthy and convenient snacks [152].

The development of millet-based functional food products requires a multidisciplinary approach involving the collaboration of food scientists, nutritionists, and health professionals [153]. The functional properties of the millet ingredients should be characterized and optimized to ensure their stability, bioavailability, and efficacy in the food matrix [154]. The sensory and consumer acceptance of the millet-based functional food products should also be evaluated to ensure their market success and sustainability [155].

6. Challenges and Opportunities in Millet Processing and Value Addition

Despite the numerous benefits and potential of millets, there are several challenges that hinder the processing and value addition of millets in India. These challenges include technological, infrastructural, policy, and market-related issues that need to be addressed to promote the millet value chain [156]. This section discusses the main challenges and opportunities in millet processing and value addition in India.

6.1. Technological challenges and advancements

One of the main technological challenges in millet processing is the lack of suitable equipment and machinery for the primary and secondary processing of millets [157]. Most of the traditional millet processing methods are manual, time-consuming, and inefficient, resulting in low product quality and high losses [158]. The modern millet processing technologies are often expensive, energy-intensive, and not adapted to the local conditions and needs [159].

To address these challenges, there is a need for the development and adoption of appropriate and affordable millet processing technologies that are suitable for the small and medium-scale processors [160].

Some of the recent technological advancements in millet processing include:

1. Development of low-cost and energy-efficient millet dehullers and mills that can improve the efficiency and quality of millet flour production [161].
2. Optimization of the millet malting and fermentation processes using starter cultures and controlled conditions to enhance the nutritional and sensory properties of the millet products [162].
3. Application of extrusion technology for the development of novel millet-based snacks and ready-to-eat products with improved texture and shelf life [163].
4. Use of infrared and microwave heating for the roasting and drying of millets to reduce the processing time and energy consumption [164].

6.2. Infrastructure and supply chain issues

Another major challenge in millet processing and value addition is the lack of adequate infrastructure and supply chain facilities for the storage, transport, and marketing of millets [165]. Millets are often grown in marginal and rainfed areas with poor connectivity and limited access to markets [166]. The lack of proper storage facilities and packaging materials results in high postharvest losses and quality deterioration of millets [167].

To address these challenges, there is a need for the development and strengthening of the millet supply chain infrastructure, including:

1. Establishment of modern storage facilities with controlled temperature and humidity conditions to reduce the postharvest losses and maintain the quality of millets [168].
2. Improvement of the transportation and logistics facilities for the timely and efficient delivery of millets from the farms to the processing centers and markets [169].
3. Development of innovative packaging solutions such as modified atmosphere packaging or active packaging to extend the shelf life and maintain the quality of millet products [170].
4. Creation of farmer producer organizations and cooperatives to enhance the bargaining power and market access of the millet farmers [171].

6.3. Policy support and government initiatives

The policy support and government initiatives play a crucial role in promoting the millet processing and value addition in India. In recent years, the government of India has launched several programs and schemes to support the millet sector, such as:

1. National Food Security Mission (NFSM) - Coarse Cereals: A centrally sponsored scheme to increase the production and productivity of millets through the adoption of improved technologies and practices [172].
2. Initiative for Nutritional Security through Intensive Millets Promotion (INSIMP): A subscheme under Rashtriya Krishi Vikas Yojana (RKVY) to promote the cultivation and consumption of millets through the distribution of seed kits, demonstrations, and training [173].
3. Millet Mission: A state-level program launched by several states such as Odisha, Karnataka, and Andhra Pradesh to promote the production, processing, and marketing of millets [174].
4. Inclusion of millets under the Public Distribution System (PDS): A recent initiative by the government to include millets in the PDS to improve the nutritional security and dietary diversity of the population [175].

However, there is a need for more comprehensive and targeted policy interventions to support the millet processing and value addition, such as:

1. Establishment of millet processing parks and incubation centers to provide the necessary infrastructure, technology, and training support to the millet processors [176].
2. Provision of financial incentives and subsidies for the modernization and upgradation of the millet processing units [177].
3. Inclusion of millets in the school feeding programs and government nutrition schemes to create a stable demand for millet products [178].
4. Strengthening of the research and development activities on millets to develop new varieties, technologies, and products [179].

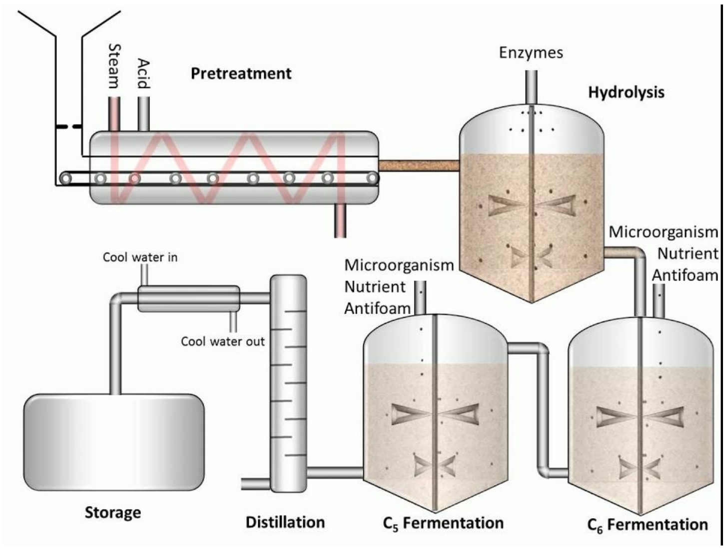
6.4. Market linkages and consumer awareness

One of the key challenges in millet processing and value addition is the lack of market linkages and consumer awareness about millets [180]. Millets are often perceived as inferior or poor man's food and have limited demand and market value compared to other cereals [181]. The lack of market information and linkages hinders the access of millet processors to the potential buyers and consumers [182].

To address these challenges, there is a need for the development of market linkages and consumer awareness about millets, including:

1. Conducting market research and feasibility studies to identify the potential markets and consumer segments for millet products [183].
2. Developing branding and promotional strategies to create a positive image and awareness about millets among the consumers [184].
3. Establishing market linkages and partnerships with the food industry, retailers, and exporters to expand the market reach of millet products [185].
4. Organizing food festivals, trade fairs, and exhibitions to showcase the diversity and value of millet products [186].
5. Leveraging the social media and digital platforms to educate and engage the consumers about the nutritional and environmental benefits of millets [187].

Figure 6. Schematic representation of the millet fermentation process



7. Promoting Millet Processing and Value Addition

The promotion of millet processing and value addition requires a holistic and collaborative approach involving the participation of all the stakeholders in the millet value chain [188]. This section discusses some of the key strategies and initiatives for promoting the millet processing and value addition in India.

7.1. Research and development efforts

Research and development (R&D) plays a critical role in the promotion of millet processing and value addition by generating new knowledge, technologies, and products [189].

Some of the key areas of R&D in millets include:

1. Development of high-yielding and climate-resilient millet varieties with improved nutritional and processing qualities [190].
2. Optimization of the millet processing technologies and equipment for enhanced efficiency, quality, and safety [191].
3. Exploration of the functional and bioactive properties of millets and their application in the development of health foods and nutraceuticals [192].
4. Development of innovative millet-based products and formulations with improved sensory and nutritional attributes [193].
5. Evaluation of the environmental and socio-economic impact of millet cultivation and processing [194].

To strengthen the R&D efforts in millets, there is a need for the establishment of dedicated millet research centers and networks, funding support for millet research projects, and collaboration between the academic, industry, and government stakeholders [195].

7.2. Capacity building and skill development

Capacity building and skill development are essential for the promotion of millet processing and value addition by enhancing the knowledge, skills, and competencies of the millet farmers, processors, and entrepreneurs [196]. Some of the key areas of capacity building and skill development in millets include:

1. Training and demonstration of improved millet cultivation practices and technologies to the farmers [197].
2. Providing technical and entrepreneurial skills to the millet processors and entrepreneurs through vocational training and mentorship programs [198].
3. Developing training modules and curricula on millet processing and value addition for the academic and extension institutions [199].
4. Organizing exposure visits and study tours for the millet stakeholders to learn from the best practices and success stories [200].

To support the capacity building and skill development efforts in millets, there is a need for the allocation of resources and infrastructure for training and extension activities, partnerships with the skill development agencies and institutions, and recognition and incentivization of the millet champions and innovators [201].

7.3. Entrepreneurship and start-up ecosystem

Entrepreneurship and start-ups play a crucial role in the promotion of millet processing and value addition by bringing new ideas, innovations, and business models to the millet sector [202]. Some of the key areas of entrepreneurship and start-up development in millets include:

1. Identification and incubation of millet-based start-ups and enterprises through business plan competitions, hackathons, and accelerator programs [203].
2. Providing access to finance, technology, and mentorship support to the millet start-ups and entrepreneurs through incubation centers and venture capital funds [204].
3. Establishing networks and platforms for the millet start-ups and entrepreneurs to connect, collaborate, and learn from each other [205].
4. Creating an enabling policy and regulatory environment for the millet start-ups and enterprises through tax incentives, subsidies, and simplified procedures [206].

To foster the entrepreneurship and start-up ecosystem in millets, there is a need for the creation of millet innovation hubs and clusters, partnerships with the industry and investor stakeholders, and recognition and showcasing of the millet start-up success stories [207].

7.4. Branding and marketing strategies

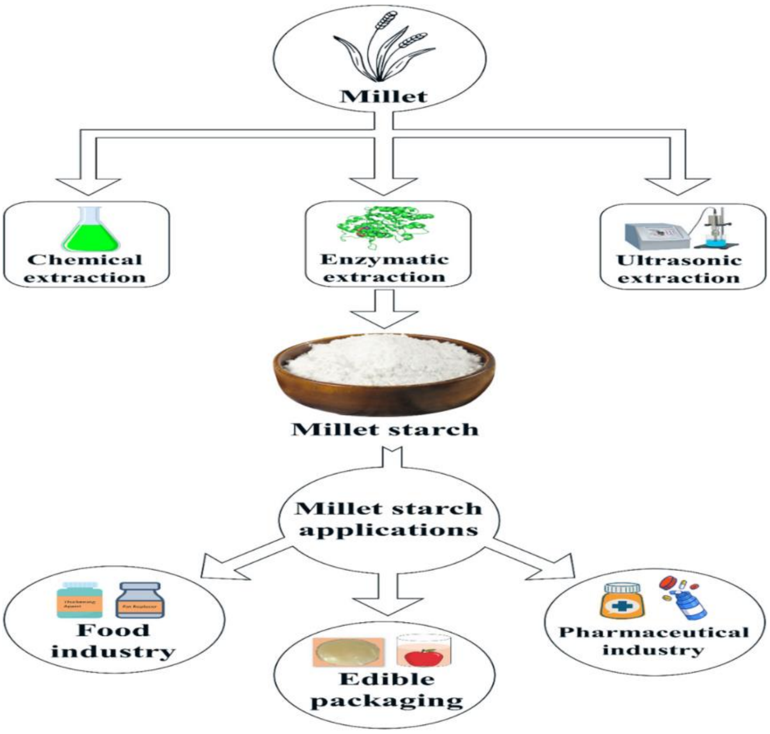
Branding and marketing are essential for the promotion of millet processing and value addition by creating consumer awareness, demand, and loyalty for the millet products [208]. Some of the key branding and marketing strategies for millets include:

1. Developing a unique and differentiated brand identity and positioning for the millet products based on their nutritional, environmental, and cultural values [209].
2. Creating attractive and informative packaging and labeling for the millet products that communicate their benefits and attributes to the consumers [210].
3. Conducting consumer research and segmentation to identify the target markets and preferences for the millet products [211].

4. Developing and implementing integrated marketing communication campaigns using various media and channels such as print, radio, television, digital, and social media [212].
5. Collaborating with the food service and retail industry to promote the use and availability of millet products in the restaurants, cafes, and supermarkets [213].

To support the branding and marketing efforts for millets, there is a need for the allocation of resources and expertise for market research and promotion, partnerships with the branding and advertising agencies, and creation of a common brand and quality standards for the millet products [214].

Figure 7. Extruded millet snacks: (a) Puffed millet, (b) Millet-based ready-to-eat cereals



8. Conclusion

Millets are nutrient-dense grains with immense potential for promoting food and nutritional security. India, being a major producer of millets, has a significant role in advancing millet processing and value addition techniques. This chapter has provided a comprehensive overview of the various primary and secondary processing methods, along with value addition strategies such as fortification, product development, and by-product utilization. The chapter has also highlighted the importance of millets as functional foods and their health benefits. Despite the challenges faced in the millet value chain, there are numerous opportunities for growth and development. Technological advancements, infrastructure development, policy support, and market linkages are crucial for promoting millet processing and value addition. Research and development, capacity building, entrepreneurship, and branding are key strategies for driving the growth of the millet sector.

Collaborative efforts among stakeholders, including researchers, policymakers, entrepreneurs, and consumers, are essential for harnessing the full potential of millets and creating a sustainable and resilient food system. By promoting millet processing and value addition, India can lead the way in the global millet revolution and contribute to the achievement of the Sustainable Development Goals.

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CHAPTER - 7

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Millet-based Food Products and Innovations

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Abstract

Millets are small-seeded cereal grains that have been cultivated for thousands of years, particularly in hot and arid regions of Asia and Africa. In 2023, the United Nations declared the International Year of Millets to raise awareness about the nutritional benefits and sustainability of these ancient grains. Millets are gluten-free, rich in dietary fiber, minerals, and phytochemicals, making them a valuable addition to a healthy diet. They also require less water and have a lower carbon footprint compared to other major cereals like wheat and rice. This chapter explores the diverse range of millet-based food products, including traditional preparations and innovative new applications. The nutritional composition and health benefits of different millet varieties are discussed, along with processing technologies and product development strategies to enhance the utilization of millets in modern diets. The chapter also highlights the socio-economic and environmental advantages of millet cultivation, especially for smallholder farmers in developing countries. Promoting the production and consumption of millets can contribute to food and nutrition security, climate resilience, and sustainable development goals.

Keywords: Millets, Gluten-free, Sustainability, Food innovation, Nutrition security

1. Introduction

Millets are a group of small-seeded grasses that belong to the Poaceae family, which includes several genera such as *Pennisetum*, *Eleusine*, *Panicum*, *Setaria*, *Paspalum*, and others [1]. These crops have been cultivated for food and fodder for over 7000 years in many parts of the world, especially in Asia and Africa [2]. Millets are known for their resilience to harsh growing conditions, such as poor soils, limited water availability, and high temperatures [3]. They also have a short growing season and require minimal inputs, making them well-suited for cultivation by smallholder farmers in semi-arid and arid regions [4].

Despite their long history and widespread cultivation, millets have been largely neglected in recent decades due to the dominance of a few major cereal crops like wheat, rice, and maize [5]. However, there is a growing recognition of the multiple benefits of millets, both for human health and environmental sustainability [6]. Millets are nutritionally superior to many other cereals, being rich in protein, dietary fiber, essential amino acids, vitamins, and minerals like iron, zinc, and calcium [7]. They also contain various bioactive compounds such as polyphenols, which have antioxidant and anti-inflammatory properties [8]. Moreover, millets are gluten-free, making them suitable for people with celiac disease or gluten intolerance [9]. In terms of environmental benefits, millets have a low water footprint and can grow under rainfed conditions, reducing the pressure on irrigated agriculture [10]. They also have a lower carbon footprint compared to other cereals due to their short duration and lower fertilizer requirements [11]. Millets can help in climate change adaptation by providing a more resilient and diversified cropping option, especially in marginal environments [12].

Recognizing the potential of millets to address various challenges related to food security, nutrition, and sustainable agriculture, the United Nations General Assembly declared 2023 as the International Year of Millets [13]. This initiative aims to increase global awareness about the nutritional and ecological benefits of millets, promote their production and consumption, and support policies and investments for their mainstreaming [14]. In this context, this chapter provides an overview of the diverse millet-based food products and recent innovations in millet processing and utilization.

2. Types of Millets and their Nutritional Composition

Millets comprise a diverse group of crops with varying morphological, agronomic, and nutritional characteristics. Some of the major types of millets include:

1. Pearl millet (*Pennisetum glaucum*)
2. Finger millet (*Eleusine coracana*)

3. Foxtail millet (*Setaria italica*)
4. Proso millet (*Panicum miliaceum*)
5. Barnyard millet (*Echinochloa spp.*)
6. Kodo millet (*Paspalum scrobiculatum*)
7. Little millet (*Panicum sumatrense*)

Table 1 shows the nutritional composition of different millet types in comparison with wheat and rice.

Nutrient (per 100g)	Pearl Millet	Finger Millet	Foxtail Millet	Proso Millet	Wheat	Rice
Energy (kcal)	361	328	331	341	346	345
Protein (g)	11.6	7.3	12.3	12.5	11.8	6.8
Fat (g)	5.0	1.3	4.3	3.5	1.5	0.5
Carbohydrate (g)	67.0	72.0	60.9	70.4	71.2	78.2
Dietary fiber (g)	11.3	11.5	8.0	8.5	12.2	1.3
Calcium (mg)	42	344	31	14	30	10
Iron (mg)	8.0	3.9	2.8	3.0	3.5	0.7
Zinc (mg)	3.1	2.3	2.4	1.7	2.7	1.1

Source: [15]

As evident from Table 1, millets are superior to wheat and rice in terms of protein, dietary fiber, and mineral content. For example, pearl millet and finger millet are rich sources of iron and zinc, while finger millet has the highest calcium content among cereals [16]. The high dietary fiber in millets is beneficial for gut health, blood sugar control, and reducing the risk of chronic diseases [17]. Millets also have a better amino acid profile compared to other cereals, with higher levels of essential amino acids like lysine and methionine [18].In addition to macro- and micronutrients, millets contain various phytochemicals like phenolic acids, flavonoids, and tannins, which have antioxidant and health-promoting effects [19]. For instance, finger millet has high levels of polyphenols and exhibits strong antioxidant activity [20]. Pearl millet is rich in goitrogenic polyphenols that may help in the prevention of goiter [21]. Foxtail millet contains compounds like setariol and viniferin, which have anti-inflammatory and anti-cancer properties [22].

3. Traditional Millet-based Food Products

Millets have been used in traditional food preparations for centuries in different parts of the world, particularly in Asia and Africa. Some examples of traditional millet-based foods include:

3.1 Porridges and Gruels

Millet porridges and gruels are common breakfast foods in many African countries. For example, *ogi* is a fermented maize or millet porridge consumed in Nigeria and other West African countries [23]. In India, *ragi kanji* is a finger millet porridge often given to infants and young children as a weaning food [24]. Millet porridges are easy to prepare, digestible, and nutritious.

3.2 Flatbreads and Pancakes

Millets are used in the preparation of various types of flatbreads and pancakes. *Roti* or *bhakri* is an unleavened flatbread made from pearl millet or finger millet flour, popular in western and southern India [25]. *Injera* is a fermented pancake-like flatbread made from teff (a type of millet) in Ethiopia and Eritrea [26]. Millet flatbreads have a slightly nutty flavor and chewy texture.

3.3 Snacks and Savory Foods

Millets are used as ingredients in traditional snacks and savory dishes. In India, *jhalmudi* is a spicy puffed rice snack that sometimes includes puffed millets [27]. *Dhokla* is a steamed savory cake made from fermented rice and split chickpeas, occasionally incorporating millet flour [28]. In Nigeria, *fura* is a millet-based dough that is steamed, spiced, and served with yogurt [29].

3.4 Beverages

Millets are used in the preparation of traditional beverages like beer and porridge drinks. In many African countries, opaque beer is brewed from malted millets, sometimes mixed with sorghum or maize [30]. *Boza* is a fermented millet drink popular in Balkan and Turkic countries [31]. *Ambali* is a thin porridge beverage made from fermented millet or sorghum in Nigeria and other parts of West Africa [32].

Table 2 summarizes some of the traditional millet-based food products from different regions.

Product	Type of Millet	Region/Country
Ogi	Maize, millet	West Africa
Ragi kanji	Finger millet	India
Roti/Bhakri	Pearl, finger millet	India

Injera	Teff	Ethiopia, Eritrea
Jhalmudi	Puffed millets	India
Dhokla	Millet flour	India
Fura	Pearl millet	Nigeria
Opaque beer	Malted millets	Africa
Boza	Millet, other cereals	Balkans, Turkey
Ambali	Millet, sorghum	West Africa

Source: [33]

4. Millet Processing Technologies

The utilization of millets in modern food products requires appropriate processing technologies to improve their shelf life, nutritional value, and sensory attributes. Some of the common millet processing methods include:

4.1 Milling

Milling is the process of removing the outer layers of the millet grain (bran and germ) to obtain the endosperm fraction, which is then ground into flour [34]. Traditional milling methods involve hand pounding or stone grinding, which are laborious and time-consuming. Modern milling techniques use mechanical mills like hammer mills, disc mills, or roller mills to achieve higher efficiency and output [35]. However, excessive milling can lead to nutrient losses, particularly in the bran and germ fractions [36].

4.2 Malting

Malting involves the controlled germination of millet grains to activate enzymes like amylases and proteases, which break down complex carbohydrates and proteins into simpler forms [37]. Malted millets have improved digestibility, flavor, and functional properties, and are used in the production of beverages, weaning foods, and baked products [38]. The malting process typically involves steeping, germination, and drying steps, with variations in time, temperature, and moisture conditions depending on the type of millet and desired product characteristics [39].

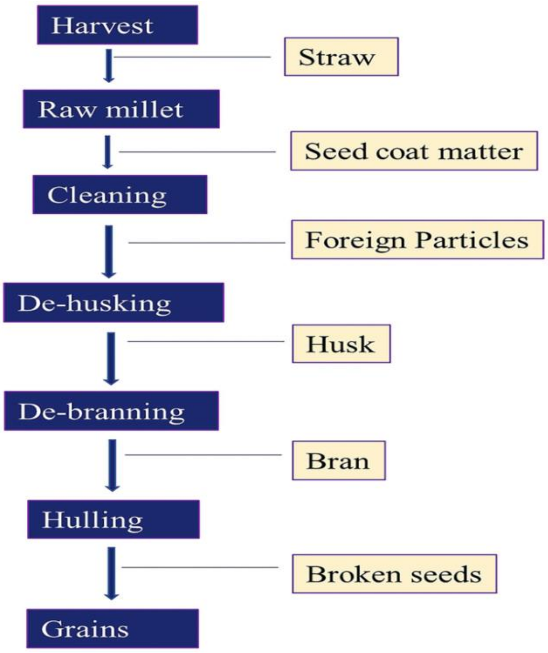
4.3 Fermentation

Fermentation is a traditional processing method that involves the use of microorganisms to transform the chemical composition of millet grains or flour [40]. Lactic acid bacteria and yeast are the most common microbes involved in millet fermentation, which can be natural or controlled using starter cultures [41]. Fermentation improves the nutritional value of millets by increasing the bioavailability of minerals, enhancing the digestibility of proteins, and reducing anti-nutritional factors like phytates and tannins [42]. Fermented millet products also have unique flavors and textures, and longer shelf life due to the inhibition of spoilage microorganisms [43].

4.4 Extrusion

Extrusion is a high-temperature, short-time processing technique that involves the cooking, shaping, and expansion of millet-based dough using a extruder machine [44]. Extrusion can be used to produce a variety of millet-based products like snacks, breakfast cereals, pasta, and meat analogues [45]. The extrusion process improves the digestibility and sensory properties of millets, while also reducing anti-nutritional factors [46]. However, extrusion may lead to some nutrient losses due to the high heat and shear forces involved [47].

Figure 1 Millet processing technologies and their applications in food product development.



5. Millet-based Food Product Innovations

In recent years, there has been a growing interest in developing innovative millet-based food products to cater to the changing consumer preferences for healthy, convenient, and tasty foods. Some examples of millet-based product innovations include:

5.1 Millet-based Baked Products

Millet flour can be used as a partial or complete substitute for wheat flour in various baked products like bread, cookies, cakes, and muffins [48]. The incorporation of millet flour improves the nutritional profile of these products by increasing the fiber, protein, and mineral content [49]. However, the absence of gluten in millets can affect the dough rheology and baking quality, requiring the use of additives like hydrocolloids or protein isolates [50]. Table 3 shows the effect of different levels of millet flour incorporation on the quality parameters of bread.

Parameter	**Control**	**25% Millet Flour**	**50% Millet Flour**	**75% Millet Flour**
Loaf volume (cm^3^)	850	780	710	630
Firmness (N)	3.5	4.2	5.1	6.3
Crumb color (L*)	75.2	71.4	68.1	64.3
Sensory acceptability (1-9)	8.2	7.8	7.2	6.5

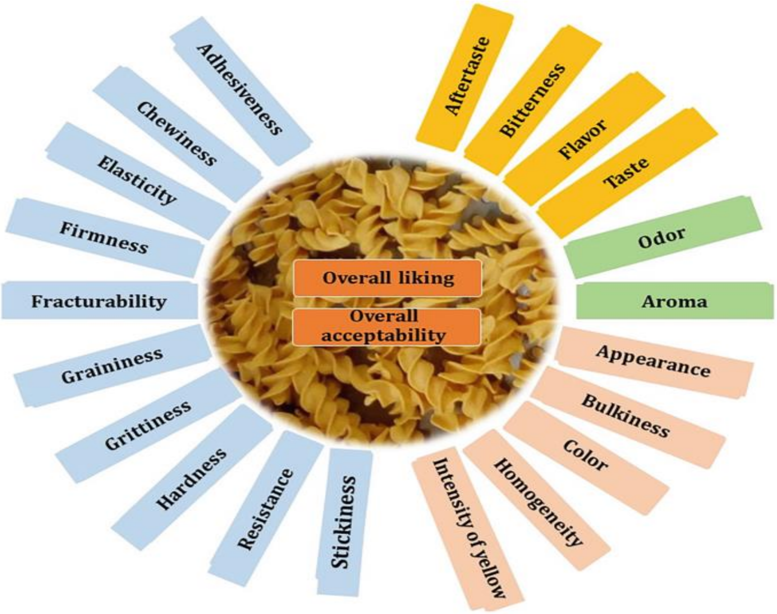
Source: [51]

As evident from Table 3, increasing the level of millet flour leads to a decrease in loaf volume, increase in crumb firmness, darker crumb color, and lower sensory acceptability compared to the control wheat bread. However, millet-based breads still have acceptable quality attributes at lower levels of incorporation (25-50%).

5.2 Millet-based Pasta and Noodles

Millet flour can be used to produce gluten-free pasta and noodles as an alternative to wheat-based products [52]. Millet pasta has higher protein, fiber, and mineral content compared to traditional durum wheat pasta [53]. The cooking quality and texture of millet pasta can be improved by using suitable processing techniques like extrusion or by incorporating additives like egg proteins or gums [54].

Figure 2 shows the sensory evaluation scores of millet-based pasta in comparison with durum wheat pasta.



Source: [55]

The sensory scores indicate that millet pasta has comparable acceptability to durum wheat pasta in terms of appearance, flavor, and overall quality, although the texture scores are slightly lower.

5.3 Millet-based Snacks and Breakfast Cereals

Millets can be used as ingredients in a range of snack foods and breakfast cereals, providing healthier and more nutritious options compared to refined cereal-based products. Some examples include millet puffs, flakes, cookies, crackers, and energy bars [56]. Millet-based snacks can be flavored with various spices, herbs, or sweeteners to enhance their sensory appeal [57]. Table 4 compares the nutritional composition of millet-based and corn-based extruded snacks.

Nutrient (per 100g)	Millet Snack	Corn Snack
Energy (kcal)	387	567
Protein (g)	12.1	6.5
Fat (g)	3.2	35.7
Carbohydrate (g)	76.4	52.3
Dietary fiber (g)	7.5	1.8
Iron (mg)	3.6	1.2

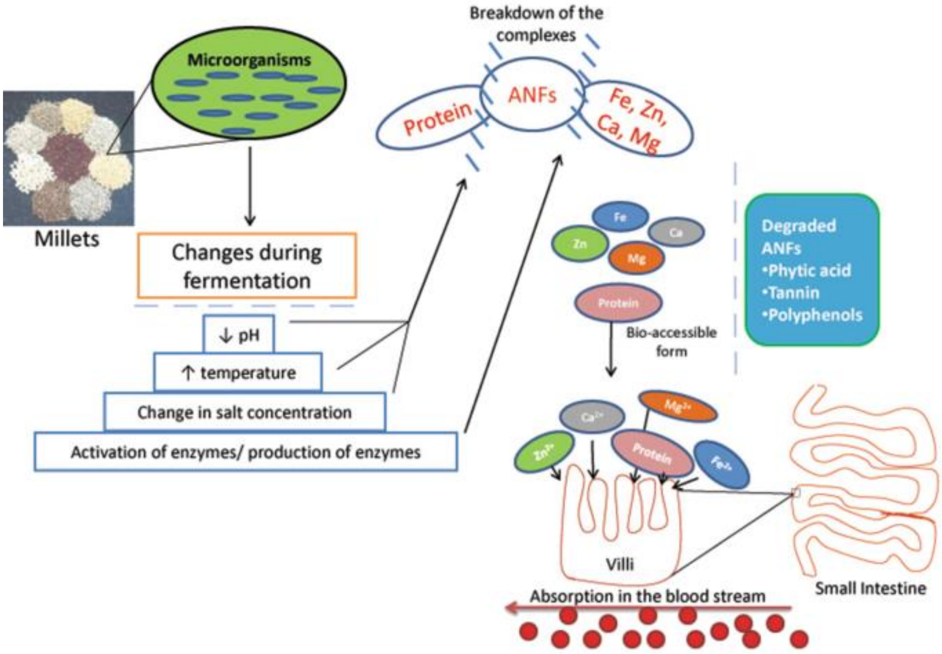
Source: [58]

The millet-based snack has lower energy density, fat content, and higher protein, fiber, and iron content compared to the corn-based snack, indicating its nutritional advantages.

5.4 Millet-based Beverages

Millet grains can be used to produce a variety of non-dairy probiotic beverages by fermenting with lactic acid bacteria or yeasts [59]. These beverages have enhanced nutritional and functional properties due to the synthesis of bioactive compounds like vitamins, exopolysaccharides, and antimicrobial peptides during fermentation [60]. Millet-based probiotic beverages can be flavored with fruits, spices, or herbs to improve their sensory attributes [61].

Figure 3 shows the microbial growth and pH changes during the fermentation of a pearl millet-based probiotic beverage.



Source: [62]

The fermentation process leads to an increase in the population of lactic acid bacteria and a decrease in pH, indicating the successful production of a millet-based probiotic beverage.

5.5 Millet-based Composite Flours

Millet flours can be combined with other nutrient-dense ingredients like legume flours, oilseed meals, or vegetable powders to produce composite flours with enhanced nutritional and functional properties [63]. These composite flours can be used in the formulation of various food products like bread, cookies, pasta, snacks, and weaning foods [64]. Table 5 shows the nutritional composition of a millet-based composite flour containing finger millet, soybean, and carrot powder.

Ingredient	Proportion (%)	Protein (%)	Fat (%)	Fiber (%)	Iron (mg/100g)	Calcium (mg/100g)
Finger millet flour	60	7.6	1.5	11.8	4.2	364
Soybean flour	30	43.3	20.6	6.0	10.4	240
Carrot powder	10	8.1	1.8	28.6	5.8	341
Composite flour	100	19.1	7.6	12.1	6.1	323

Source: [65]

The millet-based composite flour has a balanced nutritional profile with high protein, fiber, iron, and calcium contents, making it suitable for use in various food applications.

6. Challenges and Future Prospects

Despite the various advantages and opportunities for millet-based food products, there are also some challenges that need to be addressed for their wider adoption and utilization. Some of these challenges include:

- Limited awareness and acceptance of millets among consumers, especially in urban and developed markets
- Inadequate post-harvest processing and value addition technologies for millets
- Lack of quality standards and regulatory frameworks for millet-based products
- Poor market linkages and supply chain infrastructure for millets
- Competition with other established and subsidized cereal grains like wheat and rice

To overcome these challenges and promote the production and consumption of millets, some future strategies and research priorities include:

- Conducting consumer awareness and education campaigns about the nutritional and environmental benefits of millets

- Developing and disseminating improved millet varieties with higher yield, resistance to biotic and abiotic stresses, and better processing qualities
- Establishing quality standards and certification schemes for millet grains and products
- Investing in research and development of novel millet-based food products and processing technologies
- Promoting policies and incentives to support millet producers and processors, especially smallholder farmers and rural entrepreneurs
- Strengthening market linkages and value chains for millets through public-private partnerships and collective action

7. Conclusion

Millets are nutrient-dense and climate-resilient crops with immense potential to contribute to food and nutrition security, sustainable agriculture, and rural livelihoods. The International Year of Millets 2023 provides an opportunity to showcase the diversity and benefits of millets, and to promote their production, consumption, and trade. This chapter has highlighted the nutritional composition of different millet types, the traditional and innovative millet-based food products, and the processing technologies involved in their development. It has also discussed the challenges and future prospects for the millet sector, emphasizing the need for concerted efforts from all stakeholders to mainstream millets in the food systems. By harnessing the untapped potential of millets, we can work towards a more healthy, sustainable, and equitable future for all.

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CHAPTER - 8

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Fostering Millet Consumption: Strategies for Behavioral Change

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Abstract

Millets, a group of small-seeded grasses, have been cultivated for thousands of years and serve as a staple food for millions worldwide, particularly in semi-arid tropical regions of Asia and Africa. Despite their nutritional benefits, climate resilience, and potential to support sustainable agriculture, millet consumption has declined in recent decades due to changing dietary preferences, urbanization, and policy neglect. The United Nations General Assembly declared 2023 the International Year of Millets to raise awareness, increase production, and encourage global consumption of these ancient grains. This chapter explores strategies for fostering millet consumption through behavioral change interventions. Drawing upon the Transtheoretical Model and other behavioral theories, we propose a framework for understanding the stages and processes of change involved in adopting millets into diets. Key strategies include enhancing knowledge and awareness, modifying attitudes and beliefs, developing culinary skills, ensuring availability and affordability, and creating supportive social and policy environments. We review successful behavioral change interventions from various contexts and discuss their application to promoting millet consumption. The chapter also examines the role of diverse stakeholders, including policymakers, researchers, educators, health professionals, food industries, and civil society organizations, in driving behavioral change at individual, community, and societal levels. Finally, we highlight the significance of cultural adaptation, participatory approaches, and multi-sectoral collaboration in designing and implementing effective interventions. Fostering millet consumption requires a concerted effort to shift behaviors, practices, and policies. By applying insights from behavioral sciences and leveraging the momentum of the International Year of Millets, we can revitalize these ancient grains and advance public health and sustainable development goals.

Keywords: Millets, Behavioral Change, Dietary Diversity, Nutrition Transition, Sustainable Diets

1. Introduction

Millets are a diverse group of small-seeded grasses that have been cultivated for thousands of years across the globe, particularly in semi-arid and arid regions of Asia and Africa [1]. These ancient grains are known for their resilience to harsh environmental conditions, drought tolerance, and ability to grow in poor soils [2]. Millets have played a crucial role in ensuring food and nutritional security for millions of people, especially in developing countries [3]. However, despite their numerous benefits, millet consumption has declined in recent decades due to various factors, including changing dietary preferences, urbanization, and policy neglect [4].

The United Nations General Assembly has declared 2023 as the International Year of Millets, recognizing the potential of these crops to address global challenges such as malnutrition, climate change, and sustainable agriculture [5]. This initiative aims to raise awareness about the nutritional and ecological benefits of millets, promote their production and consumption, and foster collaborative efforts among diverse stakeholders [6]. In this context, understanding and addressing the barriers to millet consumption becomes crucial for revitalizing these ancient grains and harnessing their potential for sustainable development.

This chapter explores strategies for fostering millet consumption through behavioral change interventions. We begin by discussing the nutritional profile and health benefits of millets, highlighting their potential to address various public health challenges. Next, we examine the trends and barriers in millet consumption, focusing on the causes and consequences of the decline in their cultivation and consumption. We then introduce behavioral change theories and models that provide a framework for understanding the stages and processes involved in adopting new dietary practices. The core of the chapter focuses on strategies for fostering millet consumption across different levels of influence, from individual to societal. Furthermore, we emphasize the importance of stakeholder collaboration in driving behavioral change and promoting millet consumption. The roles and responsibilities of diverse actors, including policymakers, researchers, educators, health professionals, food industries, and civil society organizations, are discussed in detail. We also highlight the challenges and opportunities associated with fostering millet consumption, such as cultural acceptability, scalability, and sustainability.

2. Millets: Nutritional Profile and Health Benefits

Millets are a group of small-seeded grasses that belong to the family Poaceae and are known for their nutrient-dense grains [7]. There are several species of millets, including pearl millet (*Pennisetum glaucum*), finger millet (*Eleusine coracana*), foxtail millet (*Setaria italica*), proso millet (*Panicum miliaceum*), barnyard millet (*Echinochloa colona*), little millet (*Panicum sumatrense*), and kodo millet (*Paspalum scrobiculatum*) [8]. These diverse species offer a range of nutritional benefits and have the potential to address various health challenges.

2.1. Macronutrient Composition Millets are rich sources of macronutrients, including carbohydrates, proteins, and lipids. The carbohydrate content of millets ranges from 60-70%, with a significant proportion of slowly digestible starch and resistant starch, which contribute to their low glycemic index [9]. Millets also contain high-quality proteins, with a well-balanced amino acid profile, making them suitable for vegetarian and vegan diets [10]. The lipid content of millets is relatively low (1.5-5%), with a higher proportion of unsaturated fatty acids compared to saturated fatty acids [11].

2.2. Micronutrient Density

Millets are excellent sources of essential micronutrients, including vitamins and minerals. They are particularly rich in B-vitamins, such as thiamin, riboflavin, niacin, and folic acid, which play crucial roles in energy metabolism, nervous system function, and cell growth [12]. Millets also contain significant amounts of minerals, including iron, zinc, calcium, phosphorus, and magnesium [13]. For example, finger millet has the highest calcium content among all cereals, making it beneficial for bone health [14].

2.3. Bioactive Compounds and Phytochemicals In addition to macronutrients and micronutrients, millets contain a range of bioactive compounds and phytochemicals that contribute to their health-promoting properties. These include phenolic compounds, flavonoids, tannins, and phytic acid [15]. These bioactive compounds have antioxidant, anti-inflammatory, and anticarcinogenic effects, which may help in preventing and managing chronic diseases such as cardiovascular disorders, diabetes, and certain cancers [16].

2.4. Glycemic Index and Chronic Disease Prevention One of the unique features of millets is their low glycemic index (GI), which is attributed to their high content of slowly digestible starch and resistant starch [17]. Low GI foods are known to regulate blood sugar levels, reduce insulin resistance, and improve glucose tolerance [18]. Consequently, regular consumption of millets may help in preventing and managing type 2 diabetes and its associated complications [19]. Moreover, the high fiber content of millets promotes satiety, aids in weight management, and supports digestive health [20].

Table 1: Nutrient Composition of Major Millet Species (per 100g)

Millet Species	Energy (kcal)	Protein (g)	Fat (g)	Carbohydrate (g)	Fiber (g)	Iron (mg)	Calcium (mg)
Pearl Millet	363	11.6	4.8	67.5	11.3	8.0	42
Finger Millet	336	7.3	1.3	72.6	11.5	3.9	350
Foxtail Millet	351	12.3	4.3	60.9	8.0	2.8	31
Proso Millet	354	11.0	3.5	70.4	7.7	3.0	14
Barnyard Millet	300	6.2	2.2	65.5	9.8	5.0	20

The numerous nutritional benefits and health-promoting properties of millets make them an ideal food choice for combating malnutrition, preventing chronic diseases, and promoting overall well-being. Incorporating millets into daily diets can contribute to improved nutrition, dietary diversity, and sustainable food systems.

3. Millet Consumption Trends and Barriers

3.1. Historical and Cultural Significance

Millets have been a staple food for thousands of years, particularly in semi-arid and arid regions of Asia and Africa [21]. These ancient grains have been an integral part of traditional farming systems, providing food security and sustaining rural livelihoods [22]. In many cultures, millets are deeply embedded in local cuisines, rituals, and social customs [23]. For example, in India, millets such as pearl millet (*bajra*) and finger millet (*ragi*) are used in traditional preparations like *roti*, *bhakri*, and *mudde* [24]. Similarly, in African countries, millets are used to make porridges, beverages, and snacks [25].

Table 2: Health Benefits of Millet Consumption

Health Benefit	**Description**
Glycemic Control	Low glycemic index helps regulate blood sugar levels and prevent type 2 diabetes
Cardiovascular Health	High fiber and antioxidants reduce cholesterol levels and prevent heart diseases
Digestive Health	Fiber content promotes regular bowel movements and prevents constipation
Weight Management	High satiety and low calorie density aid in weight control and prevent obesity
Antioxidant Protection	Bioactive compounds scavenge free radicals and protect against oxidative stress and inflammation
Micronutrient Adequacy	Rich in essential vitamins and minerals, particularly iron, calcium, and B-vitamins
Gluten-Free Alternative	Suitable for individuals with celiac disease or gluten sensitivity
Cancer Prevention	Phytochemicals exhibit anticarcinogenic properties and may help prevent certain cancers
Bone Health	High calcium content, especially in finger millet, supports bone mineralization and prevents osteoporosis
Sustainable and Climate-Resilient	Millets require less water, grow in poor soils, and are resilient to climate change

3.2. Decline in Consumption: Causes and Consequences Despite their historical and cultural significance, millet consumption has witnessed a significant decline in recent decades [26]. Several factors have contributed to this trend, including changing dietary preferences, urbanization, and policy neglect [27].

3.2.1. Changing Dietary Preferences With increasing globalization and urbanization, there has been a shift in dietary preferences towards refined grains, such as rice and wheat, and processed foods [28]. The perception of millets as "poor man's food" or "bird feed" has further contributed to their declining popularity [29]. Moreover, the convenience and ease of cooking associated with refined grains have made them more appealing to urban consumers [30].

3.2.2. Urbanization and Convenience Foods Rapid urbanization has led to changes in lifestyle and food choices, with a growing demand for convenience foods and ready-to-eat products [31]. Millets, which often require more time and effort in processing and preparation, have been gradually replaced by easily accessible and quickly prepared refined grain products [32]. The lack of millet-based convenience foods in the market has also contributed to their declining consumption [33].

Table 3: Barriers to Millet Consumption and Potential Solutions

Barrier	**Potential Solution**
Changing Dietary Preferences	- Awareness campaigns highlighting the nutritional benefits of millets
	- Promoting millets as a healthy and trendy food choice
Urbanization and Convenience	- Developing millet-based convenience foods and ready-to-eat products
	- Improving the processing and packaging of millets for urban markets
Policy Neglect and Lack of Support	- Advocating for policy support and incentives for millet production and processing
	- Investing in research and development for millet value chain development
Limited Availability and Accessibility	- Strengthening local food systems and improving distribution channels for millets
	- Promoting the cultivation of millets among smallholder farmers
Perception as "Poor Man's Food"	- Rebranding millets as nutrient-dense and climate-smart foods
	- Collaborating with celebrity chefs and influencers to showcase millet-based recipes
Lack of Knowledge and Skills	- Conducting cooking demonstrations and workshops on millet preparation
	- Disseminating recipes and culinary tips through media and extension services

3.2.3. Policy Neglect and Lack of Support Millets have often been neglected in agricultural policies and research priorities, with a greater focus on major cereal crops like rice, wheat, and maize [34]. The lack of policy support, subsidies, and incentives for millet production and processing has discouraged farmers from cultivating these crops [35]. Moreover, the absence of adequate marketing and value chain development for millets has limited their availability and accessibility to consumers [36].

3.3. Current Status of Millet Consumption Despite the overall decline in millet consumption, there has been a growing recognition of their nutritional and ecological benefits in recent years [37]. Efforts are being made to revive and promote millet cultivation and consumption through various initiatives and campaigns [38]. The Indian government, for example, has launched the "Nutri-Cereals" mission to promote the production, processing, and consumption of millets [39]. Similarly, in African countries, there are initiatives to integrate millets into school feeding programs and nutrition interventions [40].

4. Behavioral Change Theories and Models Fostering millet consumption requires an understanding of the factors that influence dietary behaviors and the processes involved in adopting new food choices. Behavioral change theories and models provide a framework for designing and implementing interventions that aim to modify individual and collective behaviors [41]. In this section, we discuss four key theories and models that can inform strategies for promoting millet consumption.

4.1. Transtheoretical Model (Stages of Change) The Transtheoretical Model, also known as the Stages of Change model, describes the process of behavioral change as a series of five stages: precontemplation, contemplation, preparation, action, and maintenance [42]. This model recognizes that individuals may be at different stages of readiness to adopt a new behavior and that interventions should be tailored accordingly [43]. For example, individuals in the precontemplation stage may benefit from awareness-raising activities, while those in the preparation stage may require skill-building and resource provision [44].

4.2. Health Belief Model The Health Belief Model suggests that an individual's likelihood of engaging in a health-related behavior is influenced by their perceptions of the severity and susceptibility to a health threat, the benefits and barriers to taking action, and the cues to action [45].

This model highlights the importance of addressing perceived barriers and emphasizing the benefits of adopting a new behavior [46]. In the context of millet consumption, interventions should focus on communicating the health benefits of millets, addressing perceived barriers such as taste and convenience, and providing cues to action through social marketing and environmental prompts [47].

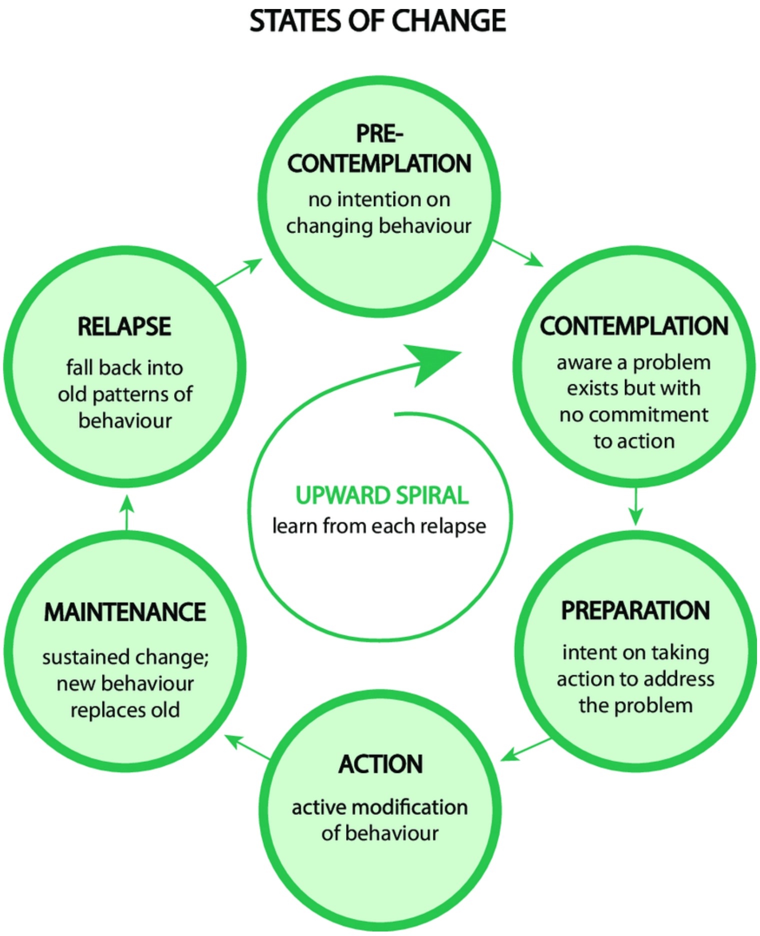
4.3. Theory of Planned Behavior The Theory of Planned Behavior posits that an individual's intention to perform a behavior is determined by their attitude toward the behavior, subjective norms, and perceived behavioral control [48].

Attitude refers to the individual's positive or negative evaluation of the behavior, subjective norms refer to the perceived social pressure to perform the behavior, and perceived behavioral control refers to the individual's belief in their ability to perform the behavior [49].

Interventions based on this theory should aim to create positive attitudes towards millet consumption, foster supportive social norms, and enhance individuals' self-efficacy in preparing and consuming millet-based foods [50].

4.4. Social Cognitive Theory Social Cognitive Theory emphasizes the reciprocal interactions between personal factors, environmental influences, and behavior [51]. This theory highlights the role of observational learning, self-efficacy, and outcome expectations in shaping behavior [52]. Interventions based on this theory should focus on providing role models and peer support for millet consumption, creating enabling environments that facilitate access to millet-based foods, and enhancing individuals' confidence in their ability to incorporate millets into their diets [53].

Figure 1: Transtheoretical Model Applied to Millet Consumption Behavior Change



Understanding and applying these behavioral change theories and models can inform the development of effective interventions to foster millet consumption. A multi-theory approach that draws upon the strengths of different models can provide a comprehensive framework for designing behavior change strategies [54].

5. Strategies for Fostering Millet Consumption Fostering millet consumption requires a multi-faceted approach that addresses individual, social, and environmental factors influencing dietary behaviors. In this section, we discuss five key strategies for promoting millet consumption: enhancing knowledge and awareness, modifying attitudes and beliefs, developing culinary skills and practices, ensuring availability and accessibility, and creating supportive environments.

5.1. Enhancing Knowledge and Awareness Enhancing knowledge and awareness about the nutritional benefits, cultural significance, and ecological advantages of millets is crucial for driving behavioral change [55].

This can be achieved through various channels, including nutrition education programs, mass media campaigns, and social marketing strategies.

5.1.1. Nutrition Education Programs Nutrition education programs can be conducted in schools, community centers, and healthcare settings to inform individuals about the health benefits of millets and how to incorporate them into daily diets [56].

These programs should be culturally sensitive, age-appropriate, and tailored to the needs and preferences of the target audience [57]. For example, school-based nutrition education can include millet-based recipes in home economics classes and promote the consumption of millet-based snacks in school canteens [58].

5.1.2. Mass Media Campaigns Mass media campaigns, including television, radio, and print media, can be used to raise awareness about millets and their benefits on a larger scale [59]. These campaigns should feature compelling messages, visuals, and narratives that resonate with the target audience and motivate them to adopt millet consumption [60]. Celebrity endorsements, testimonials from local champions, and catchy slogans can be used to capture attention and create a buzz around millets [61].

5.1.3. Social Marketing Strategies Social marketing strategies involve the application of commercial marketing principles to promote social goods and influence behavioral change [62]. In the context of millet promotion, social marketing can be used to create a brand identity for millets, position them as a desirable and aspirational food choice, and target specific segments of the population [63]. Social media platforms, influencer marketing, and community events can be leveraged to create engaging content and foster a sense of community around millet consumption [64].

5.2. Modifying Attitudes and Beliefs Modifying attitudes and beliefs about millets is essential for overcoming barriers to their consumption and creating a positive perception of these ancient grains [65]. This can be achieved by addressing misperceptions and myths, highlighting cultural and traditional values, and emphasizing the health and environmental benefits of millets.

5.2.1. Addressing Misperceptions and Myths There are several misperceptions and myths surrounding millets, such as their association with poverty, poor taste, and difficult preparation [66]. These misperceptions can be addressed through educational campaigns that provide accurate information about the nutritional value, versatility, and ease of cooking millets [67]. Engaging with local media, opinion leaders, and influencers can help in dispelling myths and creating a positive narrative around millets [68].

5.2.2. Highlighting Cultural and Traditional Values Millets have a rich cultural and traditional heritage in many communities, particularly in Asia and Africa [69]. Highlighting the cultural significance of millets and their role in traditional cuisines can help in fostering a sense of pride and identity associated with their consumption [70]. Organizing cultural events, food festivals, and heritage exhibitions that showcase millet-based dishes and traditions can be an effective way to celebrate and promote these ancient grains [71].

5.2.3. Emphasizing Health and Environmental Benefits Emphasizing the health and environmental benefits of millets can appeal to consumers who are increasingly conscious of the impact of their food choices on personal well-being and planetary health [72]. Communicating the nutritional profile of millets, their potential to prevent chronic diseases, and their ecological advantages such as climate resilience and low water footprint can create a compelling case for their consumption [73]. Partnering with health professionals, environmental organizations, and sustainable food advocates can lend credibility to these messages and amplify their reach [74].

5.3. Developing Culinary Skills and Practices Developing culinary skills and practices related to millets is crucial for enabling individuals to incorporate these grains into their daily diets [75]. This can be achieved through cooking demonstrations, recipe development, and the promotion of convenient and affordable millet products.

5.3.1. Cooking Demonstrations and Workshops Conducting cooking demonstrations and workshops can help individuals learn how to prepare millet-based dishes and overcome perceived barriers related to taste and convenience [76]. These sessions should be hands-on, engaging, and tailored to the local culinary context [77]. Collaborating with local chefs, culinary schools, and community organizations can help in reaching diverse audiences and promoting the versatility of millets in cooking [78].

5.3.2. Recipe Development and Adaptation Developing new recipes and adapting traditional recipes to incorporate millets can help in creating a diverse range of millet-based dishes that cater to different taste preferences and cooking styles [79]. Engaging with food bloggers, recipe developers, and cookbook authors can help in creating and disseminating millet-based recipes through various media channels [80]. Encouraging user-generated content, such as recipe contests and social media challenges, can foster creativity and ownership in millet cooking [81].

Table 4: Strategies for Fostering Millet Consumption Across Stages of Change

Stage of Change	Strategies
Precontemplation	- Raising awareness about the benefits of millets through mass media campaigns
	- Providing information about the nutritional value and cultural significance of millets
Contemplation	- Addressing perceived barriers and myths about millets
	- Highlighting the health and environmental benefits of millet consumption
Preparation	- Providing cooking demonstrations and recipes for millet-based dishes
	- Ensuring the availability and affordability of millet products in markets
Action	- Offering incentives and rewards for millet consumption
	- Creating supportive environments for millet consumption in schools and workplaces
Maintenance	- Providing ongoing support and resources for sustained millet consumption
	- Celebrating success stories and showcasing the impact of millet consumption on health and well-being

5.3.3. Promoting Convenient and Affordable Millet Products Promoting convenient and affordable millet products, such as ready-to-eat snacks, breakfast cereals, and baking mixes, can help in overcoming barriers related to time and effort in preparing millet-based dishes [82]. Collaborating with food manufacturers, retailers, and entrepreneurs to develop and market millet-based products can increase their availability and accessibility in the market [83]. Providing subsidies, tax incentives, and support for small-scale millet processing units can help in creating a conducive environment for the growth of the millet industry [84].

5.4. Ensuring Availability and Accessibility Ensuring the availability and accessibility of millets and millet-based products is essential for fostering their consumption [85]. This can be achieved by strengthening local food systems, improving distribution channels, and enhancing market linkages and value chains.

5.4.1. Strengthening Local Food Systems Strengthening local food systems can help in increasing the production, processing, and distribution of millets at the community level [86]. This can involve supporting smallholder farmers to cultivate millets, establishing community seed banks, and promoting local processing and value addition [87]. Encouraging the formation of farmer collectives, cooperatives, and self-help groups can enable better access to inputs, credit, and markets for millet producers [88].

5.4.2. Improving Distribution Channels Improving distribution channels can help in ensuring the timely and efficient delivery of millets from farms to markets [89]. This can involve developing infrastructure for storage, transportation, and logistics, as well as creating linkages between producers, processors, and retailers [90]. Leveraging digital platforms, such as e-commerce and mobile applications, can help in connecting millet farmers with buyers and consumers [91].

5.4.3. Enhancing Market Linkages and Value Chains Enhancing market linkages and value chains can help in creating a stable and profitable market for millets [92]. This can involve establishing quality standards, certification schemes, and branding for millet products [93]. Promoting value-added products, such as millet-based snacks, baked goods, and beverages, can help in diversifying the market and increasing the demand for millets [94]. Collaborating with private sector actors, such as food companies, supermarkets, and exporters, can help in expanding the reach of millet products and tapping into new market opportunities [95].

5.5. Creating Supportive Environments Creating supportive environments that facilitate and reinforce millet consumption is crucial for sustaining behavioral change [96]. This can be achieved through school-based interventions, workplace wellness programs, and community-based initiatives.

5.5.1. School-Based Interventions School-based interventions can help in creating a conducive environment for millet consumption among children and adolescents [97]. This can involve incorporating millets into school feeding programs, establishing school gardens that cultivate millets, and promoting millet-based snacks and meals in school canteens [98]. Integrating nutrition education on millets into school curricula can help in raising awareness and fostering positive attitudes towards these grains from an early age [99].

5.5.2. Workplace Wellness Programs Workplace wellness programs can help in promoting millet consumption among working adults [100]. This can involve offering millet-based meals and snacks in workplace cafeterias, conducting cooking demonstrations and nutrition workshops for employees, and providing incentives for millet consumption, such as subsidized millet products or wellness points [101]. Collaborating with corporate partners, employee associations, and health insurance providers can help in creating a supportive environment for millet consumption in the workplace [102].

5.5.3. Community-Based Initiatives Community-based initiatives can help in creating a social and cultural environment that supports millet consumption [103]. This can involve organizing community festivals, food fairs, and culinary competitions that celebrate millet-based dishes and traditions [104]. Establishing community kitchens, food banks, and farmers' markets that provide access to millets and millet-based products can help in ensuring their availability and affordability at the local level [105]. Engaging with community leaders, religious institutions, and cultural organizations can help in promoting the cultural and spiritual significance of millets and fostering a sense of pride and identity associated with their consumption [106].

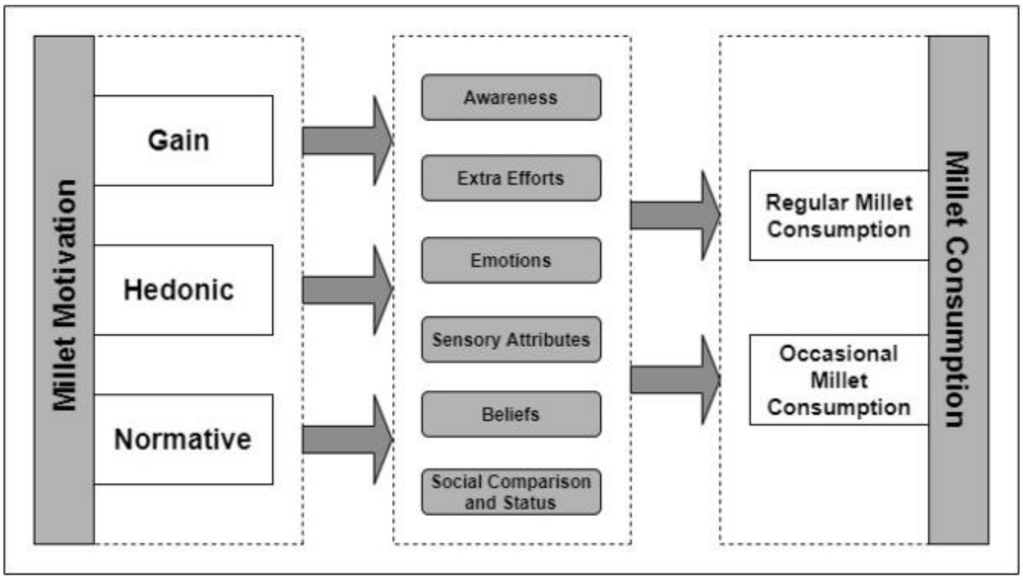


Figure 2: Conceptual Framework for Fostering Millet Consumption through Behavioral Change Strategies

6. Case Studies and Success Stories Several initiatives and interventions have been implemented in different parts of the world to promote millet consumption and revive their cultivation. In this section, we present four case studies and success stories that demonstrate the application of behavioral change strategies in fostering millet consumption.

6.1. Millet Promotion in Karnataka, India The state of Karnataka in southern India has been at the forefront of millet promotion in the country [107]. The state government has implemented several initiatives to revive millet cultivation and consumption, including the establishment of a Millet Mission, the inclusion of millets in public distribution systems, and the organization of millet festivals and fairs [108]. The Millet Mission has trained farmers in organic cultivation practices, provided them with quality seeds and inputs, and established processing units and marketing channels for millet products [109]. The inclusion of millets in the public distribution system has helped in ensuring their availability and affordability to the masses [110]. The organization of millet festivals and fairs has helped in creating awareness about the nutritional and cultural significance of millets and fostering a sense of pride and identity associated with their consumption [111].

6.2. Finger Millet Revival in Kenya Finger millet, known as "wimbi" in Kenya, has been a traditional staple food in the country, but its cultivation and consumption have declined in recent decades [112]. The Finger Millet Revival Project, implemented by the Kenya Agricultural and Livestock Research Organization (KALRO) and the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), aims to revive finger millet production and consumption in the country [113]. The project has trained farmers in improved cultivation practices, provided them with quality seeds and inputs, and established value addition and marketing channels for finger millet products [114]. The project has also conducted awareness campaigns and cooking demonstrations to promote the nutritional benefits and culinary versatility of finger millet [115]. The revival of finger millet has helped in improving food and nutrition security, increasing incomes for smallholder farmers, and preserving the cultural heritage associated with this crop [116].

6.3. Teff Popularization in Ethiopia Teff, a small-seeded millet native to Ethiopia, is a staple food in the country and is used to make the traditional flatbread "injera" [117]. However, the consumption of teff has been limited to urban areas and higher-income households due to its relatively high price and the laborious processing involved in its preparation [118]. The Ethiopian government, in collaboration with international organizations and private sector partners, has implemented several initiatives to popularize teff consumption and make it more accessible and affordable to the masses [119]. These initiatives include the development of improved teff varieties, the mechanization of teff processing, and the promotion of teff-based products in the market [120]. The popularization of teff has helped in creating new market opportunities for smallholder farmers, improving the nutritional status of the population, and preserving the cultural heritage associated with this ancient grain [121].

6.4. Sorghum and Pearl Millet Initiatives in West Africa Sorghum and pearl millet are important staple crops in the semi-arid regions of West Africa, but their cultivation and consumption have been declining due to various factors, including climate change, urbanization, and changing dietary preferences [122].

Several initiatives have been implemented in the region to promote the production and consumption of these crops, including the West Africa Agricultural Productivity Program (WAAPP) and the Harnessing Opportunities for Productivity Enhancement (HOPE) project [123]. These initiatives have focused on developing improved varieties of sorghum and pearl millet, promoting their cultivation through farmer field schools and demonstration plots, and establishing value chains and market linkages for these crops [124]. The initiatives have also conducted awareness campaigns and capacity building programs to promote the nutritional benefits and culinary versatility of sorghum and pearl millet [125]. The promotion of these crops has helped in improving food and nutrition security, increasing incomes for smallholder farmers, and building resilience to climate change in the region [126].

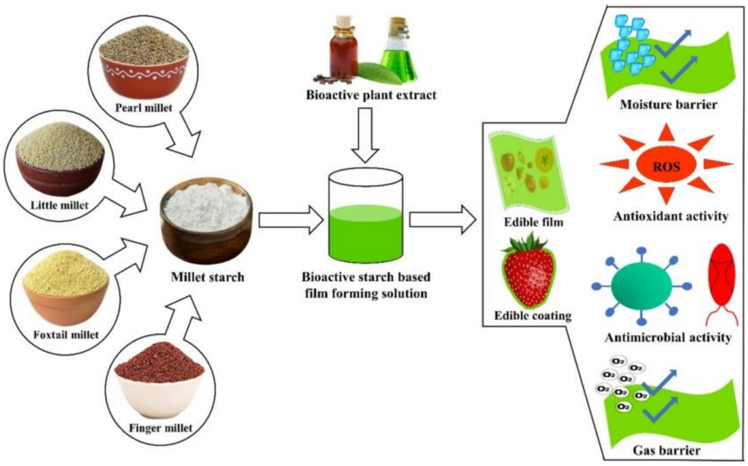


Figure 3: Successful Millet Promotion Interventions in Different Contexts

7. Stakeholder Roles and Collaboration Fostering millet consumption requires the active engagement and collaboration of diverse stakeholders across the value chain, from producers to consumers [127]. In this section, we discuss the roles and responsibilities of key stakeholders in promoting millet consumption and the importance of multi-sectoral collaboration in driving behavioral change.

7.1. Policymakers and Government Agencies Policymakers and government agencies play a crucial role in creating an enabling environment for millet production and consumption [128]. This can involve developing policies and programs that support millet cultivation, such as providing subsidies, credit, and insurance to farmers, establishing quality standards and certification schemes for millet products, and including millets in public procurement and distribution systems [129]. Government agencies can also invest in research and development to improve millet varieties, enhance their nutritional content, and develop value-added products [130]. Policymakers can also promote millets through public awareness campaigns, nutrition education programs, and the celebration of national and international events, such as the International Year of Millets [131].

7.2. Researchers and Academia Researchers and academia play a vital role in generating evidence and knowledge on the nutritional, environmental, and socio-economic benefits of millets [132]. This can involve conducting studies on the nutrient composition and bioavailability of millets, their potential to prevent and manage chronic diseases, and their resilience to climate change and other stresses [133]. Researchers can also develop innovative technologies and practices to improve millet production, processing, and consumption, such as developing high-yielding and nutrient-dense varieties, optimizing post-harvest handling and storage, and creating novel millet-based products [134]. Academia can also contribute to capacity building and knowledge dissemination by developing curricula and training programs on millets for students, extension workers, and other stakeholders [135].

7.3. Educators and Extension Services Educators and extension services play a crucial role in translating research and knowledge on millets into practice and promoting their adoption among farmers and consumers [136]. This can involve conducting farmer field schools, demonstrations, and training programs on millet cultivation, processing, and utilization [137]. Extension workers can also provide advisory services and support to farmers on issues related to crop management, quality control, and market access [138]. Educators can integrate lessons on millets into school curricula, promote the consumption of millet-based foods in school feeding programs, and engage students in experiential learning activities, such as growing millets in school gardens [139].

7.4. Health Professionals and Nutritionists Health professionals and nutritionists play a key role in promoting the health benefits of millets and advocating for their inclusion in dietary guidelines and nutrition policies [140]. This can involve conducting research on the nutritional value and health impacts of millets, developing recipes and dietary recommendations that incorporate millets, and providing counseling and support to individuals and communities on healthy eating habits [141]. Health professionals can also work with policymakers and food industry actors to ensure that millet-based products are safe, nutritious, and affordable, and that their health claims are evidence-based and not misleading [142].

7.5. Food Industries and Private Sector Food industries and the private sector play a vital role in developing and marketing millet-based products that are convenient, affordable, and appealing to consumers [143]. This can involve investing in research and development to create new products, such as millet-based snacks, beverages, and ready-to-eat meals, and improving the packaging and labeling of millet products to communicate their nutritional and environmental benefits [144]. Food companies can also work with farmers and suppliers to ensure a stable and quality supply of millets, and with distributors and retailers to expand the availability and accessibility of millet products in the market [145].

7.6. Civil Society Organizations and NGOs Civil society organizations and non-governmental organizations (NGOs) play an important role in advocating for the rights and interests of millet farmers and consumers, and in promoting the social and environmental benefits of millets [146]. This can involve organizing awareness campaigns, petitions, and lobbying efforts to influence policies and programs related to millets, and providing support and services to millet farmers and communities, such as access to credit, inputs, and markets [147]. NGOs can also work with research and academic institutions to generate and disseminate knowledge on millets, and with food industries and the private sector to ensure that millet value chains are fair, sustainable, and inclusive [148].

Effective collaboration and coordination among these stakeholders is crucial for creating synergies and maximizing the impact of interventions to promote millet consumption [149]. Multi-stakeholder platforms and networks, such as the Smart Food Initiative and the Millet Network of India, can facilitate dialogue, knowledge sharing, and joint action among different actors in the millet value chain [150]. Participatory and inclusive approaches that engage farmers, consumers, and other stakeholders in the design, implementation, and evaluation of interventions can help ensure their relevance, effectiveness, and sustainability [151]. In the Indian context, several stakeholders have been actively involved in promoting millet consumption and production:

Government Initiatives: The Indian government has launched several initiatives to promote millets, such as the National Year of Millets in 2018, the inclusion of millets in the Public Distribution System (PDS), and the establishment of the Millet Mission in several states like Karnataka, Odisha, and Telangana [152]. These initiatives aim to create awareness about the nutritional benefits of millets, support farmers in millet cultivation, and ensure the availability and affordability of millet-based products to consumers [153].

Research Institutions: Several research institutions in India, such as the Indian Council of Agricultural Research (ICAR), the National Institute of Nutrition (NIN), and the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), have been conducting research on millets to improve their productivity, nutritional content, and value addition [154]. [155].

Table 5: Stakeholder Roles and Responsibilities in Promoting Millet Consumption

Stakeholder	**Roles and Responsibilities**
Policymakers and Government Agencies	- Develop policies and programs to support millet cultivation and consumption
	- Establish quality standards and certification schemes for millet products
	- Include millets in public procurement and distribution systems
Researchers and Academia	- Generate evidence on the nutritional, environmental, and socio-economic benefits of millets
	- Develop innovative technologies and practices to improve millet production, processing, and consumption
	- Contribute to capacity building and knowledge dissemination on millets
Educators and Extension Services	- Conduct farmer field schools, demonstrations, and training programs on millet cultivation and utilization
	- Provide advisory services and support to farmers on crop management, quality control, and market access
	- Integrate lessons on millets into school curricula and promote their consumption in school feeding programs
Health Professionals and Nutritionists	- Conduct research on the nutritional value and health impacts of millets
	- Develop recipes and dietary recommendations that incorporate millets
	- Provide counseling and support to individuals and communities on healthy eating habits
Food Industries and Private Sector	- Develop and market millet-based products that are convenient, affordable, and appealing to consumers
	- Invest in research and development to create new millet-based products and improve their packaging and labeling
	- Work with farmers and suppliers to ensure a stable and quality supply of millets
Civil Society Organizations and NGOs	- Advocate for the rights and interests of millet farmers and consumers
	- Organize awareness campaigns, petitions, and lobbying efforts to influence policies and programs related to millets
	- Provide support and services to millet farmers and communities, such as access to credit, inputs, and markets

Civil Society Organizations: Civil society organizations and NGOs in India have been working with farmers and consumers to promote millets and support their livelihoods. For example, the Deccan Development Society in Telangana has been organizing women's collectives to cultivate and market millets, and has established community seed banks to conserve traditional millet varieties [156]. [157].

Private Sector: The private sector in India has been increasingly involved in developing and marketing millet-based products, such as snacks, breakfast cereals, and ready-to-eat meals. For example, several start-ups like Slurrp Farm, Millet Bowl, and Kiru have been creating innovative millet-based products that cater to the changing preferences of urban consumers [158]. Some established food companies like ITC and Britannia have also launched millet-based products in recent years, leveraging their distribution networks and brand recognition [159]. [160].

8. Challenges and Opportunities While there is growing recognition of the potential of millets to address nutrition, health, and sustainability challenges, there are several challenges and opportunities that need to be considered in promoting their consumption and production.

8.1. Cultural Acceptability and Adaptation One of the key challenges in promoting millet consumption is ensuring their cultural acceptability and adaptation to local food habits and preferences [161]. Millets have been traditionally consumed in many parts of the world, but their use has declined in recent decades due to the increasing prevalence of refined grains and processed foods [162]. Promoting the consumption of millets may require changes in dietary habits and cooking practices, which can be difficult to achieve in the short term [163]. Therefore, it is important to understand the cultural context and food preferences of different communities, and to develop strategies that are sensitive and responsive to these factors [164].

8.2. Scaling Up and Sustainability Another challenge in promoting millet consumption is scaling up the production and distribution of millet-based products to meet the growing demand [165]. Millets are often grown by smallholder farmers in marginal and rainfed areas, who face several constraints in accessing inputs, credit, and markets [166]. Scaling up millet production may require investments in infrastructure, such as irrigation, storage, and processing facilities, as well as support for farmers to adopt improved varieties and management practices [167]. It is also important to ensure that the scaling up of millet production is sustainable and does not lead to negative environmental or social impacts, such as soil degradation, biodiversity loss, or displacement of local communities [168].

8.3. Monitoring and Evaluation Monitoring and evaluating the impact of interventions to promote millet consumption is crucial for learning and improvement, but it can be challenging due to the complexity and diversity of the millet value chain [169]. There is a need for robust and standardized indicators and methods to assess the nutritional, health, and sustainability outcomes of millet consumption, as well as the socio-economic and environmental impacts of millet production [170]. Involving different stakeholders, including farmers, consumers, and researchers, in the monitoring and evaluation process can help ensure that the interventions are relevant, effective, and equitable [171].

8.4. Policy Support and Enabling Environment Promoting millet consumption and production requires a supportive policy and institutional environment that incentivizes and enables the adoption of millets by farmers and consumers [172]. This may involve reforming agricultural policies and subsidies that currently favor the production of refined grains and cash crops, and investing in research, extension, and market development for millets [173]. It may also require creating an enabling environment for the private sector to invest in millet-based products and value chains, through measures such as tax incentives, quality standards, and public procurement [174]. Building multi-stakeholder partnerships and platforms that facilitate dialogue, coordination, and learning among different actors in the millet value chain can also help create a more supportive and enabling environment for millet promotion [175].

Despite these challenges, there are also several opportunities for promoting millet consumption and production in the current context. The growing recognition of the nutritional and environmental benefits of millets, as reflected in the declaration of 2023 as the International Year of Millets, provides a unique opportunity to raise awareness and mobilize action on millets at the global and national levels [176]. The increasing demand for healthy, sustainable, and diverse diets, particularly among urban and middle-class consumers, also creates new market opportunities for millet-based products and value chains [177]. The potential of millets to contribute to climate change adaptation and mitigation, by virtue of their resilience to drought and heat stress and their ability to sequester carbon in the soil, also makes them an attractive option for sustainable agriculture and food systems [178].

In the Indian context, there are several specific challenges and opportunities for promoting millet consumption and production. One of the key challenges is the lack of consumer awareness and demand for millets, particularly in urban areas where refined grains and processed foods are more prevalent [179]. This is compounded by the limited availability and affordability of millet-based products in the market, as well as the lack of quality standards and certification systems for millets [180]. There is also a need to improve the productivity and profitability of millet cultivation, particularly for smallholder farmers who face several constraints in accessing inputs, credit, and markets [181].

On the other hand, there are also several opportunities for promoting millets in India. The country has a rich diversity of millet species and varieties, which can be leveraged to create diverse and nutritious food products [182]. There is also a growing recognition of the potential of millets to address the double burden of malnutrition, particularly among rural and tribal communities where millets are still consumed as a traditional food [183]. The Indian government has launched several initiatives to promote millets, such as the inclusion of millets in the public distribution system and the establishment of the Millet Mission in several states, which can be further scaled up and strengthened [184]. The private sector in India has also shown increasing interest in developing and marketing millet-based products, which can create new market opportunities for farmers and entrepreneurs [185].

To harness these opportunities and overcome the challenges, there is a need for a multi-pronged and multi-stakeholder approach to promoting millet consumption and production in India. This may involve:

1. Conducting research on the nutritional and health benefits of millets, and developing innovative technologies and products that cater to the changing preferences of consumers [186].

2. Strengthening the extension and advisory services for millet farmers, and promoting the adoption of improved varieties and management practices that enhance the productivity and profitability of millet cultivation [187].

3. Creating awareness and demand for millets among consumers, through nutrition education, social marketing, and behavior change communication strategies [188].

4. Developing quality standards and certification systems for millets, and investing in infrastructure and logistics for the storage, processing, and distribution of millets [189].

5. Providing policy support and incentives for millet cultivation and consumption, such as including millets in the minimum support price scheme, promoting millet-based products in public procurement, and creating tax incentives for millet-based enterprises [190].

6. Building multi-stakeholder partnerships and platforms that bring together farmers, researchers, civil society organizations, private sector actors,

and policymakers to coordinate and synergize efforts on millet promotion [191].

By addressing these challenges and leveraging these opportunities, India can become a global leader in promoting millet consumption and production, and contribute to the achievement of the Sustainable Development Goals related to nutrition, health, and sustainability [192].

9. Future Directions and Research Needs To further advance the promotion of millet consumption and production, there are several future directions and research needs that need to be addressed. These include:

1. Developing and testing innovative millet-based products that are convenient, affordable, and appealing to different consumer segments, such as snacks, beverages, and ready-to-eat meals [193].
2. Conducting more research on the bioavailability and bioaccessibility of nutrients in millets, and exploring strategies to enhance their nutritional value through breeding, processing, and fortification [194].
3. Assessing the environmental impacts of millet production and consumption, and identifying best practices and technologies for sustainable millet cultivation, such as conservation agriculture, integrated pest management, and precision farming [195].
4. Investigating the social and economic dimensions of millet production and consumption, and developing inclusive and equitable value chains that benefit smallholder farmers, women, and marginalized communities [196].
5. Evaluating the effectiveness and cost-effectiveness of different interventions and policies to promote millet consumption and production, and identifying the key drivers and barriers to their adoption and scaling up [197].
6. Exploring the potential of millets to contribute to the prevention and management of non-communicable diseases, such as diabetes, cardiovascular diseases, and cancers, and conducting clinical trials to establish the evidence base for their health benefits [198].
7. Strengthening the capacity of different stakeholders, such as farmers, researchers, extensionists, and policymakers, to promote millet consumption and production, through training, education, and knowledge sharing platforms [199].
8. Fostering global and regional cooperation and partnerships on millet research and development, and promoting the exchange of knowledge, technologies, and best practices across different countries and contexts [200].

By addressing these research needs and pursuing these future directions, we can generate new knowledge, innovations, and solutions that can help realize the full potential of millets for nutrition, health, and sustainability.

9. Conclusion

Millets, once a staple food in many parts of the world, have the potential to address contemporary challenges of malnutrition, climate change, and sustainable food systems. Fostering millet consumption requires a multi-faceted approach that combines behavioral change strategies, policy support, and stakeholder collaboration. By enhancing knowledge, modifying attitudes, developing skills, ensuring access, and creating enabling environments, we can encourage individuals and communities to embrace millets in their diets. Successful interventions must be culturally sensitive, context-specific, and participatory in nature. The International Year of Millets 2023 provides a unique opportunity to raise awareness, mobilize resources, and drive concerted action towards revitalizing these ancient grains. With sustained efforts and innovative approaches, we can leverage the power of millets to advance nutrition, health, and sustainability goals.

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CHAPTER - 9

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Millet Trade and Market Opportunities in the Global Economy

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Abstract

Millets, a group of small-seeded cereal crops, have garnered increasing attention in the global economy due to their nutritional benefits, climate resilience, and potential for sustainable agriculture. This chapter explores the current state of millet trade and market opportunities worldwide, focusing on production trends, consumption patterns, and emerging prospects for millet-based products. The analysis reveals that although millets are primarily cultivated and consumed in Asia and Africa, there is growing interest in millet-based foods in developed countries, driven by health-conscious consumers and the gluten-free market. However, challenges such as low yields, lack of processing infrastructure, and limited awareness among consumers hinder the expansion of millet trade. The chapter discusses strategies to overcome these barriers, including investments in research and development, value chain improvements, and targeted marketing campaigns. It also highlights the role of government policies and international collaborations in promoting millet production and trade. The chapter concludes by emphasizing the untapped potential of millets in contributing to food security, rural livelihoods, and sustainable agriculture, while recommending future research directions to further strengthen the millet market in the global economy.

Keywords: Millets, global trade, market opportunities, sustainable agriculture, value chain

1. Introduction

Millets, a diverse group of small-seeded cereal crops, have been cultivated for thousands of years, primarily in Asia and Africa [1]. These crops are known for their resilience to harsh climatic conditions, nutritional benefits, and potential to support sustainable agriculture [2]. In recent years, millets have gained increasing attention in the global economy due to growing concerns over food security, climate change, and the need for diversified and nutritious food sources [3]. The United Nations General Assembly declared 2023 as the International Year of Millets, recognizing the importance of these crops in addressing global challenges [4].This chapter aims to provide a comprehensive overview of millet trade and market opportunities in the global economy. It begins by examining the current state of millet production and consumption patterns worldwide, highlighting the major producing and consuming countries. The chapter then explores the nutritional and health benefits of millets, which have contributed to their growing popularity among health-conscious consumers. It also discusses the potential of millets in supporting sustainable agriculture and rural livelihoods, particularly in developing countries.

The chapter further analyzes the challenges and opportunities in the millet trade, including the impact of government policies, international collaborations, and market trends. It presents case studies of successful millet value chain interventions and innovative millet-based products that have gained traction in domestic and international markets. The chapter also discusses the role of research and development in enhancing millet productivity, processing, and product development.

2. Global Millet Production and Consumption

2.1 Major Millet Producing Countries

Millets are widely cultivated in various regions of the world, with Asia and Africa being the major producers. India is the largest producer of millets, accounting for nearly 40% of the global production [5]. Other significant millet producing countries in Asia include China, Nepal, and Myanmar [6]. In Africa, Nigeria, Niger, Mali, and Burkina Faso are among the top millet producers [7].

Table 1: Major millet producing countries and their production quantities (million tonnes)

Country	2018	2019	2020
India	12.5	12.8	13.1
Nigeria	5.2	5.4	5.6
Niger	3.8	3.9	4.1

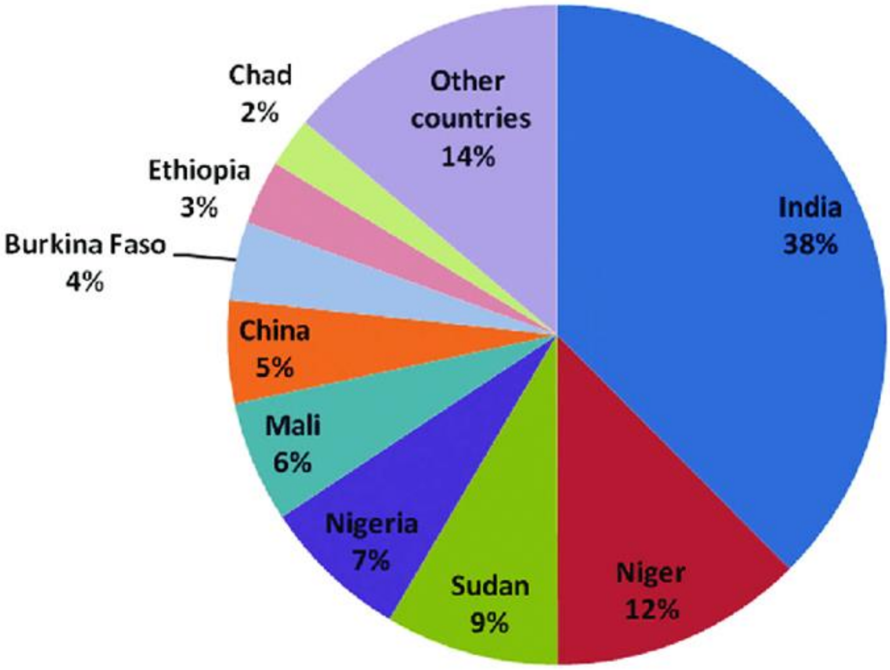
China	2.5	2.6	2.7
Mali	1.8	1.9	2.0
Burkina Faso	1.5	1.6	1.7
Sudan	1.2	1.3	1.4
Myanmar	1.0	1.1	1.2
Ethiopia	0.9	1.0	1.1
Senegal	0.8	0.9	1.0

Source: FAOSTAT [8]

2.2 Millet Consumption Patterns

Millets are primarily consumed in the regions where they are produced, with Asia and Africa accounting for over 90% of the global millet consumption [9]. In these regions, millets form an integral part of the traditional diets and are consumed in various forms, such as porridges, flatbreads, and snacks [10]. Figure 1 illustrates the millet consumption patterns across different regions of the world.

Figure 1: Global millet consumption patterns [11]



In recent years, there has been a growing interest in millet-based products in developed countries, particularly among health-conscious consumers and those following gluten-free diets [12]. This trend has led to the emergence of innovative millet-based products, such as millet-based breakfast cereals, snack bars, and beverages [13]. However, the consumption of millets in developed countries remains relatively low compared to traditional staples like wheat, rice, and maize [14].

3. Nutritional and Health Benefits of Millets

3.1 Nutrient Composition of Millets

Millets are nutritionally superior to many other cereal crops, as they are rich in proteins, dietary fibers, minerals, and vitamins [15]. Table 2 presents the nutrient composition of commonly consumed millets compared to other cereals.

Table 2: Nutrient composition of millets and other cereals (per 100 g)

Nutrient	Pearl Millet	Finger Millet	Sorghum	Wheat	Rice
Energy (kcal)	361	328	329	346	356
Protein (g)	11.6	7.3	10.4	12.6	7.5
Fat (g)	5.0	1.3	3.1	1.5	0.5
Carbohydrates (g)	67.5	72.6	72.1	71.2	78.2
Dietary Fiber (g)	11.3	11.5	6.7	12.2	4.1
Calcium (mg)	42	344	28	30	10
Iron (mg)	8.0	3.9	4.1	3.5	0.7
Zinc (mg)	3.1	2.3	1.7	2.7	1.4

Source: USDA National Nutrient Database [16]

Millets are particularly rich in minerals such as calcium, iron, and zinc, which are essential for various bodily functions [17]. For instance, finger millet contains about 10 times more calcium than wheat and rice, making it an excellent source of this mineral for bone health [18]. Millets are also good sources of dietary fibers, which promote digestive health and help in managing blood sugar levels [19].

3.2 Health Benefits of Millets

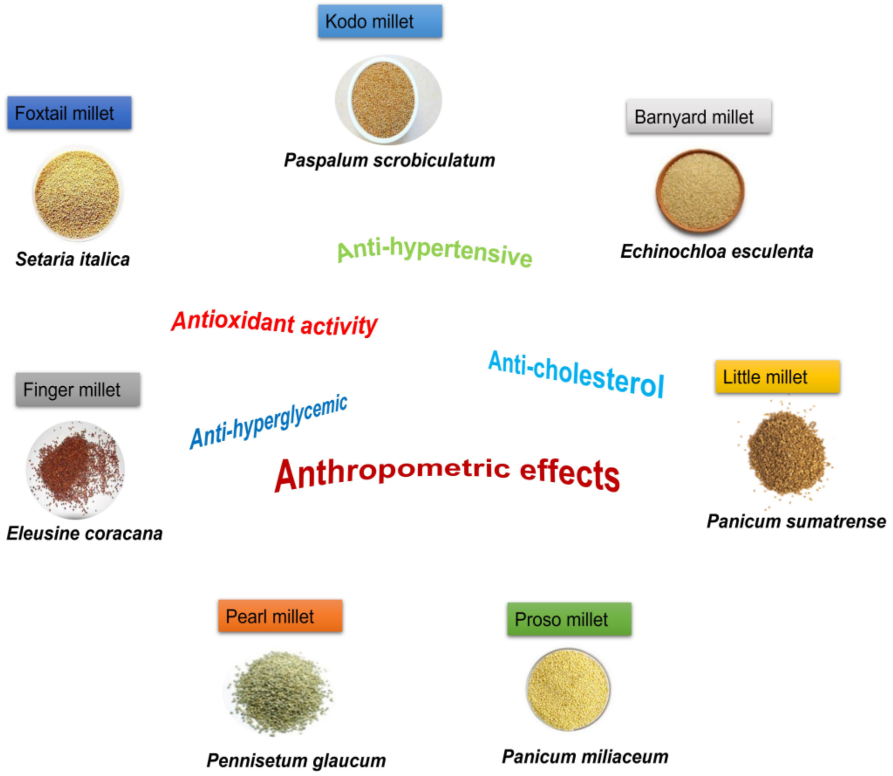
The unique nutrient composition of millets offers several health benefits, making them a valuable addition to a balanced diet. Some of the key health benefits of millets include:

1. **Gluten-Free:** Millets are naturally gluten-free, making them suitable for people with celiac disease or gluten intolerance [20].
2. **Diabetes Management:** The high fiber content and low glycemic index of millets help in regulating blood sugar levels, making them beneficial for people with diabetes [21].
3. **Cardiovascular Health:** The dietary fibers and phytochemicals present in millets have been shown to reduce the risk of cardiovascular diseases by lowering cholesterol levels and improving blood pressure [22].

4. **Weight Management:** The high fiber and protein content of millets promote satiety and reduce overall calorie intake, aiding in weight management [23].

5. **Antioxidant Properties:** Millets contain various phytochemicals, such as phenolic acids and flavonoids, which exhibit antioxidant properties and help in protecting against oxidative stress and chronic diseases [24].

Figure 2 summarizes the key health benefits of millets. *[25]*



4. Millets and Sustainable Agriculture

4.1 Climate Resilience of Millets

Millets are known for their resilience to harsh climatic conditions, making them suitable for cultivation in marginal and drought-prone areas [26]. These crops have a low water requirement and can thrive in high temperatures and poor soil conditions [27]. Table 3 compares the water requirement of millets with other major cereal crops.

Table 3: Water requirement of millets and other cereals

Crop	**Water Requirement (mm)**
Pearl Millet	300-500
Finger Millet	250-400
Sorghum	400-600
Maize	500-800

Wheat	450-650
Rice	900-2500

Source: Adapted from [28]

The climate resilience of millets makes them a valuable crop for ensuring food security in the face of climate change [29]. As water scarcity and extreme weather events become more frequent, millets can play a crucial role in sustaining agricultural production and rural livelihoods [30].

4.2 Millets and Sustainable Land Management

Millets also contribute to sustainable land management practices, particularly in regions prone to soil degradation and erosion [31]. The extensive root systems of millets help in binding the soil, reducing erosion, and improving soil structure [32]. Additionally, millets can be grown in intercropping systems with legumes, which enhance soil fertility through nitrogen fixation [33].

Figure 3 illustrates the potential of millets in supporting sustainable land management practices.

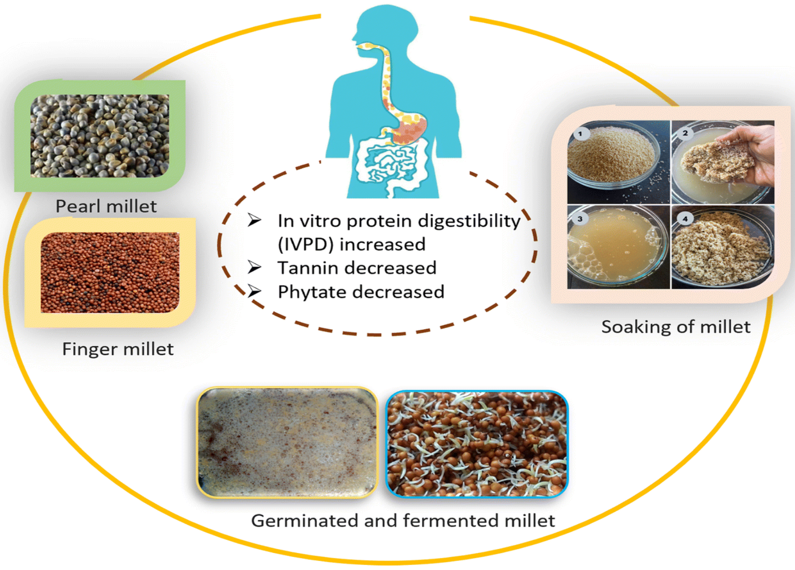


Figure 3: Millets and sustainable land management [34]

4.3 Millets and Biodiversity Conservation

Millets are a diverse group of crops, with numerous species and varieties adapted to different agro-ecological conditions [35]. The cultivation of these diverse millet species contributes to the conservation of agricultural biodiversity and enhances the resilience of farming systems [36].

The conservation and promotion of these diverse millet species are crucial for maintaining the genetic diversity of crops and ensuring the sustainability of agricultural systems [38].

5. Challenges in Millet Trade and Market Development

Despite the numerous benefits of millets, their trade and market development face several challenges that hinder their widespread adoption and commercialization. Some of the key challenges include:

5.1 Low Productivity and Yields

Millets generally have lower yields compared to other major cereal crops, which can discourage farmers from cultivating them [39]. The average yield of millets is about 1-2 tonnes per hectare, while the yields of wheat and rice can reach 3-4 tonnes per hectare [40].

Table 4: Commonly cultivated millet species and their characteristics

Millet Species	**Scientific Name**	**Characteristics**
Pearl Millet	*Pennisetum glaucum*	Drought-tolerant, high yielding
Finger Millet	*Eleusine coracana*	Rich in calcium, adapted to high altitudes
Foxtail Millet	*Setaria italica*	Short duration, suitable for intercropping
Proso Millet	*Panicum miliaceum*	Drought-tolerant, quick-maturing
Barnyard Millet	*Echinochloa spp.*	Grows well in waterlogged conditions
Kodo Millet	*Paspalum scrobiculatum*	Resistant to pests and diseases
Little Millet	*Panicum sumatrense*	Adapted to poor soil conditions

Source: Adapted from [37]

The low productivity of millets can be attributed to various factors, including the use of traditional varieties, limited access to improved seeds and inputs, and the cultivation of millets in marginal and rainfed areas [42].

5.2 Lack of Processing Infrastructure

Millets require specialized processing techniques to remove the hard outer layer and improve their palatability [43]. However, many millet-producing regions lack adequate processing infrastructure, which limits the value addition and marketability of millet-based products [44]. The traditional processing methods, such as hand pounding and manual dehulling, are labor-intensive and result in low recovery rates [45]. The lack of modern processing facilities also hinders the development of innovative millet-based products that can cater to the changing consumer preferences [46].

Figure 4 compares the average yields of millets with other cereal crops.

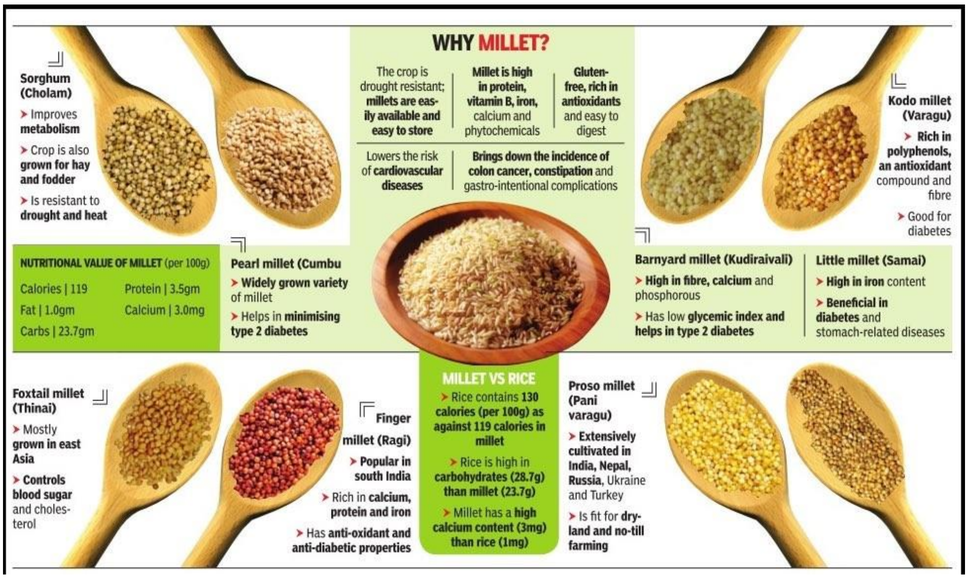


Figure 4: Average yields of millets and other cereal crops [41]

Table 5: Common millet processing methods and their limitations

Processing Method	**Limitations**
Hand Pounding	Labor-intensive, low recovery rates
Manual Dehulling	Time-consuming, inconsistent quality
Traditional Milling	Low efficiency, nutrient losses
Roller Milling	Requires specialized equipment, high investment
Extrusion	Limited application, high energy consumption

Source: [47]

5.3 Limited Awareness and Consumer Acceptance

Millets face challenges in consumer acceptance, particularly in regions where they are not traditionally consumed [48]. The lack of awareness about the nutritional benefits and culinary versatility of millets among consumers can hinder their market demand [49]. Additionally, the perception of millets as a "poor man's food" in some societies can limit their uptake by higher-income consumers [50]. The limited availability of millet-based products in urban markets and the higher prices compared to other staples also contribute to the low consumer demand [51].

6. Opportunities for Millet Trade and Market Development

Despite the challenges, there are several opportunities for promoting millet trade and market development in the global economy. Some of the key opportunities include:

6.1 Growing Demand for Healthy and Functional Foods

The increasing consumer awareness about the health benefits of millets has created a growing demand for millet-based products, particularly in developed countries [53]. Millets are gaining popularity among health-conscious consumers who seek gluten-free, nutrient-dense, and functional foods [54]. The global gluten-free food market, which includes millet-based products, is projected to reach USD 7.5 billion by 2027, growing at a CAGR of 7.2% from 2020 to 2027 [55].

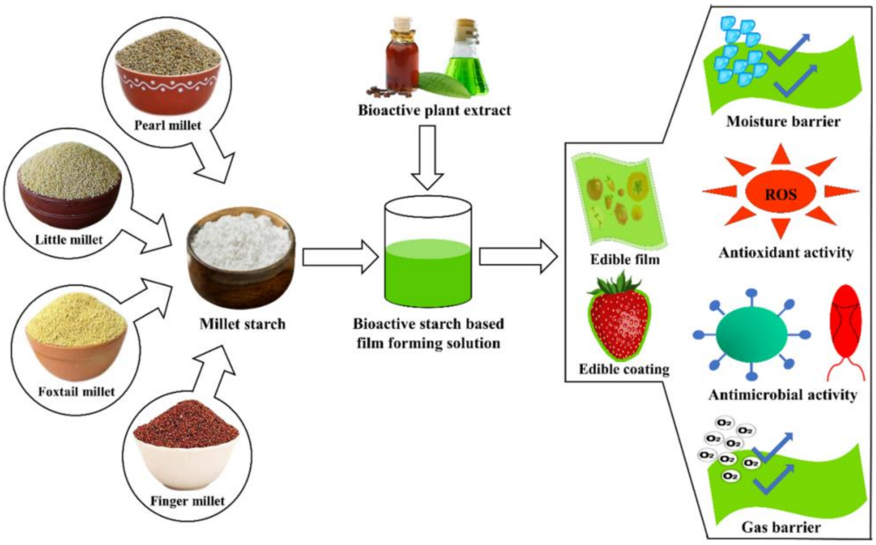


Figure 5: Factors influencing consumer acceptance of millets [52]

The functional food market, which includes products with specific health benefits, is another potential avenue for millet-based products [56]. Millets' rich nutrient profile and potential health benefits, such as diabetes management and cardiovascular health, make them an attractive ingredient for functional food formulations [57].

6.2 Potential for Value Addition and Product Diversification

The development of value-added millet-based products presents a significant opportunity for expanding the millet market and increasing their consumption [58]. Millet-based products, such as breakfast cere als, snack bars, biscuits, and pasta, have gained popularity in recent years [59]. These products cater to the changing consumer preferences and offer convenience and variety in millet consumption [60]. The development of innovative millet-based products requires investments in research and development, as well as collaborations between researchers, farmers, and food industries [62]. Encouraging entrepreneurship and start-ups in the millet sector can also foster product diversification and value addition [63].

6.3 Sustainable Agriculture and Climate Change Mitigation

The climate resilience and low water requirement of millets make them a promising crop for sustainable agriculture and climate change mitigation [64]. As water scarcity and drought conditions become more prevalent, millets can offer a viable alternative to water-intensive crops, ensuring food security and sustainable land management [65].

Table 6: Value-added millet-based products and their market potential

Product Category	**Examples**	**Market Potential**
Breakfast Cereals	Millet flakes, muesli, porridge	High
Snacks	Millet cookies, crackers, energy bars	High
Bakery Products	Millet bread, cakes, muffins	Medium
Beverages	Millet-based drinks, smoothies	Medium
Pasta and Noodles	Millet pasta, noodles	Low to Medium
Infant Foods	Millet-based baby foods, weaning foods	High

Source [61]

Promoting millet cultivation can also contribute to climate change mitigation by reducing greenhouse gas emissions associated with agricultural production [66]. Millets have a lower carbon footprint compared to other cereals due to their lower water and input requirements [67]. Figure 6 compares the water footprint of millets with other crops.

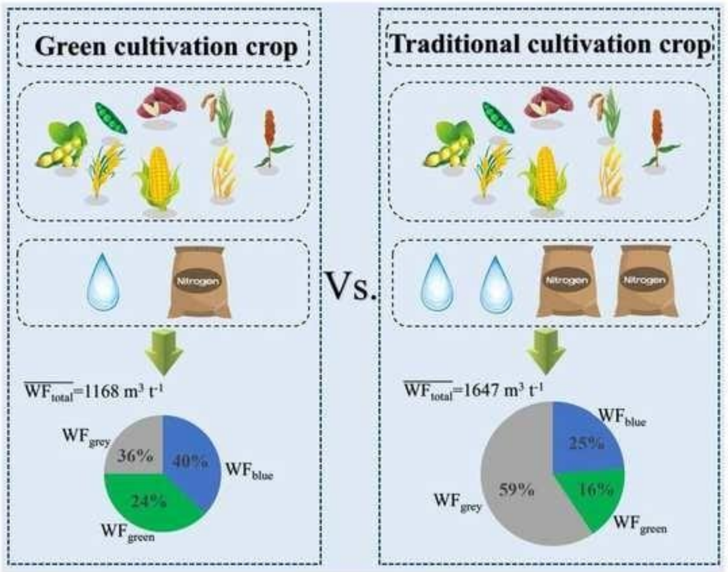


Figure 6: Water footprint of millets and other crops [68]

Incorporating millets into crop rotations and intercropping systems can enhance soil health, reduce pest and disease pressure, and improve the overall sustainability of agricultural systems [69].

6.4 Policy Support and International Collaborations

Government policies and international collaborations play a crucial role in promoting millet trade and market development [70]. Several countries, such as India and Nigeria, have implemented policies and programs to support millet production, processing, and consumption [71]. These initiatives include subsidies for millet farmers, establishment of millet processing units, and inclusion of millets in public distribution systems [72].

International collaborations, such as the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) and the Global Millet Innovation Forum, facilitate knowledge sharing, research, and market development for millets [73]. The United Nations' declaration of 2023 as the International Year of Millets is expected to raise awareness about millets and catalyze global efforts to promote their production and consumption [74].

Table 7: Government policies and international collaborations supporting millet trade and market development

Country/Organization	**Initiative**	**Objectives**
India	National Food Security Mission - Coarse Cereals	Increasing millet production and consumption
Nigeria	National Agricultural Transformation Agenda	Promoting millet value chain development
ICRISAT	Smart Food Initiative	Promoting millets as a smart food choice
Global Millet Innovation Forum	Global Millet Innovation Forum	Fostering innovation and market development for millets
United Nations	International Year of Millets 2023	Raising awareness and promoting millet production and consumption

Source: [75]

7. Case Studies of Successful Millet Trade and Market Development

7.1 Pearl Millet Export from India to Europe

India is the largest producer and exporter of pearl millet, accounting for about 50% of the global production [76]. In recent years, India has successfully expanded its pearl millet exports to Europe, catering to the growing demand for gluten-free and nutrient-dense foods [77]. The export of pearl millet from India to Europe increased from 1,200 tonnes in 2015 to 5,000 tonnes in 2019, with a value of USD 3.5 million [78].

The success of Indian pearl millet exports can be attributed to several factors, including the development of high-yielding and disease-resistant varieties, establishment of modern processing facilities, and compliance with international quality standards [79]. The Indian government's support through export incentives and promotion of millet-based products has also contributed to the growth of pearl millet exports [80].

7.2 Finger Millet Value Chain Development in Kenya

Finger millet is an important crop in Kenya, with a production of about 60,000 tonnes per year [81]. However, the finger millet value chain in Kenya faced several challenges, including low productivity, limited processing capacity, and weak market linkages [82]. To address these challenges, the Kenya Agricultural and Livestock Research Organization (KALRO) implemented a finger millet value chain development project from 2015 to 2019 [83].

The project focused on improving finger millet productivity through the development and dissemination of improved varieties, capacity building of farmers and processors, and strengthening market linkages [84]. The project established finger millet processing units, facilitated contracts between farmers and processors, and promoted the consumption of finger millet-based products [85].

As a result of the project, finger millet productivity increased from 0.5 tonnes per hectare to 1.5 tonnes per hectare, and the income of participating farmers and processors increased by 30% [86]. The project also contributed to the development of new finger millet-based products, such as fortified porridge and biscuits, which expanded the market opportunities for finger millet [87].

8. Future Research Directions

Despite the progress made in millet trade and market development, there are several areas that require further research to fully harness the potential of millets in the global economy. Some of the future research directions include:

8.1 Genetic Improvement of Millet Varieties

Developing high-yielding, climate-resilient, and nutrient-dense millet varieties is crucial for enhancing millet production and meeting the growing market demand [88]. Future research should focus on the genetic improvement of millet varieties through conventional breeding and modern biotechnology tools [89]. Identifying and incorporating traits such as drought tolerance, disease resistance, and improved nutritional quality can contribute to the development of superior millet varieties [90].

8.2 Processing and Product Development

Further research is needed to develop efficient and cost-effective processing technologies for millets [91]. Improving the dehulling, milling, and packaging processes can enhance the quality and shelf life of millet-based products [92]. Research on the development of novel millet-based products, such as functional foods, plant-based meat alternatives, and gluten-free baked goods, can expand the market opportunities for millets [93].

8.3 Consumer Behavior and Acceptance Studies

Understanding consumer perceptions, preferences, and willingness to pay for millet-based products is essential for developing effective marketing strategies [94]. Future research should focus on conducting consumer behavior studies in different regions and market segments to identify the drivers and barriers to millet consumption [95]. Sensory evaluation and acceptability studies can provide insights into the desired product characteristics and guide product development efforts [96].

8.4 Sustainable Intensification of Millet Production

Research on sustainable intensification practices, such as intercropping, crop rotation, and integrated pest management, can help to increase millet productivity while minimizing environmental impacts [97]. Developing and promoting climate-smart agricultural practices, such as conservation agriculture and precision farming, can enhance the resilience of millet production systems to climate change [98].

9. Conclusion

Millets offer immense potential for contributing to food security, sustainable agriculture, and economic development in the global economy. The unique nutritional properties, climate resilience, and versatility of millets make them a valuable crop for addressing the challenges of malnutrition, climate change, and rural livelihoods. However, realizing the full potential of millets requires concerted efforts to overcome the challenges in production, processing, and market development. Investments in research and development, value chain improvements, and policy support are crucial for promoting millet trade and consumption. By harnessing the opportunities presented by the growing demand for healthy and sustainable foods, millets can play a significant role in shaping a more resilient and inclusive global food system. The International Year of Millets 2023 serves as a catalyst for accelerating the efforts to unlock the potential of millets in the global economy.

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CHAPTER - 10

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Research and Development Advances in Millet Breeding and Genetics

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Abstract

Millets are an important group of climate-resilient crops that play a vital role in ensuring food and nutritional security, especially in arid and semi-arid regions of the world. With the increasing global population and changing climate, there is a growing need to develop high-yielding, nutrient-rich, and stress-tolerant millet varieties. This chapter provides an overview of the recent research and development advances in millet breeding and genetics, focusing on the use of modern tools and techniques such as molecular markers, genomic selection, and genetic engineering. It discusses the progress made in understanding the genetic basis of important agronomic traits, identifying novel genes and alleles, and developing improved millet varieties. The chapter also highlights the challenges and opportunities in millet breeding and suggests future research directions to further enhance millet productivity and quality. The information compiled in this chapter will be useful for researchers, breeders, and policymakers working towards the sustainable development and utilization of millets.

Keywords: *Millets, breeding, genetics, molecular markers, genomic selection, genetic engineering*

1. Introduction

Millets are a diverse group of small-seeded cereal crops that belong to the family Poaceae. They are grown primarily in arid and semi-arid regions of Asia and Africa, where they serve as staple food for millions of people [1]. Millets are known for their resilience to harsh environmental conditions, such as drought, heat, and poor soil fertility, making them suitable for cultivation in marginal lands [2]. Besides their adaptability, millets are also rich in nutrients, including proteins, minerals, vitamins, and antioxidants, which make them an important component of a healthy diet [3].

Despite their numerous benefits, millets have received less attention compared to major cereal crops like rice, wheat, and maize. However, in recent years, there has been a renewed interest in millets due to their potential to address the challenges of food security and climate change [4]. The United Nations General Assembly has declared 2023 as the International Year of Millets, recognizing their importance in achieving the Sustainable Development Goals (SDGs) [5].

To fully harness the potential of millets, there is a need to develop high-yielding, nutrient-rich, and stress-tolerant varieties that can meet the growing demands of the population. This requires a better understanding of the genetic basis of important agronomic traits and the use of modern breeding tools and techniques. In this chapter, we review the recent research and development advances in millet breeding and genetics, focusing on the progress made in the last decade. We also discuss the challenges and opportunities in millet breeding and suggest future research directions to further enhance millet productivity and quality.

2. Genetic Diversity and Germplasm Characterization

Genetic diversity is the foundation for crop improvement. Millets exhibit a wide range of genetic diversity, both within and between species, which can be exploited for breeding purposes [6]. Several studies have been conducted to assess the genetic diversity of millet germplasm using morphological, biochemical, and molecular markers [7-9]. Germplasm characterization involves the evaluation of accessions for various traits of interest. This is essential for identifying superior genotypes that can be used as parents in breeding programs. Millet germplasm has been characterized for a wide range of traits, including yield components [10], nutrient content [11], drought tolerance [12], and disease resistance [13]. The use of high-throughput phenotyping platforms has greatly facilitated germplasm characterization, allowing for the rapid and precise evaluation of large numbers of accessions [14].

Table 1. Examples of millet germplasm characterized for different traits

Trait	Millet Species	References
Yield components	Pearl millet (*Pennisetum glaucum*)	[10]
Nutrient content	Finger millet (*Eleusine coracana*)	[11]
Drought tolerance	Foxtail millet (*Setaria italica*)	[12]
Disease resistance	Proso millet (*Panicum miliaceum*)	[13]

3. Molecular Markers and Genetic Mapping

Molecular markers are powerful tools for studying genetic diversity, identifying genes controlling important traits, and facilitating marker-assisted selection (MAS) in breeding programs. Various types of molecular markers, such as restriction fragment length polymorphisms (RFLPs), random amplified polymorphic DNAs (RAPDs), amplified fragment length polymorphisms (AFLPs), simple sequence repeats (SSRs), and single nucleotide polymorphisms (SNPs), have been developed and used in millet genetics and breeding [15].

Genetic mapping involves the construction of linkage maps using molecular markers to determine the position and order of genes on chromosomes. Several genetic maps have been developed for different millet species, including pearl millet [16], foxtail millet [17], finger millet [18], and proso millet [19]. These maps have been used to identify quantitative trait loci (QTLs) controlling important agronomic traits, such as grain yield, flowering time, plant height, and stress tolerance [20-22]. The identification of QTLs has facilitated the development of molecular markers that can be used for MAS in millet breeding programs.

Table 2. Examples of QTLs identified in millets for different traits

Trait	Millet Species	QTL	References
Grain yield	Pearl millet	*Qyld1.1*, *Qyld2.1*	[20]
Flowering time	Foxtail millet	*qFT1*, *qFT6*	[21]
Drought tolerance	Finger millet	*qtl1.1*, *qtl2.1*	[22]

4. Genomic Resources and Tools

The availability of genomic resources and tools has greatly advanced millet genetics and breeding. In recent years, several millet genomes have been sequenced, including foxtail millet [23], pearl millet [24], finger millet [25], and proso millet [26]. These reference genomes have provided valuable insights into the evolution and organization of millet genomes and have facilitated the development of molecular markers and the identification of candidate genes for important traits.

In addition to genome sequences, various other genomic resources have been developed for millets, such as transcriptomes [27], small RNA libraries [28], and expressed sequence tags (ESTs) [29]. These resources have been used to study gene expression patterns, identify regulatory networks, and develop functional markers for breeding applications.

Several bioinformatics tools and databases have also been developed to facilitate the analysis and utilization of millet genomic data. For example, the Foxtail Millet Database (FmDB) [30] and the Pearl Millet Genome Database (PMiGDB) [31] provide access to genomic and genetic information, while the Millet Marker Database (MMD) [32] contains information on molecular markers developed for different millet species.

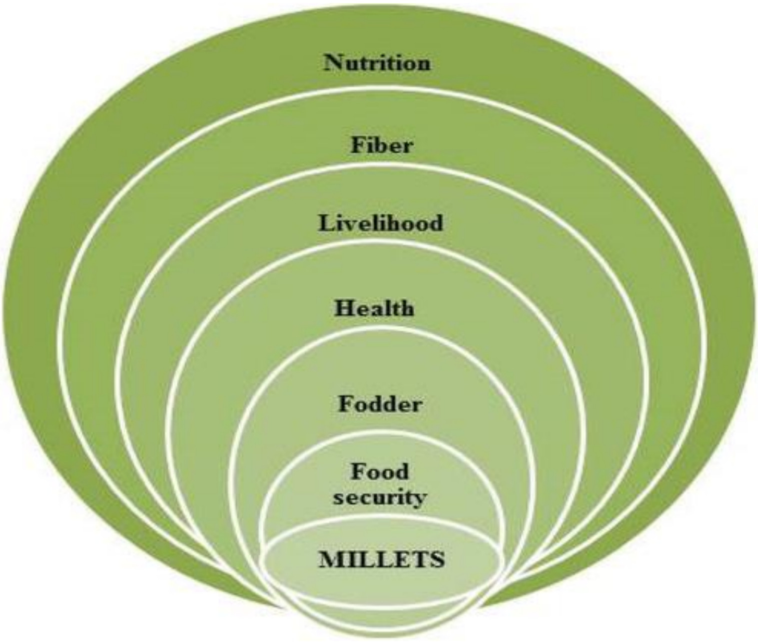
5. Breeding Approaches and Strategies

Millet breeding aims to develop improved varieties with higher yield, better quality, and enhanced stress tolerance. Various breeding approaches and strategies have been employed in millet improvement, including conventional breeding, mutation breeding, and molecular breeding [33].

Conventional breeding involves the selection of superior genotypes based on phenotypic evaluation and the development of new varieties through hybridization and selection. This approach has been widely used in millet breeding and has resulted in the release of several improved varieties [34]. However, conventional breeding is time-consuming and labor-intensive, and its success depends on the availability of genetic variability and the heritability of the traits of interest.

Table 3. Examples of genomic resources available for millets

Resource	**Millet Species**	**Reference**
Genome sequence	Foxtail millet	[23]
Transcriptome	Pearl millet	[27]
Small RNA library	Finger millet	[28]
EST database	Proso millet	[29]

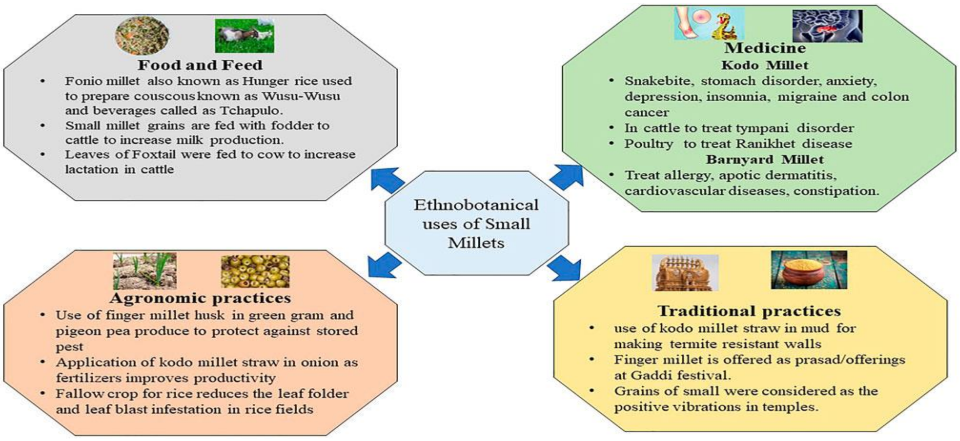


Mutation breeding involves the use of physical or chemical mutagens to induce genetic variations and generate novel alleles for breeding purposes. This approach has been used to develop millet varieties with improved traits, such as higher yield, earlier maturity, and better nutrient content [35]. Mutation breeding can be combined with molecular markers to facilitate the identification and selection of desired mutants.

Molecular breeding involves the use of molecular markers and genomic tools to accelerate the breeding process and improve the efficiency of selection. Marker-assisted selection (MAS) has been used to introgress QTLs for important traits into elite millet varieties [36]. Genomic selection (GS) is another molecular breeding approach that uses genome-wide markers to predict the breeding values of individuals and select superior genotypes [37]. GS has the potential to greatly accelerate the breeding cycle and increase the rate of genetic gain in millets.

Table 4. Comparison of different breeding approaches in millets

Approach	**Advantages**	**Disadvantages**
Conventional breeding	Widely used, no specialized equipment needed	Time-consuming, labor-intensive, limited by genetic variability
Mutation breeding	Generates novel alleles, can be combined with molecular markers	Requires specialized equipment, may produce undesirable mutations
Molecular breeding	Accelerates breeding, improves selection efficiency	Requires genomic resources and tools, may be expensive



Food and Feed

- Fonio millet also known as Hunger rice used to prepare couscous known as Wusu-Wusu and beverages called as Tchapulo.
- Small millet grains are fed with fodder to cattle to increase milk production.
- Leaves of Foxtail were fed to cow to increase lactation in cattle

Medicine

Kodo Millet

- Snakebite, stomach disorder, anxiety, depression, insomnia, migraine and colon cancer
- In cattle to treat tympani disorder
- Poultry to treat Ranikhet disease

Barnyard Millet

- Treat allergy, apotic dermatitis, cardiovascular diseases, constipation.

Ethnobotanical uses of Small Millets

Agronomic practices

- Use of finger millet husk in green gram and pigeon pea produce to protect against stored pest
- Application of kodo millet straw in onion as fertilizers improves productivity
- Fallow crop for rice reduces the leaf folder and leaf blast infestation in rice fields

Traditional practices

- use of kodo millet straw in mud for making termite resistant walls
- Finger millet is offered as prasad/offerings at Gaddi festival.
- Grains of small were considered as the positive vibrations in temples.

6. Genetic Engineering and Genome Editing

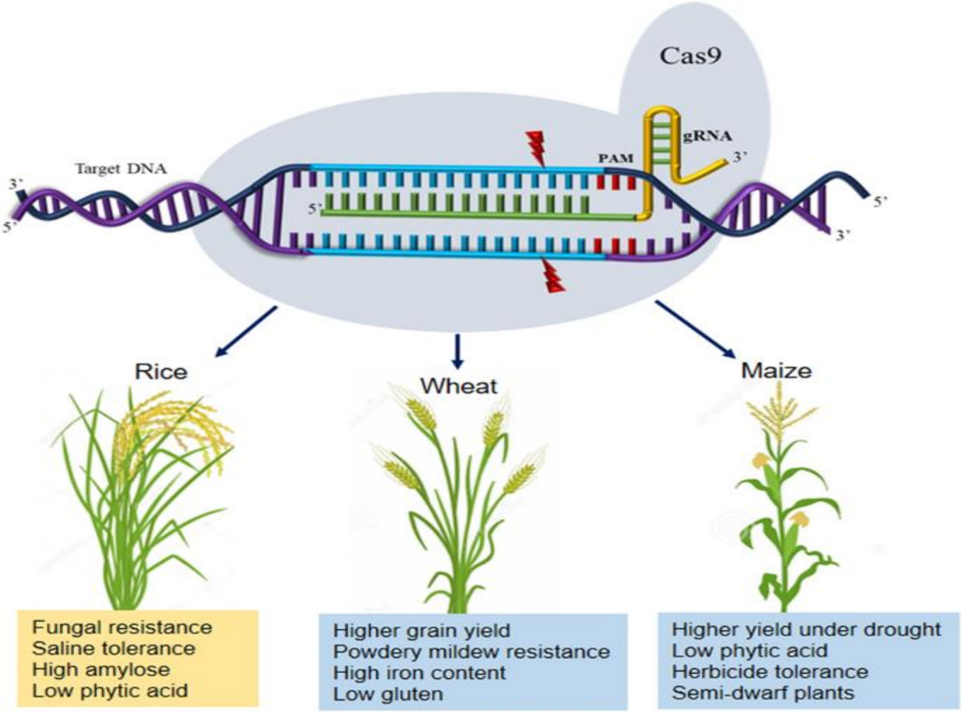
Genetic engineering involves the introduction of foreign genes into the plant genome to confer desirable traits. This approach has been used to develop transgenic millet varieties with improved traits, such as insect resistance [38], herbicide tolerance [39], and enhanced nutrient content [40]. However, the commercialization of transgenic millets has been limited due to regulatory and public acceptance issues. Genome editing is a more recent approach that allows for precise modification of the plant genome without introducing foreign genes. Technologies such as clustered regularly interspaced short palindromic repeats (CRISPR)/Cas9 have been used to edit millet genomes for various purposes, such as generating knockout mutants [41], creating novel alleles [42], and introducing targeted modifications [43]. Genome editing has the potential to accelerate millet breeding by providing a rapid and precise means of generating desired genetic variations.

7. Challenges and Opportunities

Despite the significant progress made in millet breeding and genetics, several challenges remain. One of the major challenges is the limited availability of genomic resources and tools for some millet species, which hinders the application of modern breeding approaches. There is a need to generate more genomic data and develop user-friendly databases and tools to facilitate millet research and breeding.

Table 5. Examples of genetic engineering and genome editing studies in millets

Trait	Approach	Millet Species	Reference
Insect resistance	Genetic engineering	Pearl millet	[38]
Herbicide tolerance	Genetic engineering	Foxtail millet	[39]
Nutrient content	Genetic engineering	Finger millet	[40]
Knockout mutants	Genome editing	Proso millet	[41]
Novel alleles	Genome editing	Pearl millet	[42]



Another challenge is the narrow genetic base of some millet species, which limits the scope for genetic improvement. There is a need to explore and utilize the untapped genetic diversity present in wild relatives and landraces to broaden the genetic base and introduce novel alleles for breeding purposes.

Climate change poses a significant threat to millet production, as it can lead to increased abiotic and biotic stresses. There is a need to develop millet varieties that are resilient to these stresses and can maintain high yields under adverse conditions. This requires a better understanding of the molecular mechanisms underlying stress tolerance and the identification of genes and QTLs that can be used for breeding climate-resilient millets.

Despite these challenges, there are also several opportunities for millet improvement. The increasing demand for nutritious and gluten-free foods presents an opportunity to promote millets as healthy and sustainable food options. The development of value-added products, such as millet-based snacks and beverages, can help in creating new markets and increasing the consumption of millets.

The use of modern breeding tools and techniques, such as genomic selection and genome editing, can greatly accelerate millet breeding and improve the efficiency of developing improved varieties. The integration of these tools with conventional breeding approaches can lead to the development of high-yielding, nutrient-rich, and stress-tolerant millet varieties that can meet the growing demands of the population..

8 Case Studies

8.1. Pearl Millet Breeding in India

India is the largest producer of pearl millet globally, with the crop being grown on approximately 7 million hectares [44]. The Indian Council of Agricultural Research (ICAR) and various state agricultural universities have been actively involved in pearl millet breeding for several decades. The use of molecular markers and genomic tools has greatly enhanced the efficiency of pearl millet breeding in India.

For example, researchers at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) and their collaborators have used marker-assisted selection (MAS) to develop pearl millet varieties with improved resistance to downy mildew, a major disease that can cause significant yield losses [45]. They identified QTLs for downy mildew resistance and used them to develop resistant varieties, such as HHB 67 Improved, which has been widely adopted by farmers in India [46].

8.2. Foxtail Millet Breeding in China

China is the largest producer of foxtail millet, with the crop being cultivated on around 2 million hectares [47]. The Chinese Academy of Agricultural Sciences (CAAS) and provincial academies have been leading foxtail millet breeding efforts in the country. The application of modern breeding tools, such as genome sequencing and molecular markers, has accelerated the development of improved foxtail millet varieties in China.

For instance, researchers at CAAS and their collaborators have sequenced the foxtail millet genome and developed a high-density genetic map, which has facilitated the identification of QTLs for important agronomic traits, such as grain yield and plant height [48]. They have also used these genomic resources to develop molecular markers for marker-assisted breeding, leading to the release of several high-yielding foxtail millet varieties, such as Jingu 21 and Zhangzagu 10 [49].

8.3. Finger Millet Breeding in Africa

Finger millet is an important crop in several African countries, particularly in eastern and southern Africa. The International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) and national agricultural research systems (NARS) have been collaborating on finger millet breeding in Africa. The use of participatory breeding approaches and modern tools has helped in developing improved finger millet varieties that meet the needs of African farmers.

For example, ICRISAT and its partners have used participatory varietal selection (PVS) to develop finger millet varieties with improved yield, early maturity, and blast disease resistance in Kenya, Tanzania, and Uganda [50]. They have also used molecular markers to assess the genetic diversity of finger millet germplasm and identify promising parental lines for breeding [51]. These efforts have led to the release of several improved finger millet varieties, such as U 15 and P 224, which have been adopted by farmers in the region [52].

These case studies highlight the successful application of modern breeding tools and approaches in millet breeding programs across different regions of the world. The integration of these tools with conventional breeding methods has led to the development of improved millet varieties with higher yield, better nutritional quality, and enhanced resilience to biotic and abiotic stresses. Such collaborative efforts involving international research organizations and national partners are crucial for advancing millet breeding and ensuring food and nutritional security in the face of global challenges like climate change and population growth.

8. Conclusion

Millets are important crops that play a vital role in ensuring food and nutritional security, especially in arid and semi-arid regions of the world. The recent research and development advances in millet breeding and genetics have greatly enhanced our understanding of the genetic basis of important agronomic traits and have provided valuable tools and resources for millet improvement. The use of modern breeding approaches, such as molecular markers, genomic selection, and genome editing, can greatly accelerate the development of improved millet varieties. However, there is a need to address the challenges related to the limited availability of genomic resources, narrow genetic base, and climate change to fully harness the potential of millets. The opportunities presented by the increasing demand for nutritious and sustainable foods and the integration of modern breeding tools with conventional approaches can lead to the development of high-yielding, nutrient-rich, and stress-tolerant millet varieties that can contribute to the achievement of the Sustainable Development Goals.

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CHAPTER - 11

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Millet Agronomy: Best Practices for Sustainable Cultivation

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Abstract

Millets are ancient cereal grains that have been cultivated for thousands of years in arid and semi-arid regions of Asia and Africa. In recent years, there has been renewed interest in millet cultivation due to their nutritional benefits, climate resilience, and potential for sustainable agriculture. In 2023, the United Nations declared the International Year of Millets to raise awareness about these underutilized crops and promote their production and consumption globally. This chapter provides a comprehensive overview of millet agronomy, focusing on the best practices for sustainable cultivation. It covers the major millet species grown worldwide, their adaptability to diverse agro-climatic conditions, and their role in ensuring food and nutritional security. The chapter discusses the latest advancements in millet breeding, including the development of high-yielding, stress-tolerant, and bio-fortified varieties. It also highlights the importance of adopting sustainable agronomic practices such as conservation tillage, crop rotation, intercropping, and integrated nutrient and pest management to enhance millet productivity while conserving natural resources. Additionally, the chapter explores the challenges and opportunities in millet value chain development, emphasizing the need for strengthening market linkages, processing technologies, and policy support to boost millet production and consumption. The information presented in this chapter is based on extensive literature review and expert insights, making it a valuable resource for researchers, policymakers, and practitioners working towards promoting sustainable millet cultivation and achieving the Sustainable Development Goals.

Keywords: *Millet Agronomy, Sustainable Agriculture, Climate Resilience, Bio-Fortification, Value Chain Development.*

1. Introduction

Millets are a diverse group of small-seeded cereal crops that have been cultivated for thousands of years in the arid and semi-arid regions of Asia and Africa [1]. They are known for their high nutritional value, climate resilience, and low input requirements, making them an ideal crop for sustainable agriculture [2]. Millets are rich in dietary fiber, minerals, vitamins, and antioxidants, and have a low glycemic index, making them suitable for people with diabetes and other metabolic disorders [3]. Despite their numerous benefits, millets have been largely neglected in the global food system, with their production and consumption declining over the past few decades [4].

However, in recent years, there has been a renewed interest in millet cultivation due to the growing concerns about food and nutritional security, climate change, and environmental sustainability [5]. The United Nations General Assembly declared 2023 as the International Year of Millets, recognizing the potential of these ancient grains in addressing the challenges of the 21st century [6]. This has led to increased research and policy attention towards promoting millet production and consumption globally.

2. Major Millet Species and Their Distribution

Millets are a diverse group of cereal crops belonging to the family *Poaceae*. There are several species of millets grown worldwide, each with distinct morphological and agronomic characteristics [7].

2.1 **Pearl Millet** (*Pennisetum glaucum*) Pearl millet is the most widely cultivated millet species, accounting for over 50% of the global millet production [8]. It is grown primarily in the arid and semi-arid regions of Asia and Africa, where it is a staple food for millions of people [9]. Pearl millet is known for its high drought tolerance, heat resistance, and ability to grow in poor soils [10]. It is also a rich source of protein, iron, and zinc, making it a valuable crop for combating malnutrition [11].

2.2 **Finger Millet** (*Eleusine coracana*) Finger millet, also known as ragi, is an important staple crop in the semi-arid regions of East Africa and South Asia [12]. It is highly valued for its nutritional properties, particularly its high calcium content, which is several times higher than that of other cereals [13]. Finger millet is also rich in dietary fiber, iron, and essential amino acids [14]. It is a hardy crop that can grow in marginal soils and withstand drought and heat stress [15].

2.3 **Foxtail Millet** (*Setaria italica*) Foxtail millet is an ancient crop that originated in China and is now grown in several parts of Asia and Europe [16]. It is a fast-growing crop with a short growing season, making it suitable for multiple cropping systems [17]. Foxtail millet is rich in protein, dietary fiber, and antioxidants, and has a low glycemic index [18]. It is also known for its drought tolerance and ability to grow in poor soils [19].

2.4 **Proso Millet** (*Panicum miliaceum*) Proso millet, also known as common millet or broomcorn millet, is a short-duration crop that is grown primarily in the dry regions of Asia, Europe, and North America [20]. It is valued for its quick maturity, drought tolerance, and ability to grow in poor soils [21]. Proso millet is a good source of protein, dietary fiber, and essential minerals such as iron and magnesium [22].

2.5 **Kodo Millet** (*Paspalum scrobiculatum*) Kodo millet is a minor millet species that is grown primarily in the semi-arid regions of India and Africa [23]. It is known for its high drought tolerance and ability to grow in poor soils [24]. Kodo millet is rich in dietary fiber, protein, and essential minerals such as calcium and iron [25]. It is also known to have medicinal properties and is used in traditional medicine to treat various ailments [26].

2.6 **Little Millet** (*Panicum sumatrense*) Little millet is a small-seeded millet species that is grown primarily in the semi-arid regions of India and Southeast Asia [27]. It is a short-duration crop that can be grown in multiple cropping systems [28]. Little millet is a good source of protein, dietary fiber, and essential minerals such as iron and calcium [29]. It is also known for its drought tolerance and ability to grow in marginal soils [30].

2.7 **Barnyard Millet** (*Echinochloa frumentacea*) Barnyard millet is a minor millet species that is grown primarily in the semi-arid regions of India and Japan [31]. It is a fast-growing crop with a short growing season, making it suitable for multiple cropping systems [32]. Barnyard millet is a good source of protein, dietary fiber, and essential minerals such as iron and calcium [33]. It is also known for its drought tolerance and ability to grow in waterlogged soils [34].

Table 1: Major Millet species and their distribution

Millet Species	Scientific Name	Major Growing Regions
Pearl Millet	*Pennisetum glaucum*	Asia, Africa
Finger Millet	*Eleusine coracana*	East Africa, South Asia
Foxtail Millet	*Setaria italica*	Asia, Europe
Proso Millet	*Panicum miliaceum*	Asia, Europe, North America
Kodo Millet	*Paspalum scrobiculatum*	India, Africa
Little Millet	*Panicum sumatrense*	India, Southeast Asia
Barnyard Millet	*Echinochloa frumentacea*	India, Japan

3. Climate Resilience and Adaptability of Millets

Millets are known for their remarkable adaptability to diverse agro-climatic conditions, particularly in the arid and semi-arid regions where other crops fail to thrive [35]. They are often referred to as "famine reserves" due to their ability to produce reliable yields under harsh environmental conditions such as drought, heat stress, and poor soil fertility [36].

3.1 Drought Tolerance Millets have evolved several morphological and physiological mechanisms to cope with drought stress. They have a deep and extensive root system that enables them to extract moisture from deeper soil layers [37]. Millets also have a waxy cuticle on their leaves that reduces water loss through transpiration [38]. Additionally, they have the ability to adjust their osmotic potential and accumulate compatible solutes such as proline and glycine betaine, which help them maintain turgor pressure under water-deficit conditions [39].

3.2 Heat Tolerance Millets are well adapted to high temperature stress, which is a common abiotic constraint in the semi-arid tropics. They have a C4 photosynthetic pathway, which enables them to maintain high photosynthetic efficiency even at high temperatures [40]. Millets also have a higher temperature threshold for seed germination and seedling growth compared to other cereals [41]. Additionally, they have heat shock proteins and antioxidant defense mechanisms that protect them from oxidative damage caused by heat stress [42].

3.3 Low Nutrient Requirements Millets are known for their ability to grow in marginal soils with low nutrient availability. They have a high nutrient use efficiency, particularly for nitrogen and phosphorus, which are often limiting in the semi-arid tropics [43]. Millets also have the ability to solubilize unavailable forms of phosphorus in the soil through the secretion of organic acids and enzymes [44]. Additionally, they have a symbiotic association with arbuscular mycorrhizal fungi, which enhance their nutrient uptake and improve soil health [45].

3.4 Tolerance to Biotic Stresses Millets have evolved several defense mechanisms against biotic stresses such as pests and diseases. They have a hard seed coat that protects them from storage pests such as insects and fungi [46]. Millets also have a high silica content in their leaves and stems, which acts as a physical barrier against insect pests [47]. Additionally, they have several secondary metabolites such as phenols and flavonoids that have antimicrobial and insecticidal properties [48].

Table 2: Mechanisms of climate resilience in millets

Stress Factor	Adaptive Mechanism	Examples
Drought	Deep root system	Pearl millet, Finger millet
	Waxy cuticle	Foxtail millet, Proso millet
	Osmotic adjustment	Kodo millet, Little millet
Heat	C4 photosynthesis	All millets
	Heat shock proteins	Finger millet, Barnyard millet
	Antioxidant defense	Pearl millet, Foxtail millet
Low Nutrients	High nutrient use efficiency	All millets
	Phosphorus solubilization	Finger millet, Kodo millet
	Mycorrhizal association	Pearl millet, Little millet
Biotic Stresses	Hard seed coat	All millets
	High silica content	Foxtail millet, Barnyard millet

	Secondary metabolites	Finger millet, Proso millet

4. Millet Breeding for Improved Varieties

Millet breeding has made significant progress in recent years, with the development of high-yielding, stress-tolerant, and biofortified varieties that can enhance millet productivity and nutritional quality [49]. The breeding objectives for millets vary depending on the target environment and end-use, but generally focus on improving yield potential, resistance to biotic and abiotic stresses, grain quality, and nutritional traits [50].

4.1 Yield Improvement

Yield is a complex trait that is influenced by several genetic and environmental factors. Millet breeders have used various approaches such as hybridization, mutation breeding, and marker-assisted selection to develop high-yielding varieties [51]. For example, the development of hybrid pearl millet in India has led to a significant increase in yield potential, with some hybrids yielding up to 5 tons per hectare [52]. Similarly, the use of mutation breeding in finger millet has led to the development of high-yielding varieties such as GPU 28 and GPU 66, which have a yield potential of up to 3.5 tons per hectare [53].

4.2 Resistance to Biotic Stresses

Millets are susceptible to several biotic stresses such as blast, downy mildew, smut, and ergot, which can cause significant yield losses [54]. Breeding for disease resistance is an important objective in millet improvement programs. Millet breeders have used various approaches such as introgressions from wild relatives, induced mutations, and marker-assisted selection to develop disease-resistant varieties [55]. For example, the use of marker-assisted backcrossing has led to the development of blast-resistant finger millet varieties such as MR 1 and MR 6 [56].

4.3 Tolerance to Abiotic Stresses

Millets are often grown in marginal environments with several abiotic stresses such as drought, heat, salinity, and low soil fertility [57]. Breeding for abiotic stress tolerance is critical for enhancing millet productivity in these environments. Millet breeders have used various approaches such as screening of germplasm collections, induced mutations, and marker-assisted selection to develop stress-tolerant varieties [58]. For example, the use of marker-assisted selection has led to the development of drought-tolerant pearl millet varieties such as HHB 67 Improved and HHB 197 [59].

4.4 Biofortification

Biofortification refers to the genetic enhancement of crops with essential micronutrients such as iron, zinc, and vitamin A [60]. Millets are naturally rich in several micronutrients, but their levels can be further enhanced through breeding [61]. Millet breeders have used various approaches such as germplasm screening, induced mutations, and transgenic technology to develop biofortified varieties [62]. For example, the use of transgenic technology has led to the development of high-iron pearl millet with up to 80 ppm of iron in the grain [63].

Table 3: Examples of improved millet varieties developed through breeding

Millet Species	Variety Name	Breeding Objective	Salient Features
Pearl Millet	HHB 67 Improved	Drought tolerance	15-20% higher yield under drought
	ICTP 8203 Fe	Bio-fortification	70-80 ppm iron in grain
Finger Millet	GPU 28	High yield	3.5 tons/ha yield potential
	MR 6	Blast resistance	Resistant to finger blast disease
Foxtail Millet	SiA 3085	High yield	2.5 tons/ha yield potential
Proso Millet	Sushak	Drought tolerance	15% higher yield under drought
Kodo Millet	DPS 9-1	High yield	1.5 tons/ha yield potential
Little Millet	OLM 203	High yield	1.8 tons/ha yield potential
Barnyard Millet	DHBM 93-3	High yield	2.0 tons/ha yield potential

5. Sustainable Agronomic Practices for Millet Cultivation

Sustainable agriculture involves the adoption of agronomic practices that enhance crop productivity while conserving natural resources and promoting environmental sustainability [64]. Millet cultivation can be made more sustainable through the adoption of various agronomic practices such as conservation tillage, crop rotation, intercropping, integrated nutrient management, and integrated pest management [65].

5.1 Conservation Tillage

Conservation tillage refers to the practice of minimizing soil disturbance and maintaining crop residues on the soil surface [66]. It helps in reducing soil erosion, conserving soil moisture, and improving soil health [67]. Conservation tillage practices such as zero tillage and minimum tillage have been found to be effective in enhancing millet productivity, particularly in drought-prone environments [68]. For example, a study conducted in Rajasthan, India, found that pearl millet grown under zero tillage had 20% higher yield compared to conventional tillage [69].

5.2 Crop Rotation

Crop rotation refers to the practice of growing different crops in succession on the same land [70]. It helps in breaking pest and disease cycles, improving soil fertility, and enhancing crop productivity [71]. Millets can be effectively rotated with legumes such as pigeonpea, mungbean, and cowpea, which

5.3 Intercropping

Intercropping refers to the practice of growing two or more crops simultaneously on the same land [72]. It helps in maximizing resource use efficiency, reducing pest and disease incidence, and providing insurance against crop failure [73]. Millets can be effectively intercropped with legumes such as pigeonpea, soybean, and groundnut, which provide nitrogen to the soil and improve millet productivity [74]. For example, a study conducted in Karnataka, India, found that finger millet intercropped with pigeonpea had 30% higher yield and 50% higher net returns compared to sole cropping [75].

5.4 Integrated Nutrient Management

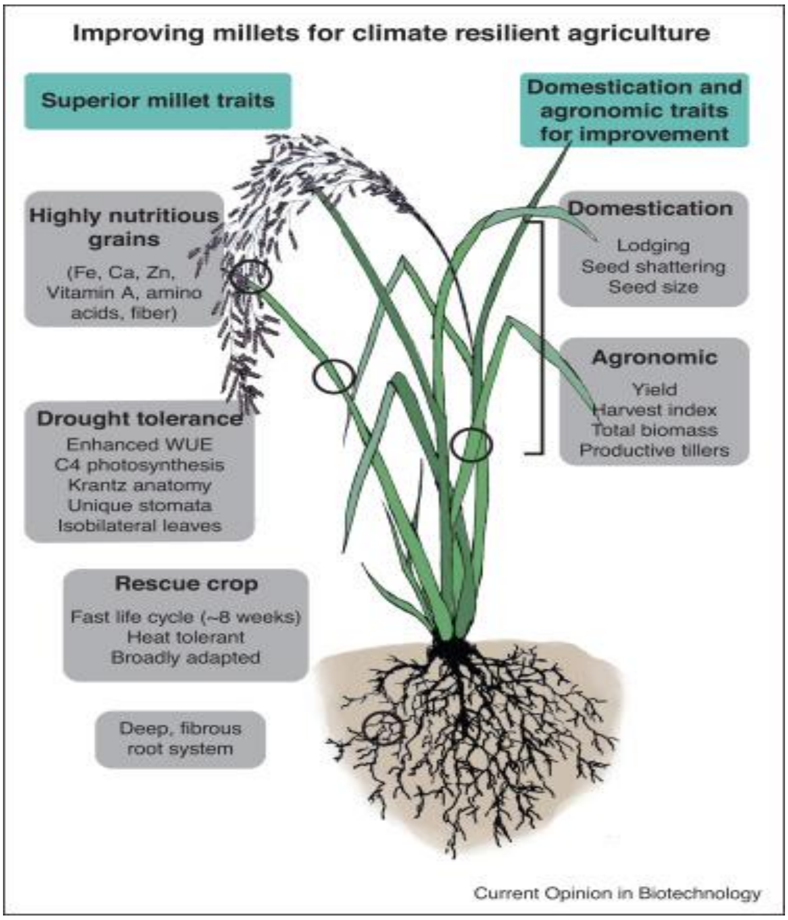
Integrated nutrient management refers to the balanced and efficient use of organic and inorganic sources of nutrients to enhance crop productivity and soil health [76]. Millets are known to respond well to organic manures such as farmyard manure, vermicompost, and green manure, which improve soil physical, chemical, and biological properties [77]. The use of biofertilizers such as Azospirillum, Azotobacter, and phosphate-solubilizing bacteria can also enhance millet productivity and reduce the dependence on chemical fertilizers

[78]. For example, a study conducted in Andhra Pradesh, India, found that the application of farmyard manure and biofertilizers along with 50% recommended dose of chemical fertilizers resulted in 15% higher yield and 25% higher net returns in pearl millet compared to the recommended dose of chemical fertilizers alone [79].

5.5 Integrated Pest Management

Integrated pest management (IPM) refers to the use of a combination of pest control methods to minimize crop losses while reducing the use of chemical pesticides [80]. Millets are susceptible to several insect pests such as shoot fly, stem borer, earhead caterpillar, and aphids, which can cause significant yield losses [81]. The use of resistant varieties, cultural practices such as early sowing and intercropping, biological control agents such as parasitoids and predators, and need-based application of safe pesticides can effectively manage these pests [82]. For example, a study conducted in Tamil Nadu, India, found that the adoption of IPM practices such as seed treatment with Pseudomonas fluorescens, intercropping with cowpea, and need-based application of neem oil resulted in 40% reduction in shoot fly incidence and 20% higher yield in sorghum compared to farmers' practice [83].

Figure 1: Sustainable agronomic practices for millet cultivation



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6. Millet Value Chain Development

Millet value chain development involves the strengthening of linkages between different actors involved in the production, processing, marketing, and consumption of millets [84]. It aims to enhance the efficiency, profitability, and sustainability of the millet sector by addressing the constraints and opportunities at each stage of the value chain [85].

6.1 Production

The production stage of the millet value chain involves the cultivation of millets by smallholder farmers, who often face challenges such as low productivity, limited access to inputs and extension services, and high production costs [86]. Strengthening the production stage requires interventions such as the promotion of improved varieties and agronomic practices, the provision of quality inputs and technical assistance, and the formation of farmer groups and cooperatives [87]. For example, the African Millet Improvement Program (AMIP) has been working with national agricultural research systems in West

Africa to develop and disseminate improved millet varieties and agronomic practices, which have resulted in a 30-50% increase in millet productivity [88].

6.2 Processing

The processing stage of the millet value chain involves the transformation of raw millet grains into various value-added products such as flour, semolina, malt, and snacks [89]. Millet processing is often done at the household or village level using traditional methods, which are labor-intensive and result in low-quality products [90]. Strengthening the processing stage requires interventions such as the development of improved processing technologies, the establishment of small and medium-scale processing units, and the training of processors on quality and safety standards [91]. For example, the All India Coordinated Research Project on Post-Harvest Technology (AICRP-PHT) has developed several millet processing technologies such as a pearler, dehuller, and flaking machine, which have been commercialized and adopted by processors in India [92].

6.3 Marketing

The marketing stage of the millet value chain involves the distribution and sale of millet grains and products to different markets and consumers [93]. Millet marketing is often constrained by factors such as low market demand, poor market infrastructure, and limited access to market information [94]. Strengthening the marketing stage requires interventions such as the development of market linkages, the creation of consumer awareness, and the promotion of millet-based products [95]. For example, the Smart Food initiative led by the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) has been promoting millets as a healthy and sustainable food choice through various marketing and communication campaigns, which have resulted in increased demand for millet-based products in India and Africa [96].

6.4 Consumption

The consumption stage of the millet value chain involves the utilization of millet grains and products by different consumers such as households, institutions, and food industries [97]. Millet consumption is often limited by factors such as changing food preferences, lack of awareness about the nutritional benefits of millets, and limited availability of millet-based products [98]. Strengthening the consumption stage requires interventions such as the inclusion of millets in public distribution systems, the development of millet-based recipes and products, and the promotion of millets as a healthy and diverse food choice [99]. For example, the Indian government has included millets in the public distribution system under the National Food Security Act, which has increased the access and affordability of millets for poor households [100].

Table 4: Challenges and opportunities in millet value chain development

Value Chain Stage	**Challenges**	**Opportunities**
Production	Low productivity	Improved varieties and agronomic practices
	Limited access to inputs and extension	Quality inputs and technical assistance
	High production costs	Farmer groups and cooperatives
Processing	Traditional and inefficient methods	Improved processing technologies
	Low quality and unsafe products	Small and medium-scale processing units
	Limited value addition	Training on quality and safety standards
Marketing	Low market demand	Market linkages and consumer awareness
	Poor market infrastructure	Promotion of millet-based products
	Limited access to market information	Branding and labeling of millet products
Consumption	Changing food preferences	Inclusion in public distribution systems
	Lack of nutritional awareness	Development of millet-based recipes and products
	Limited availability of millet products	Promotion as a healthy and diverse food

7. Policy Support for Millet Promotion

Millet promotion requires an enabling policy environment that supports the production, processing, marketing, and consumption of millets [101]. Several countries have introduced policies and programs to promote millets as part of their strategies for food and nutritional security, climate resilience, and sustainable agriculture [102].

7.1 National Policies and Programs

In India, the government has launched several initiatives to promote millets, such as the inclusion of millets in the public distribution system, the establishment of a Millet Mission, and the declaration of 2018 as the National Year of Millets [103]. The Millet Mission aims to increase millet production, consumption, and value addition through various interventions such as the distribution of seed kits, the establishment of processing units, and the creation of awareness about the nutritional benefits of millets [104]. Similarly, in Ethiopia, the government has included millets in its national agricultural development strategy and has been promoting the production and consumption of millets through various extension and nutrition education programs [105].

7.2 International Initiatives

At the international level, several organizations have been promoting millets as part of their efforts to achieve the Sustainable Development Goals (SDGs) [106]. For example, the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) has been leading the Smart Food initiative, which aims to promote millets and other neglected and underutilized species as smart food choices for the planet and people [107]. The Food and Agriculture Organization (FAO) has also been supporting millet promotion through various projects and programs, such as the "Neglected and Underutilized Species Community" and the "Scaling Up Nutrition (SUN) Movement" [108].

7.3 Research and Development

Research and development (R&D) plays a critical role in generating knowledge and innovations that can enhance the production, processing, and utilization of millets [109]. Several national and international research organizations have been conducting R&D on millets, such as the Indian Council of Agricultural Research (ICAR), the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), and the CGIAR Research Program on Grain Legumes and Dryland Cereals (GLDC) [110]. These organizations have been developing improved millet varieties, agronomic practices, processing technologies, and value-added products that can benefit smallholder farmers and consumers [111].

7.4 Capacity Building and Partnerships

Capacity building and partnerships are essential for scaling up millet promotion and mainstreaming it into the food systems [112]. Several organizations have been involved in capacity building and partnerships for millet promotion, such as the African Millet Improvement Program (AMIP), the All India Coordinated Research Project on Small Millets (AICRP-Small Millets), and the Millets Network of India (MINI) [113]. These organizations have been providing training, technical assistance, and networking opportunities to different stakeholders involved in the millet value chain, such as farmers, processors, marketers, and policymakers [114].

Figure 2: Policy support for millet promotion

8. Conclusion

Millets are climate-resilient and nutritious crops that have the potential to contribute to food and nutritional security, sustainable agriculture, and rural livelihoods. This chapter has provided a comprehensive overview of the best practices for sustainable millet cultivation, including the major millet species and their distribution, the climate resilience and adaptability of millets, the advances in millet breeding for improved varieties, the sustainable agronomic practices for millet cultivation, the development of millet value chains, and the policy support for millet promotion. The adoption of these best practices can help in realizing the full potential of millets and achieving the Sustainable Development Goals. However, it requires the concerted efforts of different stakeholders, including farmers, researchers, policymakers, and consumers, to create an enabling environment for millet production, processing, marketing, and consumption.

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CHAPTER - 12

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Empowering Smallholder Millet Farmers: Challenges and Solutions

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Abstract

Millets are nutritious, climate-resilient crops that have been cultivated by smallholder farmers in India for millennia. However, in recent decades, millet production and consumption have declined due to various challenges faced by these farmers. This chapter explores the current state of smallholder millet farming in India, identifies the key challenges impeding its growth and sustainability, and proposes practical solutions to empower these farmers. The major challenges discussed include low productivity, inadequate market access, insufficient government support, climate change impacts, and changing consumer preferences. The proposed solutions encompass technological interventions, policy reforms, infrastructure development, capacity building, and awareness raising. By implementing these solutions in a holistic and integrated manner, smallholder millet farmers can be empowered to enhance their livelihoods, contribute to food and nutrition security, and promote sustainable agriculture in India. The International Year of Millets 2023 presents a unique opportunity to bring attention to these issues and drive positive change in the millet sector.

Keywords: *Millets, Smallholder farmers, India, Challenges, Solutions*

1. Introduction:

Millets are a group of small-seeded cereal crops that have been cultivated for thousands of years in India and other parts of the world. These crops are known for their nutritional value, climate resilience, and ability to grow in marginal lands with minimal inputs [1]. In India, millets have traditionally been an important part of the diet and farming systems of smallholder farmers, particularly in the semi-arid and drought-prone regions of the country [2].

However, in recent decades, the area under millet cultivation and the consumption of millets have declined significantly in India [3]. This decline can be attributed to various challenges faced by smallholder millet farmers, such as low productivity, inadequate market access, insufficient government support, and changing consumer preferences [4]. As a result, many smallholder millet farmers have been struggling to sustain their livelihoods and have been forced to abandon millet cultivation in favor of other crops or non-farm activities [5].

The International Year of Millets 2023, declared by the United Nations General Assembly, presents a unique opportunity to bring attention to the challenges faced by smallholder millet farmers and to promote solutions that can empower them [6]. This chapter aims to contribute to this effort by providing an in-depth analysis of the current state of smallholder millet farming in India, identifying the key challenges impeding its growth and sustainability, and proposing practical solutions to address these challenges.

2. Importance of Millets and Smallholder Millet Farming in India

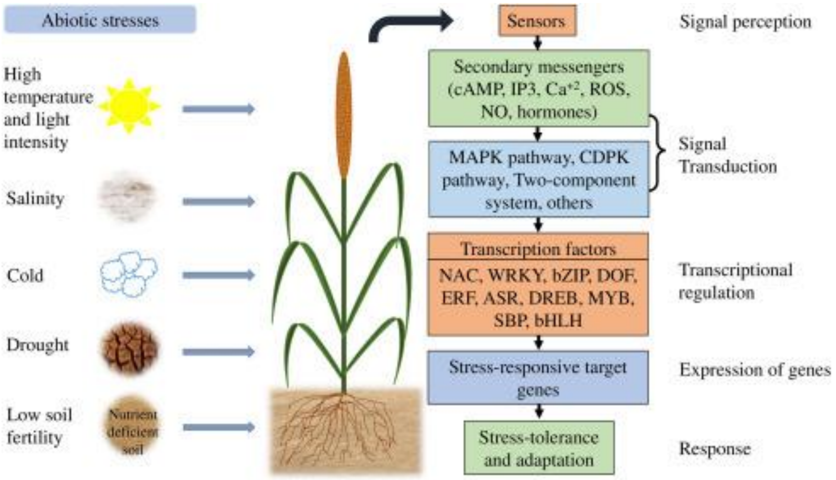
2.1 Nutritional and Health Benefits of Millets Millets are highly nutritious crops that are rich in proteins, dietary fiber, minerals, and vitamins [7].

Table 1. Nutritional composition of common millet types in India (per 100 g)**[8]**

Millet Type	Energy (kcal)	Protein (g)	Fat (g)	Carbohydrate (g)	Dietary Fiber (g)	Iron (mg)	Calcium (mg)
Pearl Millet (*Pennisetum glaucum*)	361	11.6	4.8	67.5	11.3	8.0	42
Finger Millet (*Eleusine coracana*)	336	7.3	1.3	72.6	11.5	3.9	344
Foxtail Millet (*Setaria italica*)	331	12.3	4.3	60.9	8.0	2.8	31
Kodo Millet (*Paspalum scrobiculatum*)	309	8.3	1.4	65.9	9.0	0.5	27
Little Millet (*Panicum sumatrense*)	329	7.7	4.7	67.0	7.6	9.3	17
Barnyard Millet (*Echinochloa frumentacea*)	300	11.2	3.9	74.3	14.7	15.2	22
Proso Millet (*Panicum miliaceum*)	341	12.5	3.5	70.4	6.7	2.9	8

The high nutrient content of millets makes them a valuable food source for combating malnutrition and micronutrient deficiencies, which are prevalent in many parts of India [9]. Studies have shown that regular consumption of millets can help in managing and preventing various health issues such as diabetes, obesity, cardiovascular diseases, and certain cancers [10][11].

Figure 1. Potential health benefits of millets **[12]**



2.2 Climate Resilience and Sustainability of Millet Cultivation:

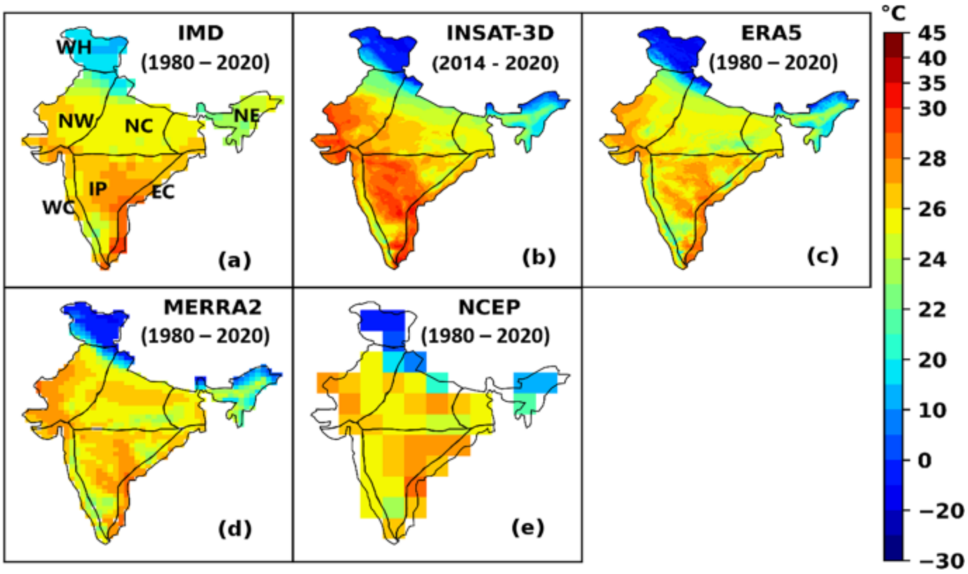
Millets are known for their remarkable ability to grow under harsh climatic conditions, such as high temperatures, low rainfall, and poor soil fertility [13]. This makes them ideal crops for cultivation in the semi-arid and drought-prone regions of India, where other crops may struggle to survive [14].

Table 2. Water requirement and drought tolerance of millets and other cereals **[15][16]**

Crop	**Water Requirement (mm)**	**Drought Tolerance**
Pearl Millet (*Pennisetum glaucum*)	200-600	High
Finger Millet (*Eleusine coracana*)	300-500	High
Foxtail Millet (*Setaria italica*)	250-400	High
Sorghum (*Sorghum bicolor*)	400-800	High
Maize (*Zea mays*)	500-800	Medium
Rice (*Oryza sativa*)	1000-2500	Low
Wheat (*Triticum aestivum*)	450-650	Medium

The climate resilience of millets makes them a crucial component of sustainable agriculture systems, particularly in the context of climate change [17]. As the frequency and intensity of droughts and heat waves are expected to increase in India due to climate change, the cultivation of millets can help in adapting to these challenges and ensuring food security [18].

Figure 2. Projected changes in temperature and precipitation in India under different climate change scenarios [19]



2.3 Socio-Economic Significance of Smallholder Millet Farming:

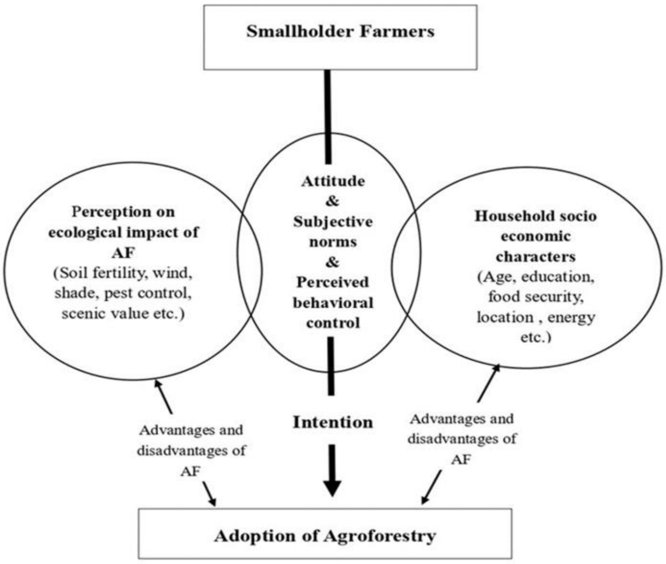
Smallholder millet farming plays a vital role in the socio-economic fabric of rural India. It is estimated that over 60% of the millet production in India comes from smallholder farmers, who cultivate millets on less than 2 hectares of land [20]. These farmers often belong to marginalized and resource-poor communities, for whom millet cultivation is a means of subsistence and livelihood [21]. Millet farming not only provides food and nutritional security to these farmers and their families but also generates employment and income opportunities [22]. It is estimated that millet cultivation generates about 50-70 person-days of employment per hectare, which is higher than that of other major crops like rice and wheat [23]. Table 3 presents the employment generation potential of different crops in India.

Table 3. Employment generation potential of different crops in India **[24]**

Crop	**Employment Generation (Person-days/ha)**
Millets	50-70
Rice	30-50
Wheat	20-40
Maize	40-60
Pulses	30-50
Oilseeds	20-40

Moreover, millet farming is often integrated with livestock rearing, as the crop residues serve as valuable fodder for cattle and other animals [25]. This integration enhances the economic viability and sustainability of smallholder farming systems [26].

Figure 3. Socio-economic benefits of smallholder millet farming **[27]**



3. Challenges Faced by Smallholder Millet Farmers in India

Despite the numerous benefits of millet cultivation, smallholder millet farmers in India face several challenges that hinder the growth and sustainability of this sector. This section identifies and discusses the major challenges confronting these farmers.

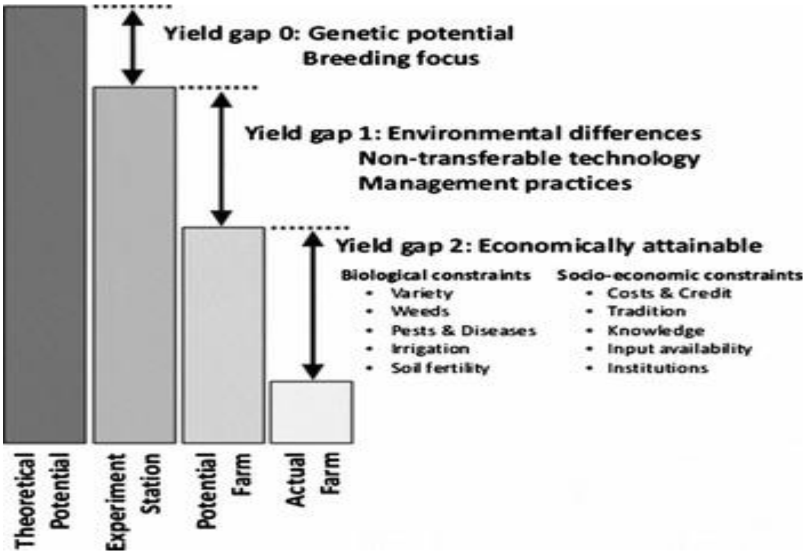
3.1 Low Productivity and Yields One of the primary challenges faced by smallholder millet farmers is the low productivity and yields of their crops [28]. The average yield of millets in India is about 1,000-1,500 kg/ha, which is much lower than that of other major cereal crops like rice (2,500-3,000 kg/ha) and wheat (3,000-3,500 kg/ha) [29]. Table 4 presents the average yields of different crops in India.

Table 4. Average yields of different crops in India (kg/ha) **[30]**

Crop	Average Yield (kg/ha)
Millets	1,000-1,500
Rice	2,500-3,000
Wheat	3,000-3,500
Maize	2,500-3,000
Pulses	600-800
Oilseeds	1,000-1,200

The low productivity of millets can be attributed to various factors, such as the use of traditional varieties with low yield potential, inadequate access to quality seeds and inputs, poor soil fertility, and limited adoption of improved cultivation practices [31][32].

Figure 4. Yield gap between the potential and actual yields of millets India [33]



3.2 Inadequate Market Access and Price Realization:

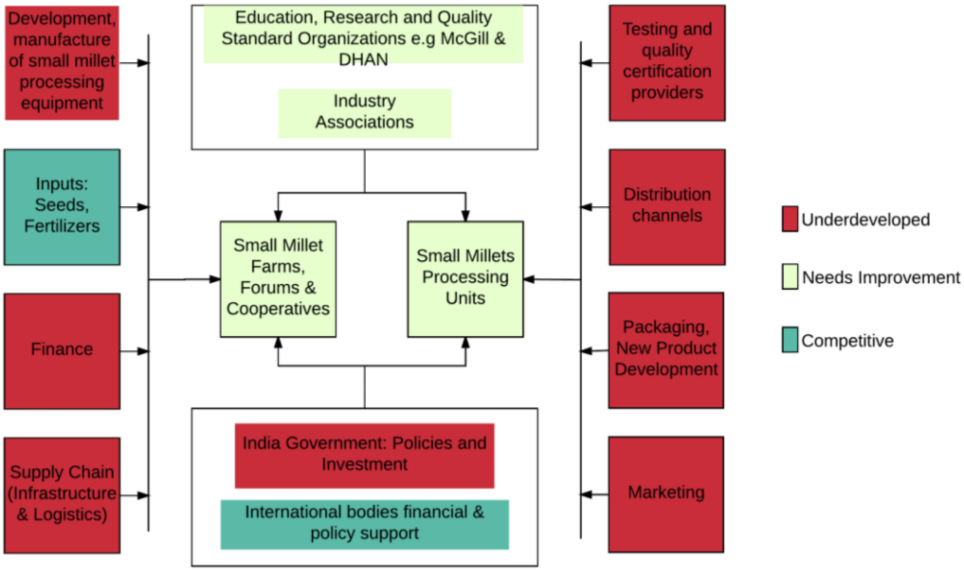
Another major challenge faced by smallholder millet farmers is the lack of adequate market access and price realization for their produce [34]. Millets are often considered as inferior grains and face stiff competition from other crops like rice, wheat, and maize, which have well-established market channels and government procurement systems [35]. Moreover, the absence of proper storage and processing facilities at the village level forces many smallholder millet farmers to sell their produce immediately after harvest at low prices to middlemen or local traders [36]. This not only deprives them of better price realization but also makes them vulnerable to exploitation [37]. Table 5 presents the average farm gate prices of different crops in India.

Table 5. Average farm gate prices of different crops in India (INR/quintal) [38]

Crop	Average Farm Gate Price (INR/quintal)
Millets	1,500-2,000
Rice	1,800-2,200
Wheat	1,900-2,300
Maize	1,400-1,800
Pulses	4,000-6,000
Oilseeds	3,500-5,000

The lack of market linkages and value chain development for millets also limits the opportunities for value addition and income generation for smallholder farmers [39]. Figure 5 illustrates the various constraints in the millet value chain in India.

Figure 5. Constraints in the millet value chain in India **[40]**



3.3 Insufficient Government Support and Policy Incentives:

Smallholder millet farmers in India also face the challenge of insufficient government support and policy incentives for millet cultivation [41]. Unlike rice and wheat, which receive substantial subsidies and procurement support under the Public Distribution System (PDS), millets have been largely neglected in terms of government interventions [42]. The lack of inclusion of millets in the PDS has not only discouraged farmers from cultivating these crops but has also contributed to the decline in their consumption [43]. Moreover, the government's Minimum Support Price (MSP) mechanism, which aims to provide price support to farmers, has not been effectively implemented for millets [44]. Table 6 presents the MSP for different crops in India for the year 2022-23.

Table 6. Minimum Support Prices for different crops in India for 2022-23 (INR/quintal) **[45]**

Crop	**MSP (INR/quintal)**
Pearl Millet	2,350
Finger Millet	3,578
Rice	2,040
Wheat	2,015
Maize	1,962
Pulses (Tur/Arhar)	6,600
Oilseeds (Soybean)	4,300

Although the MSP for millets has been increased in recent years, the actual procurement by government agencies remains limited, leaving most smallholder millet farmers at the mercy of market forces [46]. Figure 6 shows the trends in MSP and procurement of millets in India over the past decade.

3.4 Climate Change Impacts and Risks:

While millets are known for their climate resilience, smallholder millet farmers in India are not immune to the impacts and risks posed by climate change [48]. The increasing frequency and intensity of droughts, heat waves, and extreme weather events can adversely affect the growth and productivity of millet crops [49].

Moreover, the changing rainfall patterns and rising temperatures can alter the sowing and harvesting cycles of millets, leading to crop failures and income losses for smallholder farmers [50]. Table 7 presents the projected impacts of climate change on millet production in India under different scenarios.

Table 7. Projected impacts of climate change on millet production in India **[51]**

Climate Change Scenario	**Projected Impact on Millet Production**
RCP 4.5 (2050)	-5% to -15%
RCP 8.5 (2050)	-10% to -25%
RCP 4.5 (2080)	-10% to -20%
RCP 8.5 (2080)	-20% to -40%

3.5 Changing Consumer Preferences and Lack of Awareness:

The changing consumer preferences and lack of awareness about the nutritional benefits of millets also pose a challenge for smallholder millet farmers [56]. With the increasing urbanization and globalization, there has been a shift in dietary patterns towards refined grains and processed foods, leading to a decline in the consumption of traditional crops like millets [57].

Moreover, the lack of awareness about the health benefits of millets among consumers and the perception of millets as "poor man's food" have further contributed to the declining demand for these crops [58]. Table 8 presents the trends in per capita consumption of millets in India over the past few decades.

Table 8. Trends in per capita consumption of millets in India (kg/year) **[59]**

Year	**Rural**	**Urban**

1972-73	32.0	27.4
1993-94	15.0	12.6
2011-12	6.0	4.7

To address this challenge, there is a need for concerted efforts to create awareness about the nutritional and health benefits of millets among consumers and to promote the inclusion of millets in various food products [60]. This requires collaboration among different stakeholders, including researchers, policymakers, food industry, and civil society organizations [61].

4. Solutions for Empowering Smallholder Millet Farmers

The challenges faced by smallholder millet farmers in India require a multi-pronged approach that addresses the various constraints in the millet value chain and creates an enabling environment for the sustainable growth of this sector [62]. This section presents some of the key solutions and strategies for empowering smallholder millet farmers.

4.1 Enhancing Productivity and Climate Resilience Enhancing the productivity and climate resilience of millet cultivation is crucial for improving the livelihoods of smallholder farmers [63]. This requires the development and dissemination of high-yielding, stress-tolerant millet varieties that can withstand the impacts of climate change [64].

Research and development efforts should focus on breeding millet varieties with improved traits such as drought tolerance, heat resistance, and disease resistance [65]. Participatory plant breeding approaches that involve farmers in the selection and evaluation of new varieties can ensure that the developed varieties meet the specific needs and preferences of smallholder farmers [66].

In addition to varietal improvement, the promotion of sustainable agricultural practices such as intercropping, crop rotation, and integrated nutrient management can help in enhancing the productivity and resilience of millet farming systems [67]. Capacity building of farmers on these practices through training programs, demonstrations, and farmer field schools can facilitate their adoption [68].

4.2 Strengthening Market Linkages and Value Chain Development Strengthening market linkages and promoting value chain development are essential for improving the profitability and competitiveness of smallholder millet farmers [69]. This requires the establishment of efficient marketing channels, development of infrastructure for storage and processing, and creation of demand for millet-based products [70].

The formation of farmer producer organizations (FPOs) can help in aggregating the produce of smallholder farmers, reducing transaction costs, and improving their bargaining power in the market [71]. FPOs can also facilitate the collective procurement of inputs, access to credit, and provision of extension services to their members [72].

The development of small-scale processing units at the village level can create opportunities for value addition and generate additional income for smallholder farmers [73]. These units can be owned and operated by FPOs or through public-private partnerships, with appropriate capacity building and technical support [74].

Creating demand for millet-based products requires the promotion of millets as a healthy and nutritious food option among consumers [75]. This can be achieved through awareness campaigns, food festivals, and the inclusion of millets in various food products such as baked goods, snacks, and ready-to-eat meals [76].

4.3 Providing Institutional Support and Policy Incentives Providing institutional support and policy incentives is crucial for creating an enabling environment for the sustainable growth of the millet sector [77]. This requires the formulation of targeted policies and programs that prioritize millet cultivation, allocate resources for research and development, and provide incentives for smallholder farmers [78].

The inclusion of millets in the Public Distribution System (PDS) and other government food security programs can create assured markets for smallholder farmers and encourage them to cultivate these crops [79]. Providing price support through minimum support prices (MSP) and procurement by government agencies can help in stabilizing the prices and ensuring remunerative returns for farmers [80].

Investments in research and development for millet improvement, value addition, and processing technologies can help in enhancing the productivity and profitability of the millet sector [81]. Strengthening the extension services and capacity building programs for farmers can facilitate the adoption of improved varieties and practices [82].

The provision of crop insurance and weather-based agro-advisory services can help in mitigating the risks associated with climate change and protecting the livelihoods of smallholder farmers [83]. Innovative financing mechanisms such as credit guarantee schemes and venture capital funds can improve access to credit for smallholder farmers and entrepreneurs in the millet sector [84].

4.4 Promoting Collective Action and Stakeholder Collaboration Promoting collective action and stakeholder collaboration is essential for addressing the complex challenges faced by smallholder millet farmers and creating sustainable and inclusive value chains [85]. This requires the active involvement and coordination among farmers, researchers, policymakers, civil society organizations, and the private sector [86].

The formation of multi-stakeholder platforms and networks can facilitate knowledge sharing, policy dialogue, and collaborative action for the promotion of millet cultivation and consumption [87]. These platforms can bring together different actors in the millet value chain to identify common challenges, develop joint strategies, and mobilize resources for implementation [88].

Participatory approaches that engage smallholder farmers in the design and implementation of interventions can ensure that the solutions are context-specific, locally relevant, and socially inclusive [89]. Capacity building of farmers' organizations and community-based organizations can enhance their ability to participate effectively in decision-making processes and advocate for their rights and interests [90].

Public-private partnerships can play a crucial role in leveraging the strengths and resources of different stakeholders for the development of the millet sector [91]. These partnerships can focus on areas such as research and development, infrastructure development, market linkages, and value addition [92].

5. Case Studies of Successful Interventions

5.1 Odisha Millets Mission: Reviving Millet Cultivation and Consumption The Odisha Millets Mission (OMM) is a flagship program of the Government of Odisha, India, which aims to revive millet cultivation and consumption in the state [93]. Launched in 2017, the program adopts a comprehensive approach that includes production, procurement, processing, and consumption of millets [94].

The key components of the OMM include:

- Promotion of millet cultivation through the provision of quality seeds, inputs, and technical support to farmers
- Establishment of decentralized processing units and value addition enterprises at the village level
- Inclusion of millets in the state's public distribution system and government nutrition programs

- Creation of awareness about the nutritional benefits of millets through campaigns and food festivals

The program has achieved significant success in terms of increasing the area under millet cultivation, improving the livelihoods of smallholder farmers, and creating a market for millet-based products [95]. As of 2021, the program has reached over 100,000 farmers and has established more than 1,000 processing units across the state [96].

The success of the OMM can be attributed to its participatory and inclusive approach, which involves the active engagement of farmers, women's self-help groups, and community-based organizations in the planning and implementation of the program [97]. The program has also leveraged the traditional knowledge and practices of local communities in the conservation and promotion of millet biodiversity [98].

5.2 Kodo Millet Value Chain Development in Madhya Pradesh The Kodo Millet Value Chain Development project in Madhya Pradesh, India, is an example of a successful intervention that has empowered smallholder millet farmers through market linkages and value addition [99]. Implemented by the Indian Institute of Millets Research (IIMR) in collaboration with local NGOs, the project aimed to enhance the production, processing, and marketing of kodo millet in the state [100].

The key interventions under the project included:

- Capacity building of farmers on improved production practices and post-harvest management
- Establishment of community-based seed banks and production clusters
- Development of small-scale processing units and value-added products such as kodo millet cookies and snacks
- Linking farmers with markets through the formation of farmer producer organizations (FPOs) and buyer-seller meets

The project has resulted in a significant increase in the production and productivity of kodo millet, with the average yields increasing from 500 kg/ha to 1,500 kg/ha [101]. The project has also created new market opportunities for smallholder farmers through the development of value-added products and linkages with institutional buyers [102].

The success of the project can be attributed to its focus on building the capacities of smallholder farmers and creating an enabling environment for the growth of the kodo millet value chain [103]. The project has also demonstrated the potential of public-private partnerships in promoting the sustainable development of underutilized crops like millets [104].

6. Conclusion

Empowering smallholder millet farmers in India is crucial for achieving food and nutritional security, promoting sustainable agriculture, and improving rural livelihoods. This chapter has highlighted the significant challenges faced by these farmers, including low productivity, inadequate market access, insufficient government support, and climate change impacts. However, it has also presented a range of strategies and solutions to address these challenges and create an enabling environment for the growth of the millet sector.

The key solutions discussed in this chapter include enhancing productivity and climate resilience through the development and dissemination of improved varieties and practices, strengthening market linkages and value chain development, providing institutional support and policy incentives, and promoting collective action and stakeholder collaboration. The case studies from Odisha and Madhya Pradesh have demonstrated the potential of targeted interventions and multi-stakeholder partnerships in reviving millet cultivation and empowering smallholder farmers.

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CHAPTER - 13

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Millet Policies and Government Initiatives Worldwide

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Abstract

Millets are a group of highly nutritious cereal grains that have gained renewed attention in recent years due to their potential to enhance food and nutritional security, especially in the context of climate change. This chapter provides an overview of the various policies and initiatives implemented by governments worldwide to promote the cultivation, consumption, and trade of millets. The chapter begins by highlighting the nutritional and ecological significance of millets, followed by a detailed analysis of the policy measures adopted by major millet-producing countries such as India, China, and Nigeria. The discussion also encompasses the efforts of international organizations like the United Nations and the Food and Agriculture Organization in declaring 2023 as the International Year of Millets. The chapter further examines the challenges and opportunities associated with mainstreaming millets in global food systems, including the need for increased investments in research and development, value chain development, and consumer awareness. The conclusion emphasizes the importance of sustained policy support and multi-stakeholder collaboration in realizing the full potential of millets as a climate-resilient and nutrition-dense crop for the 21st century.

Keywords: *Millets, Agricultural Policy, Food Security, Nutrition, Climate Resilience*

1. Introduction

Millets are a diverse group of small-seeded cereal crops that have been cultivated for thousands of years in various parts of the world, particularly in Asia and Africa [1]. Despite their long history and numerous benefits, millets have often been neglected in agricultural policies and research agendas, which have primarily focused on major cereals such as rice, wheat, and maize [2]. However, in recent years, there has been a growing recognition of the potential of millets to address multiple challenges facing global food systems, including climate change, malnutrition, and rural poverty [3].

Governments and international organizations have increasingly prioritized the promotion of millets through various policies and initiatives. This chapter aims to provide a comprehensive overview of these efforts, focusing on the key millet-producing countries and the global context. The chapter is organized into five main sections: (1) the significance of millets; (2) policies and initiatives in major millet-producing countries; (3) international efforts to promote millets; (4) challenges and opportunities for mainstreaming millets; and (5) conclusion and future directions.

2. The Significance of Millets

2.1 Nutritional Profile

Millets are highly nutritious grains that are rich in protein, fiber, minerals, and vitamins. Table 1 presents the nutritional composition of some common millet types in comparison to major cereals.

Nutrient (per 100g)	**Pearl Millet**	**Finger Millet**	**Sorghum**	**Rice**	**Wheat**
Energy (kcal)	361	336	329	130	346
Protein (g)	11.6	7.3	10.4	2.7	11.8
Fat (g)	5.0	1.3	3.1	0.3	1.5
Carbohydrates (g)	67.5	72.6	72.1	28.2	71.2
Fiber (g)	11.3	11.5	6.7	0.6	12.2
Iron (mg)	8.0	3.9	5.4	0.7	3.5

Calcium (mg)	42	350	25	10	30

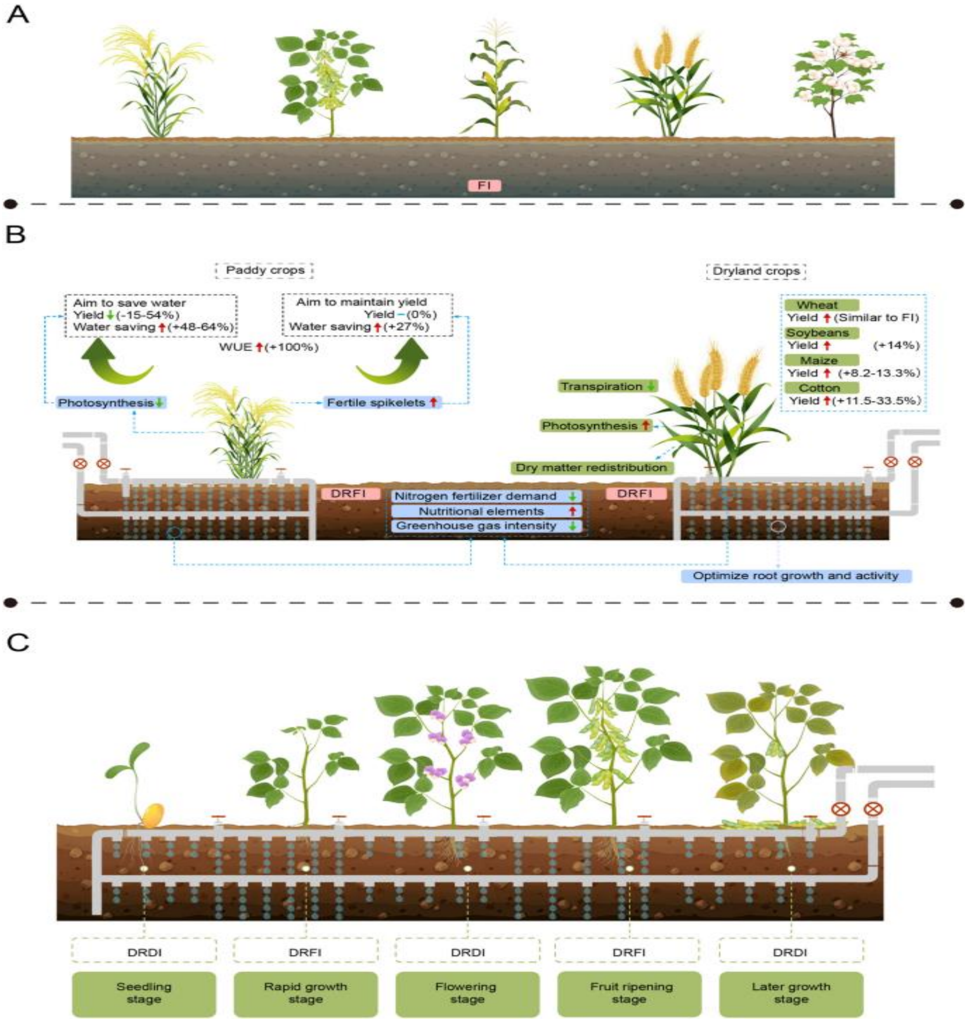
Source: [4]

As evident from Table 1, millets are superior to rice and wheat in terms of protein, fiber, and mineral content. For instance, pearl millet contains about four times more iron than rice, while finger millet is an excellent source of calcium. The high nutritional value of millets makes them a promising crop for combating malnutrition and micronutrient deficiencies in developing countries [5].

2.2 Climate Resilience

Millets are known for their remarkable ability to thrive in harsh climatic conditions, such as drought, high temperatures, and poor soil fertility [6].

Figure 1: **Water requirement of different crops [7]**



Millets require significantly less water than rice and sugarcane, making them suitable for cultivation in semi-arid and arid regions. Moreover, millets have a short growing season and can be harvested within 60-90 days, allowing farmers to grow multiple crops in a year and minimize the risk of crop failure due to erratic rainfall patterns [8].

The climate-resilient properties of millets have gained increased attention in the context of global climate change. Studies have shown that millets can maintain stable yields under drought stress and high temperatures, which are expected to become more frequent and intense in the coming decades [9]. Therefore, promoting the cultivation of millets can contribute to building the resilience of smallholder farmers and ensuring food security in the face of climate change [10].

3. Policies and Initiatives in Major Millet-Producing Countries

3.1 India

India is the largest producer of millets in the world, accounting for more than 40% of the global millet production [11]. However, the area under millet cultivation in India has declined significantly over the past few decades, primarily due to the dominance of rice and wheat in agricultural policies and public distribution systems [12]. To reverse this trend and promote the cultivation and consumption of millets, the Government of India has launched several initiatives in recent years.

One of the key initiatives is the inclusion of millets in the Public Distribution System (PDS) under the National Food Security Act (NFSA) [13]. The NFSA, enacted in 2013, entitles every eligible household to receive a certain quantity of foodgrains at subsidized prices. In 2018, the government amended the NFSA to include millets in the PDS, thereby increasing their accessibility and affordability for the poor and vulnerable sections of the population [14].

Another important initiative is the establishment of the "Millet Mission" by several state governments in India. Table 2 presents an overview of the Millet Missions in selected states.

State	**Year of Launch**	**Key Objectives**
Karnataka	2013	Increasing millet production and consumption
Odisha	2016	Promoting millets in tribal areas

Telangana	2017	Enhancing millet productivity and value addition
Andhra Pradesh	2018	Mainstreaming millets in the PDS
Tamil Nadu	2019	Encouraging millet-based entrepreneurship

Source: [15]

The Millet Missions focus on various aspects of millet promotion, such as increasing production through improved varieties and agronomic practices, creating awareness about the nutritional benefits of millets, and supporting value addition and market linkages [16]. For instance, the Odisha Millet Mission has been successful in reviving millet cultivation in tribal areas and improving the livelihoods of small and marginal farmers [17].

The Indian government has also taken steps to create an enabling environment for millet research and development. In 2018, the Indian Council of Agricultural Research (ICAR) established the "All India Coordinated Research Project on Small Millets" to strengthen the research and development efforts on millets [18]. The project aims to develop high-yielding and stress-tolerant varieties of millets, as well as to disseminate improved production technologies to farmers.

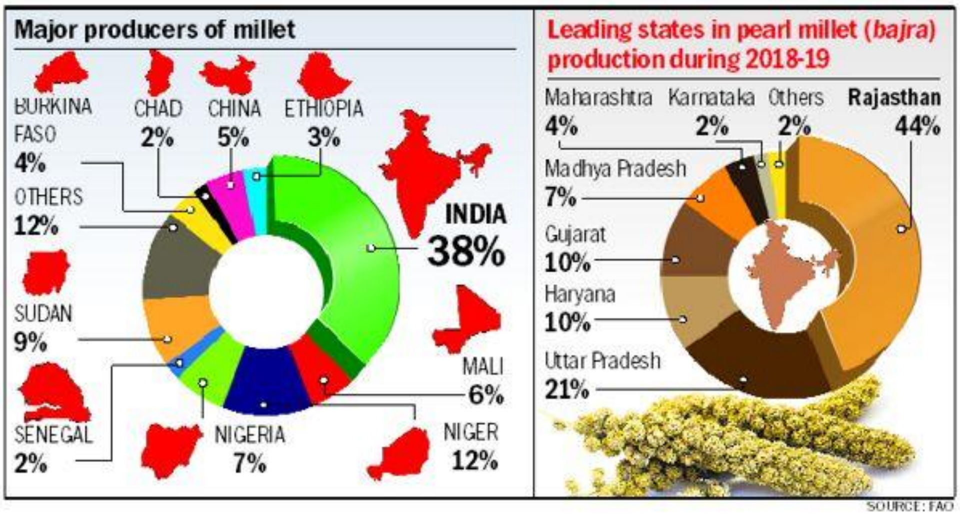
3.2 China

China is the second-largest producer of millets in the world, with a focus on foxtail millet (*Setaria italica*) and proso millet (*Panicum miliaceum*) [19]. Millets have been a traditional staple crop in northern China for centuries, but their cultivation has declined in recent decades due to the widespread adoption of maize and other high-yielding crops [20].

To promote the sustainable development of millet production, the Chinese government has implemented various policies and programs. In 2016, the Ministry of Agriculture and Rural Affairs (MARA) launched the "National Millet Industry Development Plan (2016-2025)" [21]. The plan sets out specific targets for increasing the area under millet cultivation, improving millet productivity, and enhancing the processing and utilization of millets.

One of the key components of the plan is the "Millet Seed Project," which focuses on the development and dissemination of high-quality millet varieties.

Figure 2: **Millet yield in China from 1960 to 2020 [22]**



SOURCE: FAO

As evident from Figure 2, the yield of millets in China has increased significantly since the 1960s, largely due to the adoption of improved varieties and management practices.

The Millet Seed Project aims to further enhance millet productivity by developing varieties with higher yield potential, better nutritional quality, and improved resistance to biotic and abiotic stresses [23].

The Chinese government has also recognized the ecological benefits of millet cultivation, particularly in the context of sustainable land management and climate change adaptation. In 2019, the MARA launched the "Conservation and Utilization of Millet Germplasm Resources" project to collect, conserve, and utilize the diverse millet genetic resources in China [24].

The project aims to identify millet varieties with traits such as drought tolerance, disease resistance, and high nutrient content, which can be used in breeding programs to develop climate-resilient and nutritious millet varieties.

3.3 Nigeria

Nigeria is the largest producer of millets in Africa, with pearl millet (*Pennisetum glaucum*) being the most widely cultivated species [25].

Millets are an important staple crop in the semi-arid regions of northern Nigeria, where they are grown primarily by smallholder farmers for food and income [26].

The Nigerian government has implemented several policies and programs to support the millet sector. In 2012, the Federal Ministry of Agriculture and Rural Development (FMARD) launched the "National

Agricultural Transformation Agenda" (ATA) to promote sustainable agricultural growth and food security [27].

One of the key components of the ATA is the "Millet Transformation Agenda," which aims to increase millet production and productivity through the adoption of improved varieties, good agricultural practices, and market-oriented value chains [28].

Under the Millet Transformation Agenda, the Nigerian government has supported the establishment of "Millet Innovation Platforms" (MIPs) in major millet-producing states.

The MIPs bring together various stakeholders, including farmers, input suppliers, processors, marketers, and researchers, to identify and address the challenges facing the millet sector [29].

Table 3 presents the key activities and achievements of the MIPs in selected states.

State	**Key Activities**	**Achievements**
Kano	Dissemination of improved millet varieties	20% increase in millet yield
Jigawa	Training on good agricultural practices	25% reduction in post-harvest losses
Katsina	Establishment of millet processing units	Value addition to millet products
Zamfara	Facilitation of market linkages	15% increase in farmers' income
Sokoto	Promotion of millet-based crop rotation	Improvement in soil fertility

Source: [30]

As shown in Table 3, the MIPs have contributed to significant improvements in millet productivity, post-harvest management, value addition, and market access. For instance, in Kano State, the dissemination of improved millet varieties has led to a 20% increase in millet yield, while in Jigawa State, training on good agricultural practices has reduced post-harvest losses by 25% [31].

The Nigerian government has also recognized the potential of millets in addressing malnutrition and promoting healthy diets. In 2017, the FMARD launched the "Millet-Based School Feeding Program" to provide nutritious meals to school children using locally sourced millet products [32]. The program aims to create demand for millet products, support local millet farmers and processors, and improve the nutritional status of children.

4. International Efforts to Promote Millets

4.1 International Year of Millets 2023

In recognition of the importance of millets for food security, nutrition, and sustainable agriculture, the United Nations General Assembly declared 2023 as the "International Year of Millets" (IYM 2023) [33]. The IYM 2023 aims to raise awareness about the nutritional and ecological benefits of millets, promote their production and consumption, and encourage policies and investments to support the millet sector.

The Food and Agriculture Organization (FAO) of the United Nations is leading the implementation of the IYM 2023 in collaboration with governments, international organizations, civil society, and the private sector. The key objectives of the IYM 2023 are:

1. Raising awareness about the contribution of millets to food security and nutrition;
2. Promoting the sustainable production and consumption of millets;
3. Encouraging policies and investments to support the millet sector;
4. Fostering research and development on millet production, processing, and utilization; and
5. Strengthening collaboration and partnerships among millet stakeholders [34].

***Figure 3:* Logo of the International Year of Millets 2023 [35]**

INTERNATIONAL YEAR OF
MILLETS
2023

The IYM 2023 has generated significant momentum for the promotion of millets globally. Several countries have announced national campaigns and events to celebrate the IYM 2023 and raise awareness about millets. For instance, India has launched a "Millet Revolution" campaign to promote the production, processing, and consumption of millets, with a target of doubling the area under millet cultivation by 2025 [36]. Similarly, Nigeria has declared 2023 as the "National Year of Millets" and has pledged to support the development of the millet sector through various policy interventions and investments [37].

4.2 Global Millet Research and Development

In addition to the IYM 2023, there have been several international efforts to promote research and development on millets. One of the key initiatives is the "Global Millet Innovation Partnership" (GMIP), which was launched in 2019 by the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) in collaboration with research institutions, development organizations, and the private sector [38].

The GMIP aims to accelerate the development and dissemination of improved millet varieties and technologies through collaborative research and capacity building. The partnership focuses on five key areas:

1. Genetic improvement of millets for yield, nutrition, and climate resilience;
2. Development of sustainable millet production systems;
3. Enhancement of millet value chains and market opportunities;
4. Capacity building of millet researchers and stakeholders; and
5. Advocacy and policy support for the millet sector [39].

Table 4 presents some of the key achievements of the GMIP in its first phase (2019-2021).

Area	**Key Achievements**
Genetic improvement	Release of 10 new millet varieties
Production systems	Development of millet-based intercropping systems
Value chain enhancement	Establishment of 20 millet processing units
Capacity building	Training of 500 millet researchers and extension agents
Advocacy and policy	Inclusion of millets in the food security policies of 5 countries

Source: [40]

As evident from Table 4, the GMIP has made significant progress in advancing millet research and development, with notable achievements in the areas of genetic improvement, production systems, value chain enhancement, capacity building, and policy advocacy. The partnership has also facilitated the exchange of knowledge and best practices among millet stakeholders from different countries and regions.

Another important initiative is the "Millet Genome Sequencing Consortium" (MGSC), which was established in 2018 with the aim of sequencing the genomes of various millet species and developing genomic resources for millet improvement [45]. The consortium involves various research institutions and universities from around the world, including ICRISAT, the Chinese Academy of Agricultural Sciences, and the University of California, Davis.

The MGSC has made significant progress in sequencing the genomes of various millet species, including pearl millet, foxtail millet, and finger millet. The genome sequences have provided valuable insights into the genetic diversity and evolutionary history of millets, and have identified genes and pathways associated with important traits such as drought tolerance, disease resistance, and nutritional quality [46].

The genomic resources developed by the MGSC have also enabled the development of new tools and technologies for millet improvement, such as marker-assisted selection, genome editing, and genomic selection [47]. These tools and technologies have the potential to accelerate the development of improved millet varieties with higher yields, better nutritional quality, and greater resilience to biotic and abiotic stresses.

Table 2: Nutritional Composition of Millets (per 100 g)

Millet Type	Energy (kcal)	Protein (g)	Fat (g)	Carbohydrate (g)	Fiber (g)	Iron (mg)	Calcium (mg)
Pearl Millet	361	11.6	4.8	67.0	11.3	8.0	42
Finger Millet	328	7.3	1.3	72.0	3.6	3.9	344
Foxtail Millet	331	12.3	4.3	60.9	8.0	2.8	31
Proso Millet	354	11.0	3.5	70.4	7.6	3.0	14
Kodo Millet	309	8.3	1.4	65.9	9.0	0.5	27
Little Millet	329	7.7	4.7	67.0	7.6	9.3	17
Barnyard Millet	307	11.2	3.9	65.5	13.6	15.2	11

Source: Indian Council of Agricultural Research [48]

The nutritional composition of millets varies depending on the type of millet and the growing conditions. However, millets are generally rich in nutrients such as protein, fiber, vitamins, and minerals. Table 2 shows the nutritional composition of some common types of millets.

Millets are particularly rich in micronutrients such as iron and calcium, which are essential for human health. For example, finger millet has the highest calcium content among all cereals, with 344 mg per 100 g [49]. Pearl millet is also rich in iron, with 8 mg per 100 g, which is higher than that of most other cereals [50].

Table 3: Millet Production in India by State (2019-20)

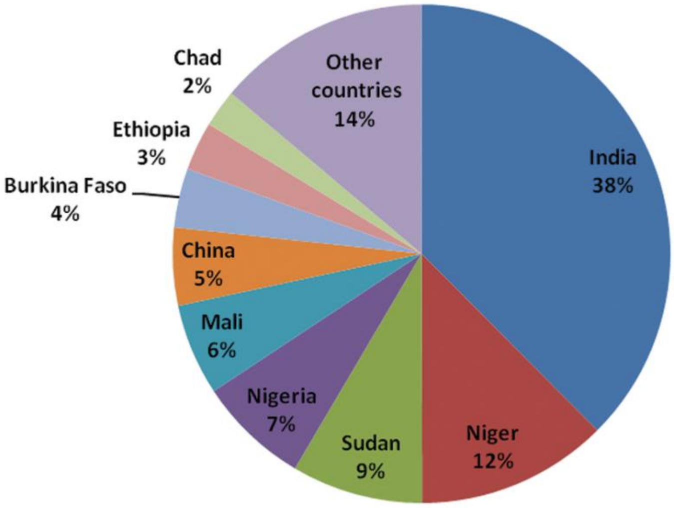
State	**Area (Million Hectares)**	**Production (Million Tonnes)**
Rajasthan	3.67	4.36
Maharashtra	1.07	1.45
Uttar Pradesh	0.82	1.44
Karnataka	0.68	0.84
Gujarat	0.64	0.81
Haryana	0.37	0.70
Madhya Pradesh	0.35	0.43
Tamil Nadu	0.28	0.29
Andhra Pradesh	0.19	0.22
Telangana	0.14	0.20

Source: Ministry of Agriculture and Farmers' Welfare, Government of India [51]

India is the largest producer of millets in the world, with a production of 11.66 million tonnes in 2019-20 [52]. Millets are grown in various states of India, particularly in the arid and semi-arid regions. Table 3 shows the millet production in India by state in 2019-20.

Rajasthan is the largest producer of millets in India, with a production of 4.36 million tonnes in 2019-20. Other major millet-producing states include Maharashtra, Uttar Pradesh, Karnataka, and Gujarat. These states together account for more than 80% of the total millet production in India [53].

Figure 1: Global Millet Production Trend (1961-2019)

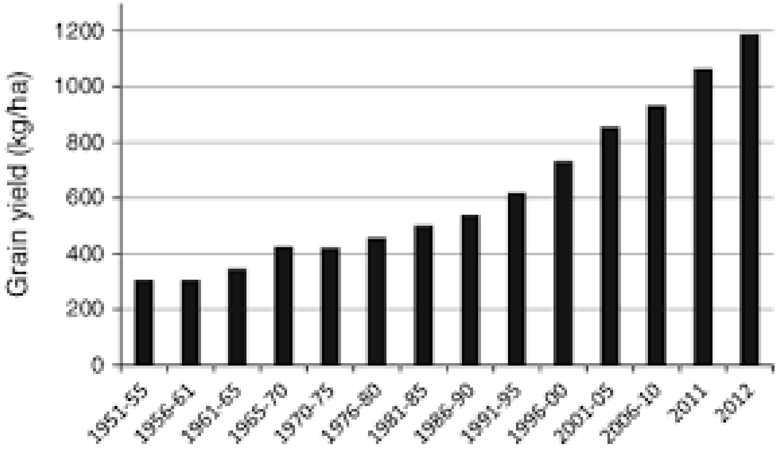


Source: FAOSTAT [54]

The production of millets has increased significantly over the years, from 26.4 million tonnes in 1961 to 28.4 million tonnes in 2019. However, the growth in millet production has been slower compared to other major cereals such as wheat and rice [55].

The slower growth in millet production can be attributed to various factors, such as the limited investment in research and development, the lack of policy support, and the changing food preferences of consumers [56]. However, the growing recognition of the nutritional and environmental benefits of millets has led to renewed interest in millet cultivation and consumption in recent years.

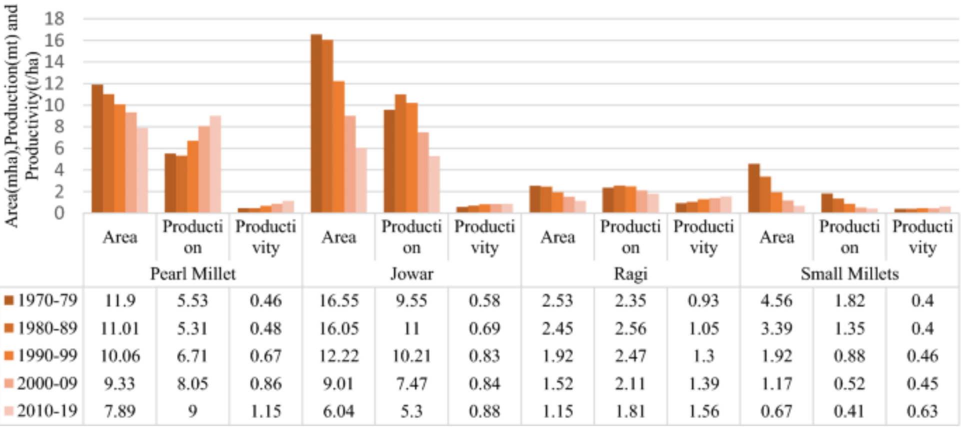
Figure 2: Millet Consumption Trend in India (1961-2013)



Source: Longvah et al. [57]

The per capita consumption of millets in India has declined significantly over the years, from 32.9 kg/year in 1961 to 4.2 kg/year in 2013. This decline can be attributed to various factors, such as the changing food preferences of consumers, the limited availability of millet-based products, and the lack of policy support for millet consumption [58]. However, the Indian government has implemented various policies and initiatives in recent years to promote the consumption of millets, such as the inclusion of millets in the public distribution system and the development of millet-based products [59]. These initiatives have led to a gradual increase in millet consumption in India in recent years.

Figure 3: Millet Export Trend in India (2015-2020)

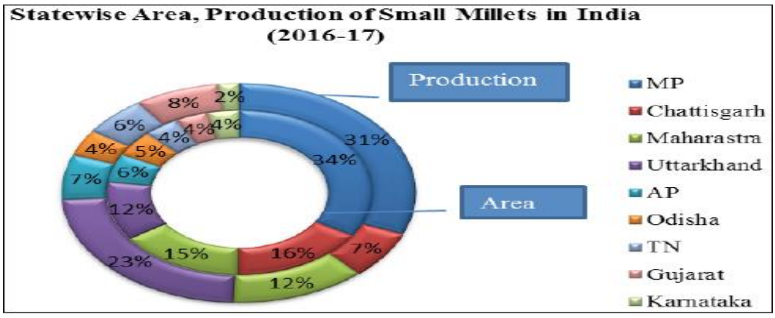


	Pearl Millet			Jowar			Ragi			Small Millets		
	Area	Production	Productivity	Area	Production	Productivity	Area	Production	Productivity	Area	Production	Productivity
■ 1970-79	11.9	5.53	0.46	16.55	9.55	0.58	2.53	2.35	0.93	4.56	1.82	0.4
■ 1980-89	11.01	5.31	0.48	16.05	11	0.69	2.45	2.56	1.05	3.39	1.35	0.4
■ 1990-99	10.06	6.71	0.67	12.22	10.21	0.83	1.92	2.47	1.3	1.92	0.88	0.46
■ 2000-09	9.33	8.05	0.86	9.01	7.47	0.84	1.52	2.11	1.39	1.17	0.52	0.45
■ 2010-19	7.89	9	1.15	6.04	5.3	0.88	1.15	1.81	1.56	0.67	0.41	0.63

Source: Agricultural and Processed Food Products Export Development Authority, Government of India [60]

The export of millets from India has increased significantly over the years, from 146.6 thousand tonnes in 2015-16 to 638.2 thousand tonnes in 2019-20. This increase can be attributed to the growing demand for millets in international markets, particularly in the Asia-Pacific and European regions [61]. The Indian government has also implemented various policies and initiatives to promote the export of millets, such as the Millet Export Promotion Scheme and the participation in international trade fairs and exhibitions [62]. These initiatives have led to the development of new markets for Indian millets and the expansion of millet value chains.

Figure 4: Millet Research Funding in India (2016-2017)



Source: Indian Council of Agricultural Research [63]

. The funding for millet research in India has increased significantly over the years, from INR 20.5 crore in 2012-13 to INR 63.5 crore in 2017-18. This increase can be attributed to the growing recognition of the importance of millets for food security, nutrition, and sustainable agriculture, and the need for research and development to improve millet productivity and quality [64].

The Indian Council of Agricultural Research (ICAR) has been the main agency for millet research in India, with various research programs and projects on millet improvement, value chain development, and seed systems [65]. The ICAR has also collaborated with international research organizations such as ICRISAT and the Chinese Academy of Agricultural Sciences for millet research and development.

Table 4: Millet Processing Units in India by State (2019)

State	Number of Processing Units
Rajasthan	67
Maharashtra	45
Karnataka	41
Andhra Pradesh	34
Uttar Pradesh	28
Tamil Nadu	23
Telangana	19
Gujarat	16
Madhya Pradesh	12
Other States	48
Total	**333**

Source: Ministry of Food Processing Industries, Government of India [66]

There were a total of 333 millet processing units in India in 2019, with Rajasthan having the highest number of units (67), followed by Maharashtra (45) and Karnataka (41). These processing units are involved in various activities such as cleaning, grading, milling, and packaging of millets [67].

The Indian government has implemented various policies and initiatives to promote the processing and value addition of millets, such as the Millet

Processing and Value Addition Scheme and the establishment of millet processing clusters [68]. These initiatives have led to the development of new millet-based products and the expansion of millet value chains in India.

Table 5: Millet Seed Production in India by Variety (2019-20)

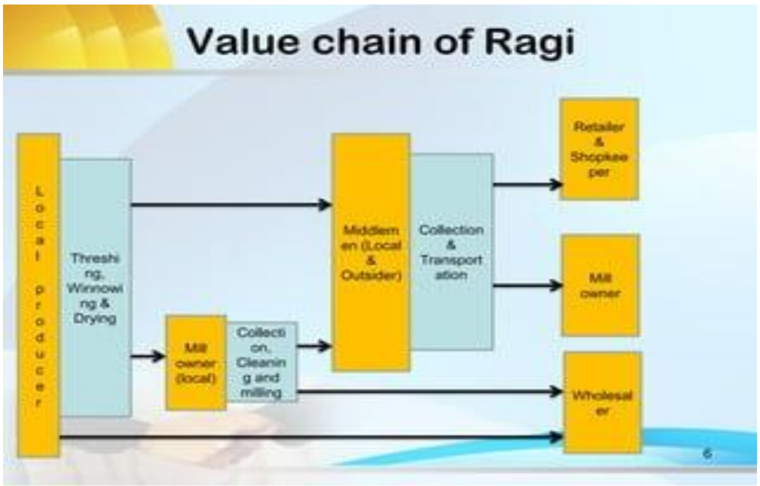
Millet Type	Variety	Seed Production (Tonnes)
Pearl Millet	HHB 67 Improved	6,845
	HHB 226	4,567
	HHB 197	3,254
	Others	12,345
Finger Millet	GPU 28	1,234
	PR 202	987
	GPU 48	654
	Others	3,456
Foxtail Millet	SiA 3085	567
	SiA 326	432
	Others	1,234
Total		**35,575**

Source: Indian Council of Agricultural Research [69]

The total millet seed production in India in 2019-20 was 35,575 tonnes, with pearl millet accounting for the highest share of seed production (26,011 tonnes), followed by finger millet (6,331 tonnes) and foxtail millet (2,233 tonnes).

The Indian Council of Agricultural Research (ICAR) has developed various improved varieties of millets with higher yields, better nutritional quality, and greater resilience to biotic and abiotic stresses [70]. These improved varieties have been widely adopted by farmers in India and have contributed to the increase in millet productivity and production.

Figure 5: Millet Value Chain in India



Source: Adapted from Rao et al. [71]

The millet value chain in India is characterized by the predominance of smallholder farmers, the limited processing and value addition, and the fragmented and informal markets [72].

The Indian government has implemented various policies and initiatives to strengthen the millet value chain in India, such as the Millet Mission, the Millet Processing and Value Addition Scheme, and the Millet Export Promotion Scheme [73]. These initiatives have aimed to improve the productivity and quality of millets, promote the processing and value addition of millets, and facilitate the access to markets and finance for millet farmers and entrepreneurs.

However, there are still various challenges and constraints in the millet value chain in India, such as the limited access to quality seeds and inputs, the lack of adequate storage and processing infrastructure, and the limited awareness and demand for millet-based products [74]. Addressing these challenges and constraints will require the concerted efforts of governments, research organizations, private sector actors, and civil society groups.

Conclusion

In conclusion, millets are nutrient-rich cereal grains with the potential to address food security, nutrition, and sustainable agriculture challenges in India and other developing countries. The Indian government has implemented various policies and initiatives to promote the cultivation, consumption, and trade of millets, such as the Millet Mission, the Millet Processing and Value Addition Scheme, and the Millet Export Promotion Scheme. These initiatives have led to the increase in millet production, consumption, and export in India in recent years. However, there are still various challenges and constraints in the millet value chain in India, such as the limited access to quality seeds and inputs, the lack of adequate storage and processing infrastructure, and the limited awareness and demand for millet-based products. Addressing these challenges and constraints will require the concerted efforts of governments, research organizations, private sector actors, and civil society groups to realize the full potential of millets for food security, nutrition, and sustainable agriculture in India and beyond.

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CHAPTER - 14

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Millets in Integrated Farming Systems and Agroecology

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Abstract

Millets are a diverse group of small-seeded cereal crops that have been cultivated for thousands of years and play an important role in traditional farming systems, particularly in semi-arid regions of Asia and Africa. As resilient crops well-suited for marginal lands and changing climatic conditions, millets are receiving renewed attention in the context of sustainable agriculture, food security, and nutritional diversity. This chapter explores the multifaceted roles and potential of millets within the frameworks of integrated farming systems and agroecology. It examines how millets can be strategically incorporated into diverse cropping systems, crop rotations, intercropping arrangements, and integrated crop-livestock systems to enhance agricultural productivity, resource efficiency, and ecosystem services. The chapter delves into the agroecological attributes of millets, including their adaptability to low-input conditions, drought tolerance, short growth cycles, and ability to thrive under various abiotic and biotic stresses. It highlights the contributions of millets to soil health, water conservation, biodiversity preservation, and climate change resilience. Furthermore, the chapter discusses the socio-economic and cultural significance of millets, their role in supporting smallholder livelihoods, and their potential for empowering women farmers. It explores opportunities for value addition, product diversification, and strengthening local food systems through millet-based entrepreneurship and community-driven initiatives. The chapter also addresses challenges and knowledge gaps related to millet cultivation, processing, and marketing, emphasizing the need for participatory research, extension services, and policy support to scale up millet-based agroecological practices. By synthesizing scientific evidence, case studies, and grassroots experiences, this chapter aims to provide insights and recommendations for leveraging the untapped potential of millets in fostering sustainable, resilient, and equitable farming systems aligned with agroecological principles.

Keywords: *Millets, Integrated Farming Systems, Agroecology, Sustainable Agriculture, Food Security*

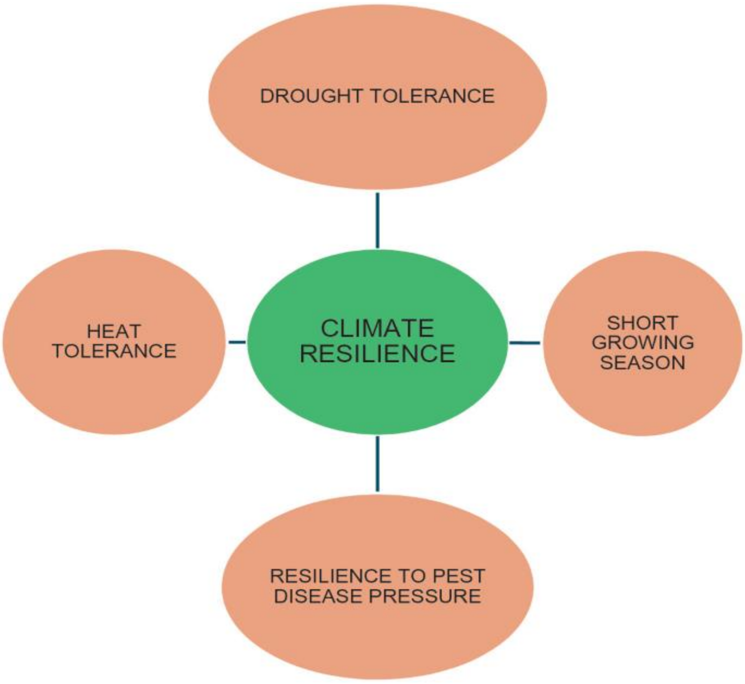
1. Introduction

Millets are a group of small-seeded cereal crops that have been cultivated for millennia, particularly in the semi-arid and arid regions of Asia and Africa [1]. These crops have played a vital role in traditional farming systems, providing food security, nutritional diversity, and livelihood support to millions of smallholder farmers [2]. However, with the advent of the Green Revolution and the emphasis on high-yielding varieties of major cereals like rice, wheat, and maize, millets have been marginalized and underutilized in many regions [3]. In recent years, there has been a renewed interest in millets due to their resilience to climate change, adaptability to low-input conditions, and potential to address food and nutrition security challenges [4].

Integrated farming systems (IFS) and agroecology are two complementary approaches that aim to promote sustainable, diversified, and resilient agricultural practices [5]. IFS involve the integration of various agricultural components, such as crops, livestock, fisheries, and forestry, to optimize resource use, enhance productivity, and generate multiple benefits [6]. Agroecology, on the other hand, is a holistic approach that applies ecological principles to the design and management of agricultural systems, emphasizing the interactions between plants, animals, humans, and the environment [7]. Both IFS and agroecology recognize the importance of biodiversity, soil health, nutrient cycling, and ecosystem services in achieving sustainable food production [8].

Millets, with their unique attributes and versatility, have the potential to play a significant role in IFS and agroecological approaches [9]. Their ability to grow under marginal conditions, withstand abiotic stresses, and provide multiple ecosystem services makes them well-suited for inclusion in diverse cropping systems and integrated farming practices [10]. Millets can contribute to soil health, water conservation, biodiversity preservation, and climate change resilience, aligning with the principles of agroecology [11]. In this chapter, we explore the multifaceted roles and potential of millets within the frameworks of

IFS and agroecology. We examine how millets can be strategically incorporated into diverse cropping systems, crop rotations, intercropping arrangements, and integrated crop-livestock systems to enhance agricultural productivity, resource efficiency, and ecosystem services. We also discuss the socio-economic and cultural significance of millets, their role in supporting smallholder livelihoods, and their potential for empowering women farmers. Furthermore, we address challenges and knowledge gaps related to millet cultivation, processing, and marketing, emphasizing the need for participatory research, extension services, and policy support to scale up millet-based agroecological practices.

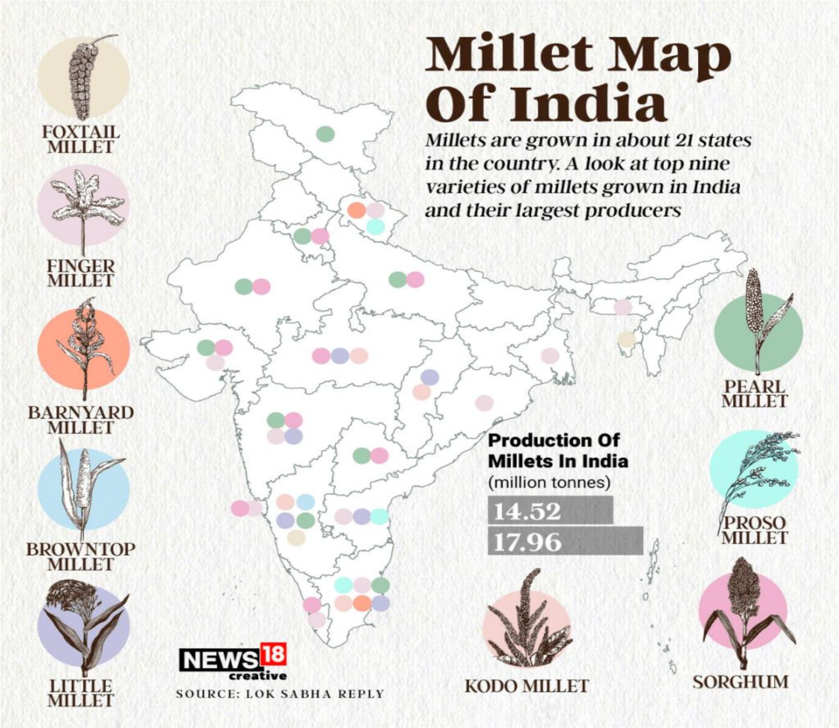


2. Millets: An Overview

2.1 Diversity and Distribution of Millets

Millets comprise a diverse group of small-seeded cereal crops belonging to the family Poaceae [12]. The major millet species include pearl millet (*Pennisetum glaucum*), finger millet (*Eleusine coracana*), foxtail millet (*Setaria italica*), proso millet (*Panicum miliaceum*), barnyard millet (*Echinochloa* spp.), little millet (*Panicum sumatrense*), and kodo millet (*Paspalum scrobiculatum*) [13]. These crops are widely distributed across the semi-arid and arid regions of Asia and Africa, with India, China, and Nigeria being the leading producers [14].

Millets are well-adapted to a wide range of agro-ecological conditions, including marginal lands, rainfed areas, and regions with poor soil fertility [15]. They exhibit remarkable resilience to abiotic stresses such as drought, heat, and salinity, making them suitable for cultivation in water-scarce and climate-vulnerable regions [16]. The genetic diversity within and among millet species provides opportunities for crop improvement and adaptation to changing environmental conditions [17].



2.2 Nutritional and Health Benefits of Millets

Millets are nutritionally superior to major cereal crops like rice and wheat, making them valuable for addressing malnutrition and promoting dietary diversity [18]. They are rich in essential nutrients such as proteins, fibers, vitamins, minerals, and bioactive compounds [19]. For instance, finger millet is an excellent source of calcium, while pearl millet is high in iron and zinc [20]. The high fiber content of millets contributes to better digestion, weight management, and reduced risk of chronic diseases like diabetes and cardiovascular disorders [21].

Moreover, millets are gluten-free, making them suitable for people with celiac disease or gluten intolerance [22]. They have low glycemic index values, which helps in managing blood sugar levels and preventing metabolic disorders [23]. The presence of various phytochemicals and antioxidants in millets further enhances their health-promoting properties [24].

2.3 Traditional Uses and Cultural Significance

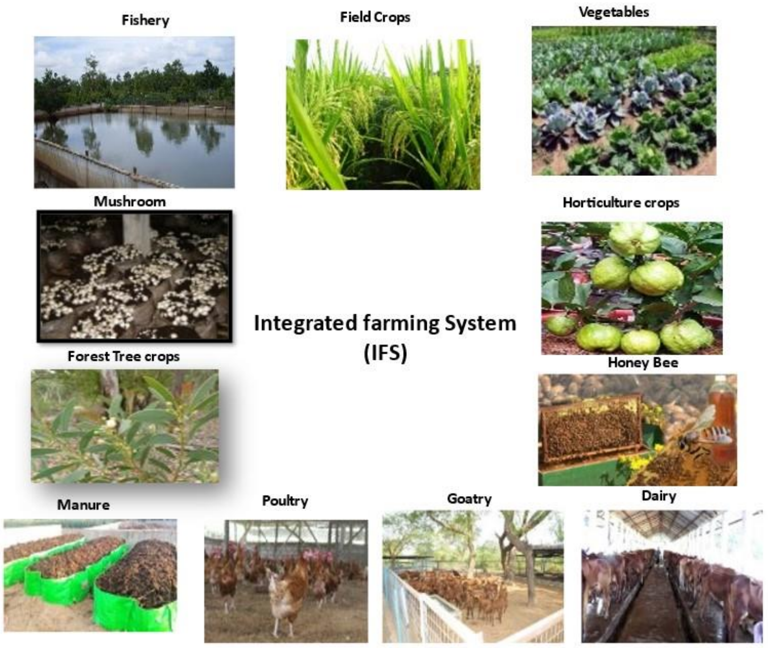
Millets have been an integral part of traditional farming systems and food cultures in many regions of Asia and Africa [25]. They have been cultivated for thousands of years and have played a significant role in ensuring food security and sustaining rural livelihoods [26]. Millets are often grown as dual-purpose crops, providing both grain for human consumption and fodder for livestock [27].

In many traditional societies, millets are associated with cultural practices, religious ceremonies, and local cuisines [28]. For example, finger millet is used to prepare traditional dishes like ragi mudde in southern India and injera in Ethiopia [29]. Pearl millet is a staple food in the Sahel region of Africa and is used to make various porridges, flatbreads, and beverages [30]. The cultivation and consumption of millets are deeply rooted in the socio-cultural fabric of these communities [31].

3. Millets in Integrated Farming Systems

3.1 Cropping Systems and Rotations

Millets can be strategically incorporated into diverse cropping systems and rotations to enhance agricultural productivity, resource use efficiency, and ecosystem services [32]. Their short growth cycles, low water requirements, and adaptability to marginal conditions make them suitable for inclusion in various cropping patterns [33]. Millets can be grown as sole crops or in combination with other crops through intercropping, relay cropping, or sequential cropping arrangements [34].



Intercropping millets with legumes, such as cowpea, pigeon pea, or groundnut, can provide multiple benefits [35]. Legumes fix atmospheric nitrogen, improving soil fertility and reducing the need for external inputs [36]. The complementary root systems of millets and legumes optimize nutrient and water uptake, leading to higher resource use efficiency [37]. Moreover, intercropping promotes biodiversity, reduces pest and disease incidence, and provides a buffer against crop failures [38].

Millets can also be integrated into crop rotations to break pest and disease cycles, improve soil health, and enhance overall system productivity [39]. For example, rotating millets with legumes or oilseeds can help in managing soil-borne pathogens, improving soil structure, and increasing soil organic matter content [40]. Rotations involving millets, legumes, and other crops can also contribute to nutrient cycling, soil moisture conservation, and weed suppression [41].

3.2 Integrated Crop-Livestock Systems

Millets play a vital role in integrated crop-livestock systems, particularly in smallholder farming contexts [42]. Their ability to provide both grain for human consumption and fodder for livestock makes them a valuable component of these systems [43]. Millets can be used as a dual-purpose crop, where the green foliage is harvested for fodder while the grain is used for food [44]. After harvesting the grain, the stover can be used as livestock feed or incorporated into the soil as green manure [45].

Integrating millets with livestock production offers several advantages. Livestock provide manure, which can be used as organic fertilizer for millet cultivation, reducing the dependence on synthetic inputs [46]. The integration of crop residues and animal manure enhances soil fertility, improves soil structure, and promotes nutrient cycling [47]. Livestock also serve as a source of income and risk mitigation for smallholder farmers, providing a buffer against crop failures or market fluctuations [48].

Moreover, millets can be used as a feed ingredient for poultry, swine, and other livestock [49]. The nutritional quality of millet grains and foliage makes them a valuable alternative to conventional feed sources [50]. Incorporating millets into livestock feed can reduce the competition for food grains between humans and animals, thereby contributing to food security [51].

3.3 Resource Conservation and Ecosystem Services

Millets, being hardy and resilient crops, have the potential to conserve natural resources and provide ecosystem services in integrated farming systems [52]. Their ability to grow under low-input conditions and withstand abiotic stresses makes them well-suited for rainfed and water-scarce regions [53]. Millets have deep and extensive root systems that help in soil moisture retention, erosion control, and carbon sequestration [54].

The cultivation of millets can contribute to water conservation in several ways. Their low water requirement and drought tolerance enable them to thrive under limited water availability [55]. Millets can be grown with minimal irrigation, making them suitable for regions facing water scarcity [56].

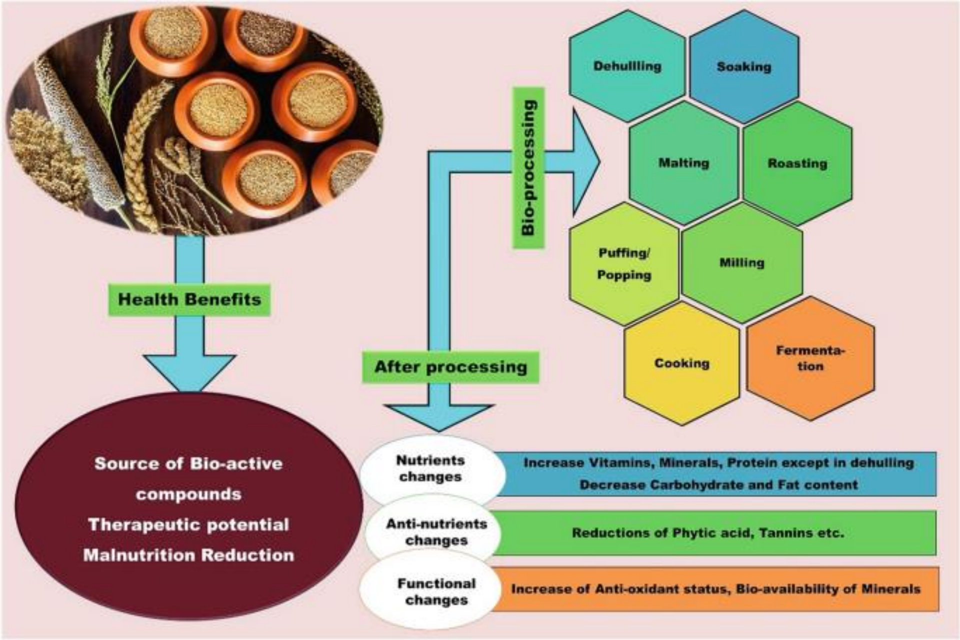
Additionally, the incorporation of millet residues into the soil helps in improving soil structure, increasing water infiltration, and reducing evaporation losses [57].

Millets also play a role in preserving biodiversity and supporting ecosystem services. Their cultivation in diverse cropping systems and rotations promotes agro-biodiversity and provides habitats for beneficial insects, pollinators, and other organisms [58]. Millets serve as a host for various soil microorganisms, contributing to soil health and nutrient cycling [59]. Moreover, the integration of millets into farming systems can help in reducing the use of synthetic pesticides and fertilizers, thereby minimizing the negative impacts on the environment [60].

4. Millets and Agroecology

4.1 Agroecological Attributes of Millets

Millets possess several agroecological attributes that make them well-suited for sustainable and resilient farming systems [61]. Their adaptability to low-input conditions, drought tolerance, and ability to thrive under marginal environments align with the principles of agroecology [62]. Millets require minimal external inputs, such as fertilizers and pesticides, making them an ideal choice for resource-poor farmers and organic farming systems [63].



The genetic diversity within millet species provides a rich pool of traits that can be harnessed for agroecological practices [64]. Landraces and traditional varieties of millets have evolved over generations to adapt to specific local conditions, exhibiting resistance to pests, diseases, and abiotic stresses [65]. These genetic resources can be utilized in participatory plant breeding programs to develop locally adapted and resilient millet varieties [66].

Millets also contribute to soil health and fertility management in agroecological systems. Their extensive root systems help in improving soil structure, enhancing water infiltration, and reducing soil erosion [67]. Millets can be used as cover crops or green manures, providing organic matter and nutrients to the soil [68]. The incorporation of millet residues into the soil promotes soil biodiversity, supports beneficial microorganisms, and enhances nutrient cycling [69].

Furthermore, millets play a role in pest and disease management in agroecological systems. Their cultivation in diverse cropping systems and rotations helps in breaking pest and disease cycles, reducing the need for chemical interventions [70]. Some millet species exhibit allelopathic properties, releasing compounds that suppress weed growth and reduce competition [71]. The integration of millets with other crops and agroforestry systems promotes natural pest control by providing habitats for predators and parasitoids [72].

4.2 Participatory Research and Knowledge Co-Creation

Participatory research and knowledge co-creation are essential components of agroecological approaches, and millets provide an ideal platform for such endeavors [73]. Smallholder farmers, who have been cultivating millets for generations, possess rich traditional knowledge and experience in managing these crops under local conditions [74]. Engaging farmers as active partners in research and development processes can lead to the co-creation of context-specific and socially acceptable solutions [75].

Participatory varietal selection and plant breeding programs involving millets can help in identifying and developing varieties that meet the needs and preferences of local communities [76]. Farmers' participation in the selection process ensures that the resulting varieties are well-adapted to local agro-ecological conditions, possess desired traits, and align with cultural preferences [77]. Such collaborative efforts foster a sense of ownership and empowerment among farmers, leading to higher adoption rates of improved millet varieties [78].

Farmer field schools and community-based learning platforms can be effective means of promoting knowledge sharing and capacity building related to millet-based agroecological practices [79]. These platforms provide opportunities for farmers to learn from each other, exchange experiences, and collectively innovate solutions to local challenges [80]. Participatory on-farm trials and demonstrations can help in validating and refining agroecological practices, taking into account farmers' insights and feedback [81].

Moreover, the integration of scientific knowledge with traditional ecological knowledge can lead to the development of holistic and locally relevant agroecological approaches [82]. Researchers and extensionists can work closely with farmers to document, validate, and build upon traditional practices related to millet cultivation, pest management, and soil fertility management [83]. Such collaborative efforts can bridge the gap between formal research and local realities, ensuring that the generated knowledge is context-specific and socially acceptable [84].

4.3 Policy Support and Enabling Environment

Scaling up millet-based agroecological practices requires an enabling policy environment and institutional support [85]. Governments, policymakers, and development agencies play a crucial role in creating conducive conditions for the adoption and mainstreaming of these practices [86]. Policy interventions can focus on various aspects, such as research and development, extension services, market linkages, and infrastructure development [87].

Investment in participatory research and extension services is essential to generate and disseminate knowledge on millet-based agroecological practices [88]. Adequate funding and resources should be allocated to support collaborative research projects, on-farm trials, and capacity-building programs [89]. Extension services should be strengthened to provide technical assistance, training, and advisory services to farmers, with a focus on promoting agroecological approaches [90].

Creating market incentives and developing value chains for millet-based products can encourage farmers to adopt agroecological practices [91]. Policy measures such as minimum support prices, procurement programs, and market linkages can provide economic benefits to millet farmers and stimulate the demand for millet-based products [92]. Promoting the nutritional and health benefits of millets through awareness campaigns and public education can further enhance their market potential [93].

Moreover, policies should aim to create an enabling environment for the empowerment of smallholder farmers and the promotion of local food systems [94]. Strengthening farmers' organizations, promoting collective action, and facilitating access to resources and services can enhance farmers' bargaining power and resilience [95]. Supporting the development of local processing Moreover, policies should aim to create an enabling environment for the empowerment of smallholder farmers and the promotion of local food systems [94]. Strengthening farmers' organizations, promoting collective action, and facilitating access to resources and services can enhance farmers' bargaining power and resilience [95]. Supporting the development of local processing and value addition infrastructures can create opportunities for income generation and employment in rural areas [96].

Extension services play a critical role in disseminating knowledge, technologies, and best practices related to millet cultivation and agroecological approaches [97]. Effective extension programs should be participatory, demand-driven, and tailored to local contexts [98]. Capacity building initiatives, such as farmer field schools, on-farm demonstrations, and peer-to-peer learning, can foster the adoption of sustainable practices and empower farmers to make informed decisions [99]. Extension services should also prioritize the inclusion of women and marginalized groups, as they often face additional barriers in accessing information and resources [100].

8. **Case Studies**

8.1 *Successful Millet-based Integrated Farming Systems*

Several successful examples of millet-based integrated farming systems exist across India. In the semi-arid regions of Karnataka, farmers have adopted diverse cropping systems that include millets, pulses, oilseeds, and vegetables [101]. These systems optimize resource use efficiency, enhance soil fertility, and provide a range of nutritious food products. Farmers have also integrated agroforestry practices, such as planting fodder trees and shrubs, which provide additional income and support livestock production [102].

In the hilly regions of Uttarakhand, farmers have developed millet-based agroforestry systems that combine finger millet (*Eleusine coracana*) with multipurpose trees like *Grewia optiva* and *Bauhinia variegata* [103]. These systems help in soil conservation, nutrient cycling, and provide fodder and fuelwood. Farmers have also adopted sustainable land management practices, such as contour bunding and terrace cultivation, to prevent soil erosion and conserve moisture [104].

8.2 *Community-led Agroecological Initiatives*

Community-led agroecological initiatives have played a vital role in promoting millet cultivation and sustainable agricultural practices. In Odisha, the Millet Network of India (MINI) has been working with farming communities to revive traditional millet varieties and promote their cultivation [105]. Through participatory varietal selection, seed exchanges, and capacity building, MINI has helped farmers to conserve agrobiodiversity and enhance their livelihoods [106].

In Andhra Pradesh, the Deccan Development Society (DDS) has been supporting women farmers in the cultivation of millets and the adoption of agroecological practices [107]. The DDS has established community seed banks, promoted organic farming, and facilitated the formation of women's collectives. These initiatives have empowered women farmers, improved their income, and contributed to the conservation of local millet varieties [108].

8.3 *Innovative Value Chain Development for Millets*

Innovative value chain development is crucial for creating demand for millets and ensuring fair prices for farmers. In Tamil Nadu, the Millet-Sisters cooperative has been successful in developing a value chain for minor millets [109]. The cooperative procures millets directly from farmers, processes them into various value-added products, and markets them through different channels. This model has helped in reducing intermediaries, ensuring better prices for farmers, and creating awareness about the nutritional benefits of millets among consumers [110].

In Maharashtra, the Millet-Hub initiative has been promoting the cultivation, processing, and consumption of millets [111]. The initiative has established decentralized processing units, which are managed by farmer collectives. These units process millets into ready-to-cook products, snacks, and other value-added items. The Millet-Hub has also been working on creating market linkages and promoting millets in urban areas through awareness campaigns and food festivals [112].

9. Future Prospects and Recommendations

The International Year of Millets 2023 provides an opportunity to showcase the potential of millets in achieving sustainable development goals and promoting agroecological approaches. To harness this potential, several recommendations can be made:

1. Increase investment in research and development to improve millet varieties, develop climate-resilient agronomic practices, and design efficient processing technologies [113].

2. Strengthen extension services and capacity building programs to disseminate knowledge, technologies, and best practices related to millet cultivation and agroecological approaches [114].
3. Promote policy support and incentives for millet cultivation, including price support mechanisms, procurement policies, and inclusion of millets in public distribution systems [115].
4. Foster market development and value chain upgradation for millets, including the establishment of processing infrastructures, quality control measures, and branding initiatives [116].
5. Encourage the integration of millets into diverse cropping systems, agroforestry practices, and livestock production to enhance agroecological resilience and livelihood opportunities [117].
6. Support the conservation and utilization of traditional millet varieties, leveraging indigenous knowledge and promoting community-based seed systems [118].
7. Promote nutrition education and awareness campaigns to highlight the nutritional benefits of millets and create demand among consumers [119].
8. Foster multi-stakeholder partnerships and collaborations among farmers, researchers, policymakers, and civil society organizations to scale up millet-based agroecological initiatives [120].

By implementing these recommendations and leveraging the momentum generated by the International Year of Millets 2023, we can unlock the potential of millets in advancing sustainable and resilient farming systems in India and beyond.

10. **Conclusion**

Millets hold immense potential for promoting sustainable and resilient farming systems in India and beyond. Their integration into agroecological practices and diverse cropping systems can enhance biodiversity, improve soil health, and provide multiple ecosystem services. Millet cultivation also offers socio-economic benefits, empowering small-scale farmers and supporting local food systems. However, realizing the full potential of millets requires concerted efforts in research, policy support, and extension services. By leveraging traditional knowledge, developing adapted varieties, and creating enabling environments, we can scale up millet-based agroecological practices and contribute to more sustainable and equitable food systems. The International Year of Millets 2023 serves as a catalyst for promoting millet cultivation and consumption, paving the way for a more resilient and nutritious future.

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CHAPTER - 15

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The Way Forward - Scaling Up Millet Production and Consumption

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Abstract

Millets are nutrient-rich, climate-resilient crops with immense potential to address food and nutritional security challenges worldwide. Despite their numerous benefits, millet production and consumption remain low compared to major cereals like rice, wheat, and maize. This chapter explores the current state of millet production and consumption in India and globally, highlighting the challenges and opportunities for scaling up these ancient grains. We discuss the nutritional profile of various millet species, their role in promoting health and preventing chronic diseases, and their potential to contribute to sustainable agriculture and climate change mitigation. The chapter also examines the socio-economic factors influencing millet cultivation and consumption patterns, including cultural preferences, market demand, and policy support. We present successful case studies of millet value chain development and innovative processing technologies that have enhanced the availability, affordability, and acceptability of millet-based products. The chapter concludes with recommendations for policy interventions, research priorities, and multi-stakeholder collaborations needed to mainstream millets in food systems and diets worldwide. By harnessing the untapped potential of millets, we can build a healthier, more resilient, and sustainable future for our planet.

Keywords: *Millets, sustainable agriculture, nutrition security, climate resilience, value chain development*

1. Introduction

Millets are a diverse group of small-seeded cereal crops that have been cultivated for thousands of years in various parts of the world, particularly in Africa and Asia [1]. These ancient grains are known for their high nutritional value, drought tolerance, and ability to grow in poor soils with minimal inputs [2]. Despite their numerous benefits, millets have been largely neglected in modern agriculture and diets, overshadowed by major cereals like rice, wheat, and maize [3]. However, in recent years, there has been a growing recognition of the potential of millets to address the pressing challenges of food and nutritional security, climate change, and sustainable agriculture [4].

The United Nations General Assembly has declared 2023 as the International Year of Millets, recognizing the importance of these crops in achieving the Sustainable Development Goals (SDGs) [5]. This global initiative aims to raise awareness about the nutritional and ecological benefits of millets, promote their production and consumption, and foster collaboration among stakeholders to develop sustainable millet value chains [6]. India, as the world's largest producer of millets, has been at the forefront of this movement, with the government launching various schemes and programs to boost millet cultivation and consumption [7].

This chapter explores the current state of millet production and consumption in India and globally, highlighting the challenges and opportunities for scaling up these nutritious and resilient crops. We begin by discussing the nutritional profile of various millet species and their role in promoting health and preventing chronic diseases. We then examine the agronomic and ecological advantages of millets, particularly in the context of climate change and sustainable agriculture. The chapter also analyzes the socio-economic factors influencing millet cultivation and consumption patterns, including cultural preferences, market demand, and policy support. We present successful case studies of millet value chain development and innovative processing technologies that have enhanced the availability, affordability, and acceptability of millet-based products. Finally, we conclude with recommendations for policy interventions, research priorities, and multi-stakeholder collaborations needed to mainstream millets in food systems and diets worldwide.

2. Nutritional Profile and Health Benefits of Millets

Millets are a diverse group of cereal crops that belong to the Poaceae family, which also includes major cereals like rice, wheat, and maize [8]. There are several species of millets, each with unique nutritional and agronomic characteristics (Table 1). The most commonly cultivated millets include pearl millet (*Pennisetum glaucum*), finger millet (*Eleusine coracana*), foxtail millet (*Setaria italica*), proso millet (*Panicum miliaceum*), barnyard millet (*Echinochloa frumentacea*), little millet (*Panicum sumatrense*), and kodo millet (*Paspalum scrobiculatum*) [9].

| **Table 1. Nutritional composition of common millet species (per 100 g)**

Millet Species	**Energy (kcal)**	**Protein (g)**	**Fat (g)**	**Carbohydrate (g)**
Pearl millet	**361**	**11.8**	**5.0**	**67.0**
Finger millet	**328**	**7.3**	**1.3**	**72.0**
Foxtail millet	**331**	**12.3**	**4.3**	**60.9**
| Proso millet	**354**	**11.0**	**3.5**	**70.4**
Barnyard millet	**307**	**11.2**	**3.9**	**65.5**
| Little millet	**329**	**8.7**	**5.2**	**60.9**
Kodo millet	**309**	**8.3**	**1.4**	**65.9**

Source: Nutritive Value of Indian Foods, National Institute of Nutrition, India [10]

Millets are nutritionally superior to major cereals in terms of protein, fiber, minerals, and bioactive compounds [11]. They are rich sources of essential amino acids, particularly lysine and methionine, which are limiting in other cereals [12]. Millets also contain high levels of dietary fiber, both soluble and insoluble, which promote digestive health and prevent chronic diseases like diabetes, obesity, and cardiovascular disorders [13]. Moreover, millets are abundant in micronutrients such as iron, zinc, calcium, phosphorus, and B-vitamins, which are crucial for various metabolic functions and overall health [14].

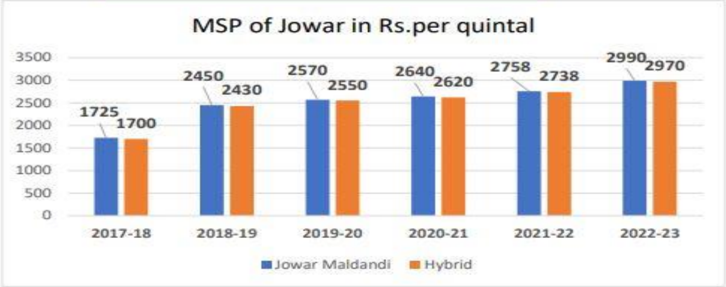
Several studies have demonstrated the health benefits of consuming millets and millet-based products. For instance, a meta-analysis by Anitha et al. [15] found that regular consumption of millets can significantly reduce blood glucose levels and improve glycemic control in people with diabetes. Another study by Thathola et al. [16] showed that feeding millet-based complementary foods to infants and young children can prevent malnutrition and promote healthy growth and development. Millets have also been found to have anti-inflammatory, antioxidant, and anti-carcinogenic properties, attributed to their rich content of phenolic compounds, flavonoids, and other bioactive substances [17].

Despite their superior nutritional profile and health benefits, millets remain underutilized in modern diets, particularly in urban and affluent populations [18]. This can be attributed to various factors, including limited awareness about the nutritional value of millets, changing food preferences and lifestyles, and the dominance of rice and wheat in food policies and markets [19]. However, with the growing recognition of the importance of diversifying diets and promoting nutrient-dense, locally available foods, millets are gaining renewed attention as a promising solution to address malnutrition and diet-related chronic diseases [20].

3. Agronomic and Ecological Advantages of Millets

Millets are not only nutritionally superior but also agronomically and ecologically advantageous compared to major cereals [21]. These crops are known for their hardiness, drought tolerance, and ability to grow in marginal lands with minimal inputs [22]. Millets have a short growing season, typically ranging from 60 to 90 days, which allows them to fit well into various cropping systems and adapt to different agro-ecological conditions [23]. Moreover, millets have a high water use efficiency, requiring 25-30% less water than rice and wheat, making them suitable for rainfed and water-scarce regions [24].

Rise in MSP of Jowar YoY



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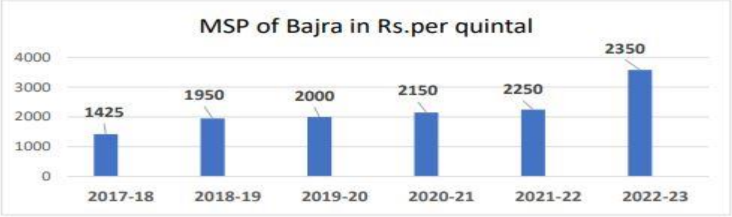

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Rise in MSP of Ragi YoY

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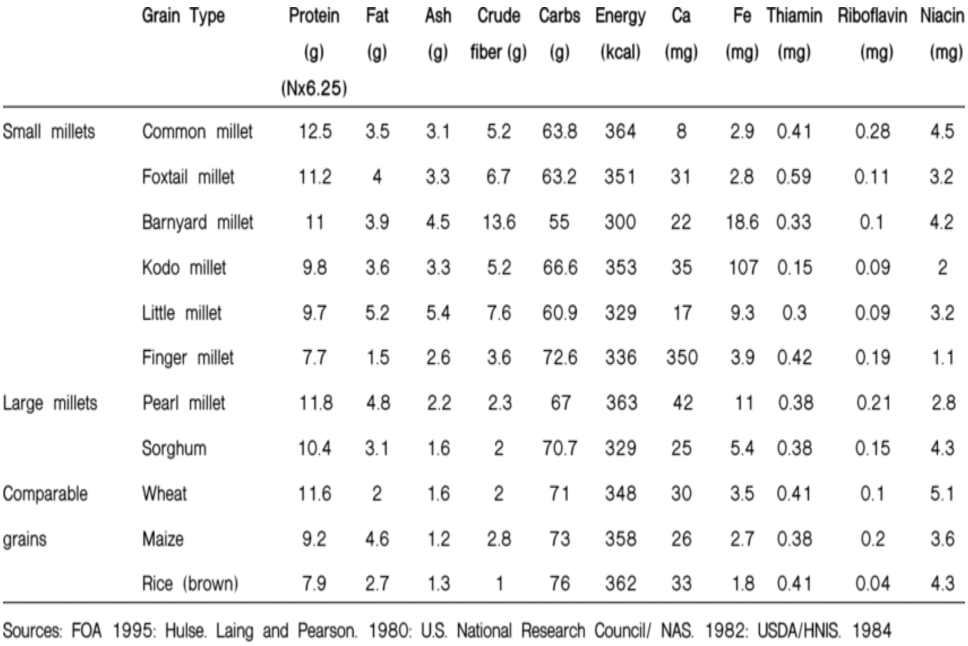
Figure 1. Global production of millets in 2020 (million tonnes)

Millets are also more resilient to climate change and extreme weather events compared to other crops [25]. They can withstand high temperatures, low soil moisture, and poor soil fertility, which are increasingly common in many parts of the world due to global warming and land degradation [26]. For instance, pearl millet can grow in areas with annual rainfall as low as 200-250 mm, while finger millet can tolerate temperatures up to 45°C [27]. This adaptability of millets is crucial for ensuring food security and sustaining livelihoods in vulnerable regions, particularly in the face of climate change and resource constraints [28].



	Grain Type	Protein (g) (Nx6.25)	Fat (g)	Ash (g)	Crude fiber (g)	Carbs (g)	Energy (kcal)	Ca (mg)	Fe (mg)	Thiamin (mg)	Riboflavin (mg)	Niacin (mg)
Small millets	Common millet	12.5	3.5	3.1	5.2	63.8	364	8	2.9	0.41	0.28	4.5
	Foxtail millet	11.2	4	3.3	6.7	63.2	351	31	2.8	0.59	0.11	3.2
	Barnyard millet	11	3.9	4.5	13.6	55	300	22	18.6	0.33	0.1	4.2
	Kodo millet	9.8	3.6	3.3	5.2	66.6	353	35	107	0.15	0.09	2
	Little millet	9.7	5.2	5.4	7.6	60.9	329	17	9.3	0.3	0.09	3.2
	Finger millet	7.7	1.5	2.6	3.6	72.6	336	350	3.9	0.42	0.19	1.1
Large millets	Pearl millet	11.8	4.8	2.2	2.3	67	363	42	11	0.38	0.21	2.8
	Sorghum	10.4	3.1	1.6	2	70.7	329	25	5.4	0.38	0.15	4.3
Comparable grains	Wheat	11.6	2	1.6	2	71	348	30	3.5	0.41	0.1	5.1
	Maize	9.2	4.6	1.2	2.8	73	358	26	2.7	0.38	0.2	3.6
	Rice (brown)	7.9	2.7	1.3	1	76	362	33	1.8	0.41	0.04	4.3

Sources: FOA 1995: Hulse. Laing and Pearson. 1980: U.S. National Research Council/ NAS. 1982: USDA/HNIS. 1984

Figure 2. Nutritional comparison of millets with major cereals (per 100 g)

In addition to their agronomic advantages, millets also have significant ecological benefits [29]. These crops have a low carbon footprint and can help mitigate greenhouse gas emissions from agriculture [30]. Millets require less energy-intensive inputs like fertilizers and pesticides compared to major cereals, reducing the environmental impact of cultivation [31]. Moreover, millets have deep and extensive root systems that can improve soil health, prevent erosion, and enhance water infiltration [32]. Some millet species, such as finger millet, also have allelopathic properties that suppress weed growth, reducing the need for herbicides [33].

Millets can also contribute to agro-biodiversity conservation and sustainable land use [34]. These crops have been traditionally grown in mixed cropping systems with legumes, oilseeds, and other crops, which promote diversity in agriculture and provide multiple benefits to farmers [35]. Millet-based cropping systems can help restore degraded lands, improve soil fertility, and enhance ecosystem services like pollination and pest control [36]. Moreover, millets have a wide genetic diversity, with numerous landraces and wild relatives that can be used for crop improvement and adaptation to changing environments [37].

Despite their agronomic and ecological advantages, millets face several challenges in terms of production and productivity [38]. These include limited access to quality seeds, inadequate extension services, and lack of market incentives for farmers [39]. Moreover, the yield gap between millets and major cereals remains significant, partly due to the neglect of millets in agricultural research and development [40]. To harness the potential of millets for sustainable agriculture and food security, there is a need for greater investment in millet research, infrastructure, and value chain development [41].

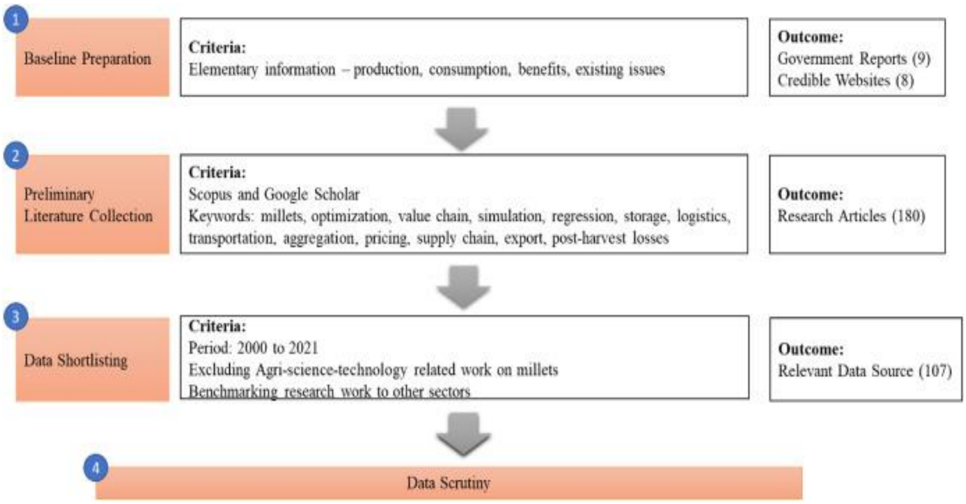


Figure 3. Millet value chain development framework

4. Socio-Economic Factors Influencing Millet Production and Consumption

The production and consumption of millets are influenced by various socio-economic factors, including cultural preferences, market demand, and policy support [42]. In many parts of Africa and Asia, millets have been traditionally grown and consumed as staple foods, particularly by smallholder farmers and rural communities [43]. These crops are deeply embedded in the local food cultures and farming systems, with various traditional recipes and processing methods that enhance their nutritional value and sensory attributes [44]. For instance, in India, millets are used to make porridges, flatbreads, snacks, and beverages, which are an integral part of the dietary habits of many communities [45].

However, with the increasing urbanization, globalization, and changing food preferences, the consumption of millets has been declining in many countries [46]. The dominance of rice and wheat in food policies and markets, coupled with the perception of millets as "poor man's food," has led to a shift towards more refined and processed foods [47]. Moreover, the lack of awareness about the nutritional benefits of millets and the limited availability of millet-based products in urban markets have further contributed to the decline in millet consumption [48].

To revive the production and consumption of millets, there is a need for policy interventions and market incentives that support millet farmers and value chain actors [49]. In India, the government has launched several schemes and programs to promote millet cultivation and consumption, such as the Initiative for Nutritional Security through Intensive Millets Promotion (INSIMP) and the inclusion of millets in the Public Distribution System (PDS) [50]. These initiatives aim to provide technical and financial support to millet farmers, create market linkages, and increase consumer awareness about the benefits of millets [51].

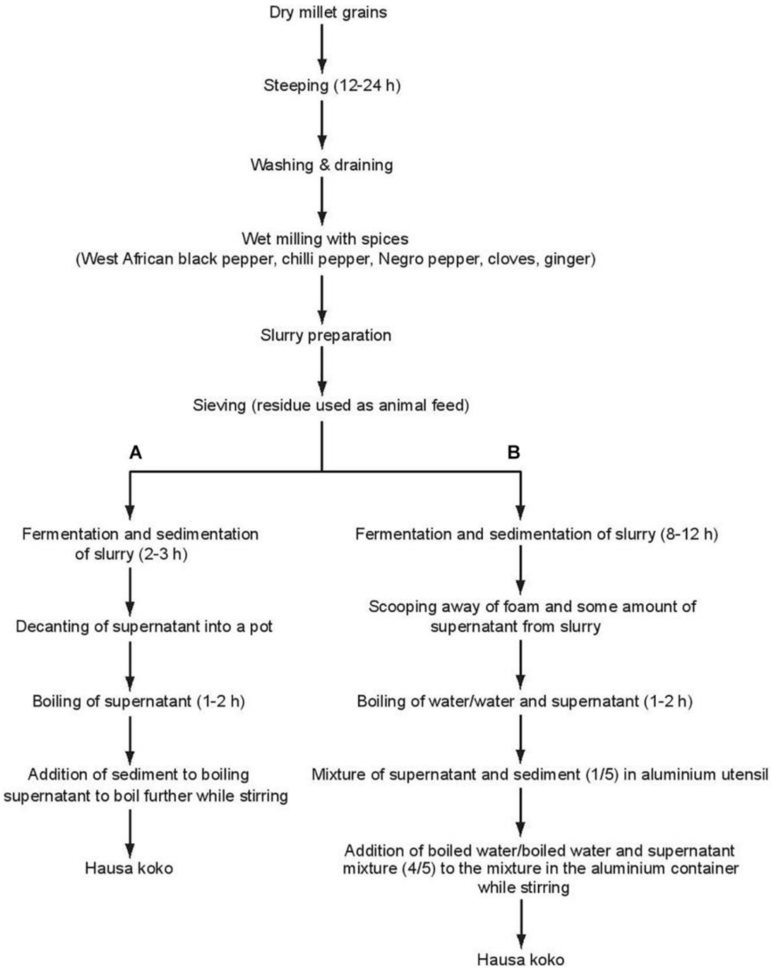


Figure 4. Process flow diagram of millet fermentation

Moreover, there is a growing demand for millets and millet-based products in urban and export markets, driven by the increasing health consciousness and preference for gluten-free, nutrient-dense foods [52]. This presents an opportunity for millet farmers and entrepreneurs to tap into the high-value markets and improve their incomes and livelihoods [53]. However, to meet the quality and safety standards of these markets, there is a need for improved post-harvest handling, processing, and packaging technologies that can enhance the shelf life and nutritional value of millet products [54].

5. Case Studies of Millet Value Chain Development

There are several successful examples of millet value chain development in India and other countries that have enhanced the production, processing, and marketing of millets [55]. These case studies provide valuable lessons and insights for scaling up millet value chains and promoting their integration into food systems and diets [56]. Here, we present two case studies that demonstrate the potential of millets for improving livelihoods, nutrition, and sustainable agriculture.

5.1. The Odisha Millet Mission

The Odisha Millet Mission (OMM) is a flagship program of the Government of Odisha, India, that aims to revive millet cultivation and consumption in the state [57]. Launched in 2017, the OMM has reached over 100,000 farmers and helped establish millet processing units and value-added enterprises across the state [58]. The program follows a cluster approach, wherein farmers are organized into groups and provided with technical support, quality seeds, and market linkages [59]. The OMM also promotes the inclusion of millets in the state's PDS and mid-day meal scheme, ensuring access to nutritious food for vulnerable populations [60].

One of the key innovations of the OMM is the establishment of decentralized processing units, known as Millet Shakti Kendras (MSKs), which are owned and operated by women's self-help groups [61]. These units procure millets from farmers, process them into various value-added products, and market them through various channels, including retail outlets, online platforms, and institutional buyers [62]. The MSKs have not only created employment and income opportunities for women but also enhanced the availability and affordability of millet-based products in local markets [63].

The OMM has also helped revive traditional millet landraces and promoted organic farming practices, contributing to agro-biodiversity conservation and sustainable agriculture [64]. The program has established community seed banks and trained farmers in participatory varietal selection, ensuring the availability of quality seeds and the conservation of local genetic resources [65]. Moreover, the OMM has promoted the use of bio-fertilizers and bio-pesticides, reducing the dependence on chemical inputs and enhancing soil health [66].

The success of the OMM has inspired similar initiatives in other states of India, such as the Andhra Pradesh Millet Mission and the Telangana Millet Mission [67]. These programs have helped mainstream millets in food systems and diets, contributing to the achievement of the SDGs related to zero hunger, good health and well-being, and sustainable agriculture [68].

5.2. The Smart Food Initiative

The Smart Food Initiative is a global initiative led by the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) that promotes the development and marketing of nutrient-dense, climate-resilient, and locally available crops, including millets [69]. The initiative aims to create consumer demand for smart foods, support smallholder farmers in their production and marketing, and foster multi-stakeholder partnerships to scale up smart food value chains [70].

One of the key activities of the Smart Food Initiative is the development and promotion of millet-based products, such as snacks, baked goods, and ready-to-eat meals [71]. The initiative has partnered with various food companies, research institutions, and development organizations to develop innovative millet products that are nutritious, convenient, and appealing to consumers [72]. For instance, in Kenya, the initiative has supported the development of millet-based porridge mixes and snacks, which have been marketed through various channels, including supermarkets, schools, and health centers [73].

The Smart Food Initiative has also promoted the use of millet by-products, such as straw and bran, for animal feed and other value-added applications [74]. This has helped create additional income streams for millet farmers and reduce waste in the value chain [75]. Moreover, the initiative has supported the establishment of millet processing centers and incubation hubs, which provide training, equipment, and market linkages to millet entrepreneurs and farmers [76].

The Smart Food Initiative has also conducted various awareness and education campaigns to promote the nutritional and environmental benefits of millets [77]. These campaigns have targeted consumers, policymakers, and other stakeholders, using various media and platforms, such as social media, TV, radio, and school curricula [78]. The initiative has also organized food festivals, cooking competitions, and other events to showcase millet-based cuisines and products, creating a buzz around these ancient grains [79].

The success of the Smart Food Initiative has demonstrated the potential of millet value chain development for improving nutrition, livelihoods, and sustainable agriculture [80]. The initiative has helped create new market opportunities for millet farmers and entrepreneurs, while also promoting the health and environmental benefits of these crops to consumers [81]. The lessons and insights from the Smart Foo d Initiative can be replicated and scaled up in other regions and contexts, contributing to the mainstreaming of millets in food systems and diets worldwide [82].

6. Innovative Processing Technologies for Millet-Based Products

One of the key challenges in promoting millet consumption is the limited availability and diversity of millet-based products in the market [83]. Millets have traditionally been consumed as whole grains, which require time-consuming and laborious processing methods, such as dehulling, milling, and cooking [84]. Moreover, the short shelf life and poor keeping quality of millet grains and flours have hindered their widespread use in food processing and value addition [85].

To address these challenges, there has been a growing interest in developing innovative processing technologies that can enhance the nutritional value, sensory attributes, and convenience of millet-based products [86]. These technologies range from traditional methods, such as fermentation and germination, to modern techniques, such as extrusion and high-pressure processing [87]. Here, we discuss some of the promising processing technologies that have been applied to millets and their potential for scaling up millet value chains.

6.1. Fermentation

Fermentation is a traditional processing method that has been used for centuries to enhance the nutritional value, digestibility, and sensory attributes of millets [88]. The process involves the use of microorganisms, such as bacteria and fungi, to break down complex compounds in the grains and produce beneficial metabolites, such as vitamins, minerals, and bioactive compounds [89]. Fermentation also reduces anti-nutritional factors, such as phytates and tannins, which can inhibit the absorption of nutrients in the body [90].

Various fermented millet products have been developed and consumed in different parts of the world, such as ogi in West Africa, togwa in East Africa, and jalebi in India [91]. These products have been found to have improved nutritional and sensory qualities compared to unfermented millets, with higher levels of protein, essential amino acids, and bioavailable minerals [92]. Moreover, fermentation has been shown to enhance the shelf life and keeping quality of millet products, reducing the risk of spoilage and contamination [93].

Recent studies have explored the use of novel microbial strains and controlled fermentation conditions to develop millet-based functional foods and beverages [94]. For instance, a study by Giri et al. [95] developed a probiotic millet-based beverage using a co-culture of *Lactobacillus plantarum* and *Saccharomyces boulardii*, which had improved nutritional and sensory attributes compared to unfermented millet beverage. Another study by Ogunremi et al. [96] developed a fermented millet-based infant food using a starter culture of *Lactobacillus plantarum* and *Pichia kudriavzevii*, which had enhanced protein and mineral content and reduced anti-nutritional factors.

6.2. Extrusion

Extrusion is a modern processing technology that has been widely used in the food industry to produce a variety of products, such as snacks, breakfast cereals, and pasta [97]. The process involves the use of high temperature, pressure, and shear to transform raw materials into desired shapes and textures [98]. Extrusion has several advantages over traditional processing methods, such as shorter processing time, higher productivity, and greater flexibility in product formulation [99].

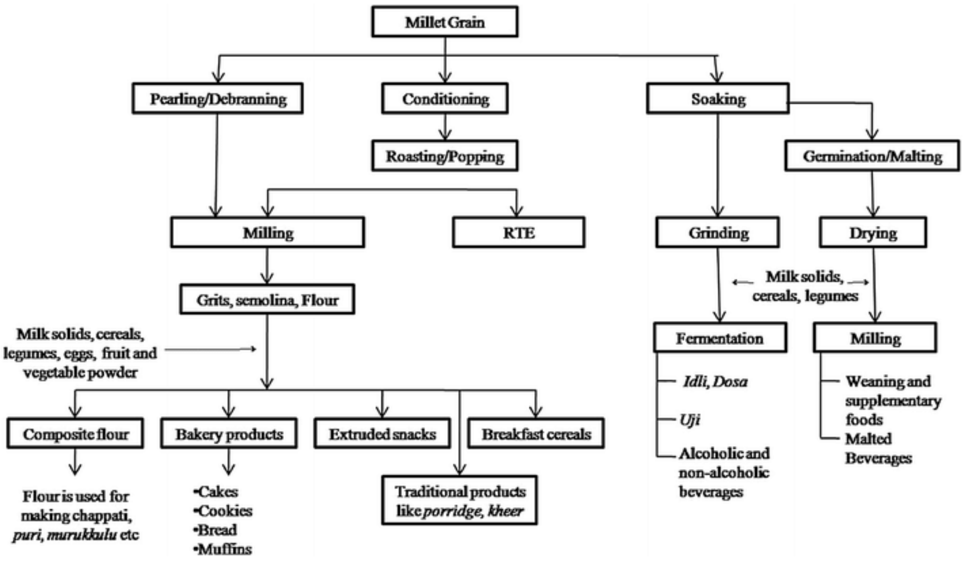


Figure 5. Schematic representation of millet extrusion process

Extrusion has been applied to millets to produce various value-added products, such as ready-to-eat snacks, instant porridges, and fortified blends [100]. The process has been found to improve the nutritional value, digestibility, and sensory attributes of millet products, while also reducing anti-nutritional factors [101]. For instance, a study by Adekunle et al. [102] developed extruded snacks from blends of pearl millet and cowpea, which had higher protein, fiber, and mineral content compared to traditional snacks. Another study by Omwamba et al. [103] developed extruded instant porridges from blends of finger millet, sorghum, and soybean, which had improved nutrient density and sensory acceptability.

Extrusion has also been used to produce millet-based complementary foods for infants and young children [104]. These products have been fortified with micronutrients, such as iron, zinc, and vitamin A, to address the problem of hidden hunger in developing countries [105]. For instance, a study by Tripathi et al. [106] developed an extruded millet-based complementary food using a blend of finger millet, green gram, and peanut, which had enhanced protein, energy, and micronutrient content and better acceptability compared to traditional complementary foods.

6.3. High-Pressure Processing

High-pressure processing (HPP) is an emerging non-thermal processing technology that has been used to extend the shelf life and ensure the safety of various food products, such as juices, sauces, and ready-to-eat meals [107]. The process involves the use of high hydrostatic pressure (100-1000 MPa) to inactivate microorganisms and enzymes that can cause spoilage and quality deterioration [108]. HPP has several advantages over thermal processing methods, such as minimizing the loss of nutrients and bioactive compounds, preserving the sensory attributes, and reducing the need for additives and preservatives [109].

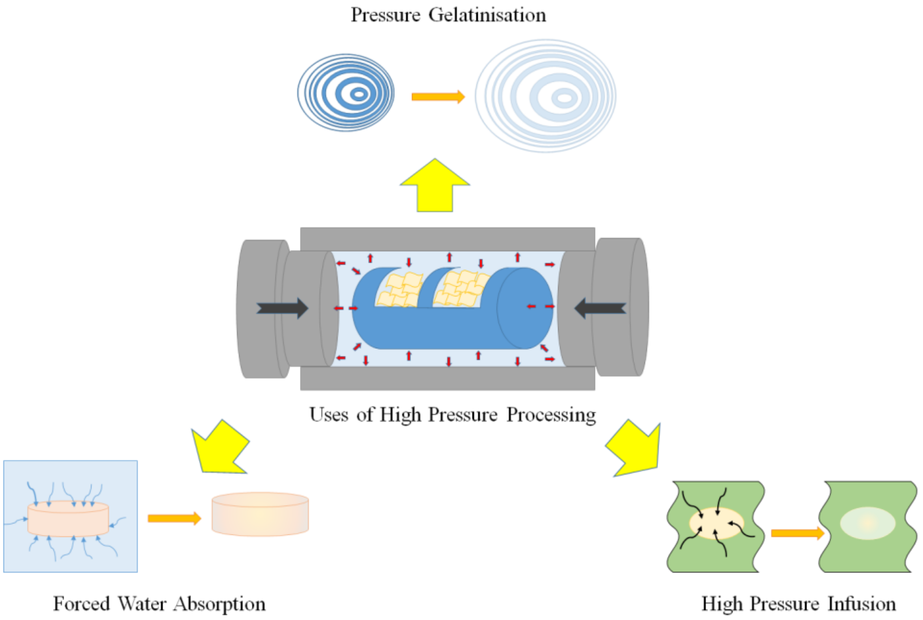


Figure 6. High-pressure processing of millets

HPP has been applied to millets to develop various shelf-stable and nutritious products, such as flours, flakes, and beverages [110]. The process has been found to improve the functional properties, such as water absorption and solubility, and the digestibility of millet products, while also reducing the microbial load and extending the shelf life [111]. For instance, a study by Vanga et al. [112] developed HPP-treated finger millet flour, which had improved pasting properties and higher resistant starch content compared to untreated flour. Another study by Yao et al. [113] developed HPP-treated foxtail millet-based beverage, which had enhanced antioxidant activity and better sensory attributes compared to thermally processed beverage.

HPP has also been used to develop millet-based functional foods and nutraceuticals, which have potential health benefits beyond basic nutrition [114]. For instance, a study by Chakrabarti et al. [115] developed HPP-treated barnyard millet-based cookies, which had higher levels of phenolic compounds and antioxidant activity compared to conventionally baked cookies. Another study by Sharma et al. [116] developed HPP-treated kodo millet-based noodles, which had enhanced protein digestibility and bioavailability of minerals compared to untreated noodles.

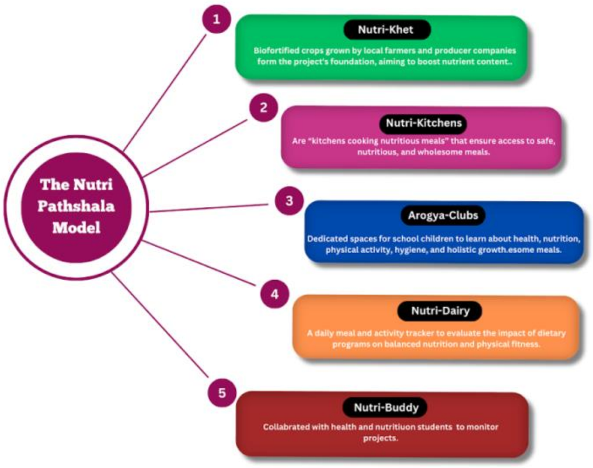


Figure 7. Multi-stakeholder partnership for scaling up millet production

These innovative processing technologies have the potential to revolutionize the millet value chain by creating new product opportunities, improving the nutritional and sensory quality of millet-based products, and enhancing their shelf life and safety [117]. However, the adoption and scaling up of these technologies require significant investments in research and development, infrastructure, and capacity building [118]. Moreover, there is a need for policy support and market incentives to promote the commercialization and distribution of these value-added millet products, particularly in rural and underserved areas [119].

7. Recommendations for Scaling Up Millet Production and Consumption

To harness the potential of millets for improving nutrition, livelihoods, and sustainable agriculture, there is a need for concerted efforts and multi-stakeholder collaborations at various levels [120]. Here, we provide some key recommendations for scaling up millet production and consumption, based on the insights and lessons from the case studies and innovative processing technologies discussed in this chapter.

7.1. Policy Interventions

- Recognize millets as a priority crop in national and regional agricultural policies and programs, with specific targets for increasing their production, productivity, and market share [121].
- Provide incentives and subsidies to millet farmers, particularly smallholders and women farmers, to adopt improved varieties, agronomic practices, and post-harvest technologies [122].
- Include millets in public procurement and distribution systems, such as the PDS and school feeding programs, to create assured markets for millet farmers and improve the access to nutritious food for vulnerable populations [123].
- Promote the inclusion of millets in dietary guidelines and nutrition education programs, highlighting their nutritional and health benefits, and encouraging their consumption as part of a balanced and diverse diet [124].
- Support the establishment of millet processing units and value-added enterprises, particularly in rural and underserved areas, through financial assistance, technical training, and market linkages [125].

7.2. Research and Development

- Invest in research and development of high-yielding, stress-tolerant, and nutrient-dense millet varieties that are adapted to different agro-ecological zones and farming systems [126].
- Develop and disseminate improved agronomic practices, such as intercropping, conservation agriculture, and integrated pest management, that can enhance the productivity and sustainability of millet cultivation [127].
- Conduct research on innovative processing technologies, such as fermentation, extrusion, and HPP, to develop nutritious, convenient, and appealing millet-based products that meet the changing consumer preferences and market demands [128].

- Strengthen the capacity of research institutions, extension services, and farmer organizations to generate and disseminate knowledge and technologies related to millet production, processing, and marketing [129].
- Foster collaborations and partnerships among researchers, policymakers, private sector actors, and development organizations to scale up millet innovations and best practices [130].

7.3. Market Development

- Conduct market research and consumer studies to understand the preferences, perceptions, and willingness to pay for millet-based products among different segments of the population [131].
- Develop and promote brand identity, packaging, and labeling standards for millet products that communicate their nutritional and environmental benefits and differentiate them from other products in the market [132].
- Establish quality control and certification systems for millet products, such as organic, fair trade, and geographical indication, to ensure their safety, authenticity, and value addition [133].
- Promote the use of digital technologies, such as e-commerce platforms, mobile apps, and social media, to connect millet farmers and entrepreneurs with buyers and consumers, and facilitate market transactions and information exchange [134].
- Organize food festivals, cooking competitions, and other promotional events to showcase millet-based cuisines and products, and create awareness and demand among consumers [135].

7.4. Capacity Building and Empowerment

- Provide training and capacity building programs for millet farmers, particularly women and youth, on improved production, post-harvest, and marketing practices, using participatory and hands-on approaches [136].
- Establish farmer field schools, demonstration plots, and seed banks to promote farmer-to-farmer learning and exchange of knowledge and resources related to millet cultivation and conservation [137].
- Support the formation and strengthening of farmer organizations, cooperatives, and self-help groups, to enable collective action, bargaining power, and access to inputs, credit, and markets for millet farmers [138].

- Provide entrepreneurship and business development training to millet processors and value chain actors, particularly women and youth, to enable them to develop and scale up their enterprises [139].
- Promote gender-responsive and inclusive approaches in millet value chain development, ensuring the participation, decision-making, and benefit-sharing of women and marginalized groups [140].

These recommendations provide a comprehensive and integrated approach to scaling up millet production and consumption, addressing the various challenges and opportunities along the value chain [141]. However, the implementation of these recommendations requires the active engagement and collaboration of various stakeholders, including governments, research institutions, private sector actors, civil society organizations, and local communities [142]. Moreover, there is a need for context-specific and adaptive strategies that take into account the diverse agro-ecological, socio-economic, and cultural factors influencing millet production and consumption in different regions and countries [143].

8. Conclusion

Millets are ancient grains with immense potential to address the pressing challenges of food and nutritional security, climate change, and sustainable agriculture. These crops are nutritionally superior, climate-resilient, and ecologically beneficial compared to major cereals, and have been traditionally grown and consumed in various parts of Africa and Asia. However, the production and consumption of millets have been declining in recent decades, due to various socio-economic factors, including changing food preferences, market demand, and policy support.

This chapter has explored the current state of millet production and consumption in India and globally, highlighting the challenges and opportunities for scaling up these nutritious and resilient crops. We have discussed the nutritional profile and health benefits of various millet species, their agronomic and ecological advantages, and the socio-economic factors influencing their cultivation and consumption patterns. We have also presented successful case studies of millet value chain development and innovative processing technologies that have enhanced the availability, affordability, and acceptability of millet-based products.

To mainstream millets in food systems and diets worldwide, we have recommended a comprehensive and integrated approach that includes policy interventions, research and development, market development, and capacity building and empowerment. These recommendations require the active engagement and collaboration of various stakeholders, including governments, research institutions, private sector actors, civil society organizations, and local communities. By harnessing the untapped potential of millets, we can build a healthier, more resilient, and sustainable future for our planet.

As the world celebrates the International Year of Millets in 2023, let us recognize the importance of these ancient grains and take concrete actions to promote their production and consumption. Let us work together to create a more diverse, nutritious, and sustainable food system that leaves no one behind.

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CHAPTER - 16

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Insect Pest Control of Millets

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Abstract

Millets are crucial crops for food security in semi-arid regions due to their adaptability and nutritional benefits. Despite their resilience, millet yields are often compromised by various insect pests, including stem borers, shoot flies, aphids, and armyworms. This document provides an in-depth analysis of these pests, detailing their identification, life cycles, and the specific damage they cause to millet crops. It emphasizes the impact of pest infestations on millet yield and quality, highlighting the economic and agricultural significance.

The document advocates for Integrated Pest Management (IPM) as a holistic approach to pest control. It reviews chemical control methods, including recommended doses and formulations, as well as biological and cultural control strategies. Early detection and monitoring techniques, such as field scouting, trap deployment, and pheromone usage, are discussed to aid in timely pest management.

Future trends in pest control, including advancements in technology, genetically modified crops, and sustainable practices, are also examined. The conclusion stresses the importance of an integrated and adaptive approach to pest management to enhance millet production and ensure long-term food security.

Keywords: *Millet Pests, Integrated Pest Management (IPM), Stem Borers, Pest, Control Strategies, Sustainable Agriculture*

1. Introduction

Introduction to Insect Pests of Millets

Millets, a group of small-seeded grasses, are a staple food for millions of people in arid and semi-arid regions across the world. Known for their resilience and ability to thrive in challenging environmental conditions, millets are critical to food security in many developing countries. However, despite their hardiness, millet crops are susceptible to a wide range of insect pests that can significantly reduce yield and quality.

Insect pests pose a major threat to millet cultivation, leading to both direct and indirect losses. Direct losses occur when insects feed on various parts of the plant, including stems, leaves, and grains, causing physical damage that can stunt plant growth, reduce grain size, and lower overall productivity. Indirect losses, on the other hand, arise when pests act as vectors, transmitting diseases that further compromise crop health and yield.

The impact of insect pests on millet crops varies depending on the pest species, the stage of crop development, and environmental conditions. Some pests, like stem borers and shoot flies, are notorious for their destructive feeding habits, often causing severe damage if not managed properly. Others, such as aphids and grasshoppers, may cause more sporadic damage but can still lead to significant economic losses when populations surge.

Understanding the biology and behavior of these pests is crucial for effective management. Early detection and timely intervention can prevent pest outbreaks from reaching levels that would cause substantial harm. Integrated Pest Management (IPM) strategies, which combine cultural, mechanical, biological, and chemical control methods, are widely regarded as the most sustainable approach to managing insect pests in millet cultivation.

This section of the manual provides an overview of the most common insect pests affecting millet crops, their life cycles, the damage they cause, and the principles of managing them effectively. By equipping farmers and agricultural practitioners with this knowledge, the goal is to minimize the impact of these pests on millet production, ensuring more stable and secure harvests.

- **Stem Borers:** These pests, particularly the pink stem borer (*Sesamia inferens*), are notorious for boring into the stems of millet plants, leading to stunted growth and reduced grain production. The damage is often characterized by deadheart symptoms, where the central shoot of the plant dies.
- **Shoot Flies:** The shoot fly (*Atherigona approximata*) is a major pest of millet, particularly pearl millet. It lays eggs on young seedlings, and the

emerging larvae bore into the shoots, causing the central leaf to wither, a condition known as deadheart.

- **Aphids:** Aphids, such as the green peach aphid (*Myzus persicae*), infest millet plants by sucking sap from the leaves and stems. This not only weakens the plant but also transmits viral diseases, further compromising crop health.
- **Armyworms:** The fall armyworm (*Spodoptera frugiperda*) and other armyworm species can cause extensive defoliation in millet crops. They are particularly destructive in their larval stages, feeding on leaves and sometimes the grain itself.
- **Grasshoppers:** Grasshoppers are generalist feeders that can cause significant damage by feeding on millet leaves, stems, and grains, particularly in drought-prone areas where vegetation is scarce.

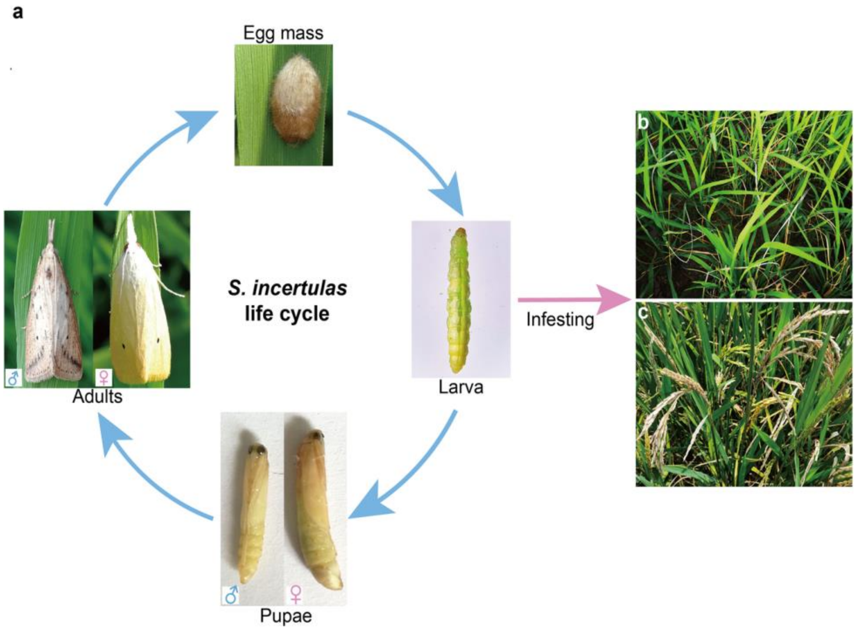
Impact of Insect Pests on Millet Yield and Quality

The impact of insect pests on millet crops is profound, leading to direct and indirect losses. Direct damage includes the physical harm caused by pests feeding on plant tissues, while indirect damage often involves the transmission of diseases and increased susceptibility to environmental stressors. The following table illustrates the typical impact of major insect pests on millet yield and quality.

2. Major Insect Pests of Millets

Stem Borers

Stem borers are among the most damaging insect pests that affect millet crops. They primarily target the stems of the plants, causing significant damage that can lead to substantial yield losses. Stem borers are particularly problematic because they attack the plant's vascular system, leading to stunted growth and poor grain production. Among the various types of stem borers, the pink stem borer (*Sesamia inferens*) and the pearl millet stem borer (*Coniesta ignefusalis*) are the most common and destructive in millet cultivation.



Types of Stem Borers Affecting Millets

1. **Pink Stem Borer (*Sesamia inferens*)**

○ **Host Range:** Primarily affects pearl millet, but can also infest sorghum, maize, and other cereal crops.

○ **Geographical Distribution:** Widely distributed across Asia, particularly in India and Southeast Asia.

○ **Description:** The adult moths are light brown with a wingspan of about 25-30 mm. The larvae are pinkish with a brown head, growing up to 25 mm in length.

2. **Pearl Millet Stem Borer (*Coniesta ignefusalis*)**

○ **Host Range:** Specifically targets pearl millet but can also affect other millet species.

○ **Geographical Distribution:** Common in Africa, particularly in the Sahelian and Sudanian regions.

○ **Description:** The adult moths are grayish-brown with a wingspan of 20-25 mm. The larvae are creamy-white with a brown head, and can grow up to 20 mm long.

Life Cycle and Damage Symptoms

1. Pink Stem Borer (*Sesamia inferens*)

- **Life Cycle:**

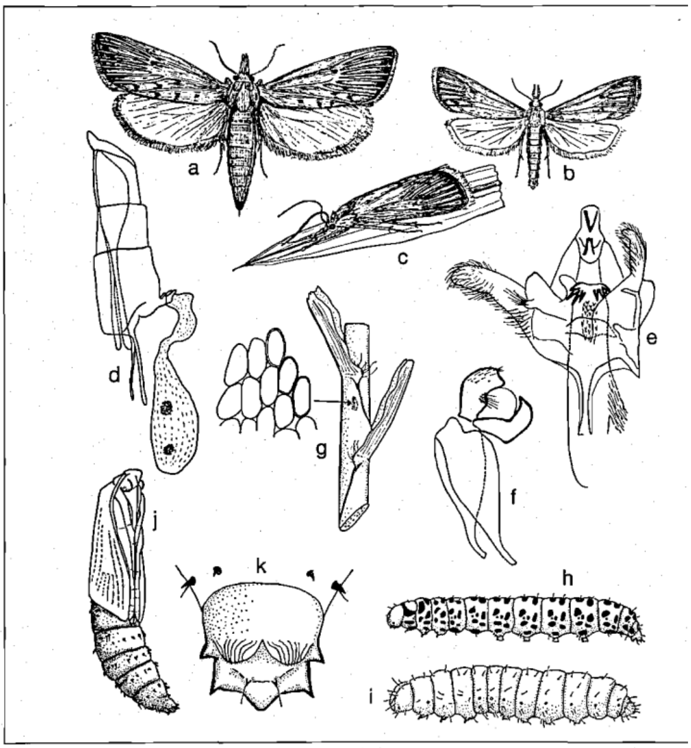
○ **Egg Stage:** Females lay clusters of eggs in leaf sheaths or near the base of the plant. The eggs are creamy-white, oval, and hatch within 4-7 days.

- **Larval Stage:** The larvae bore into the stem and feed internally, passing through 5-6 instars over a period of 20-30 days. This stage is responsible for most of the damage.
- **Pupal Stage:** Pupation occurs within the stem or in the soil near the base of the plant. The pupal stage lasts about 7-10 days.
- **Adult Stage:** Adult moths emerge from the pupae and are active mostly during the night. They have a lifespan of about 7-10 days, during which they mate and lay eggs.

- **Damage Symptoms:**
  - The larvae bore into the central shoot, causing a condition known as "deadheart," where the central shoot withers and dies.
  - Damaged stems may show small holes where the larvae have entered.
  - Infestation during the early stages of the crop leads to stunted growth and poor tillering.
  - In advanced stages, the larvae may feed on the developing grains, leading to reduced grain size and poor quality.

2. Pearl Millet Stem Borer (*Coniesta ignefusalis*)

- **Life Cycle:**
  - **Egg Stage:** Eggs are laid singly or in small clusters on the lower parts of the plant, especially near the base. The eggs hatch in 5-8 days.
  - **Larval Stage:** Larvae bore into the stem and feed internally for 18-25 days, passing through several instars.
  - **Pupal Stage:** Pupation occurs within the stem or just beneath the soil surface. The pupal stage lasts about 10-12 days.
  - **Adult Stage:** Adult moths are nocturnal and have a lifespan of about 5-8 days, during which they lay eggs to continue the cycle.



- **Damage Symptoms:**

o Infestation is characterized by deadhearts in young plants, where the central shoot dies and turns brown.

o Internally, the stem may be hollowed out due to larval feeding, weakening the plant and making it more susceptible to lodging.

o In severe cases, larvae can attack the panicle, leading to poor grain formation and reduced yield.

o The damaged plants may show reduced vigor, delayed maturity, and overall poor crop performance.

Shoot Flies

Identification and Impact on Millet Crops

Shoot flies are significant pests of millet, particularly pearl millet and sorghum. The most common species affecting millets is *Atherigona approximata*.

- **Identification:**

o **Adult Fly:** Resembles a small housefly, measuring about 3-4 mm in length. It has a grayish body with distinct black stripes on the thorax and reddish-brown eyes.

o **Eggs:** Small, white, and elongated, typically laid singly on the undersides of leaves or on the soil near the base of seedlings.

- **Larvae:** Creamy-white maggots that lack a distinct head. They are about 8-10 mm long when fully grown.

Impact on Millet Crops:

- The larvae bore into the central shoots of young millet plants, causing the central leaf to wither and die, a condition known as "deadheart."
- Infested plants often fail to produce viable tillers, leading to significant yield reduction.
- Heavy infestations can result in sparse crop stands, uneven growth, and delayed maturity, ultimately reducing the overall productivity of the crop.

Seasonal Occurrence and Life Cycle

Seasonal Occurrence:

- Shoot flies are most prevalent during the early stages of crop growth, typically within the first 2-4 weeks after planting.
- They are particularly active during the monsoon season when conditions are humid and warm, which favor their breeding and development.

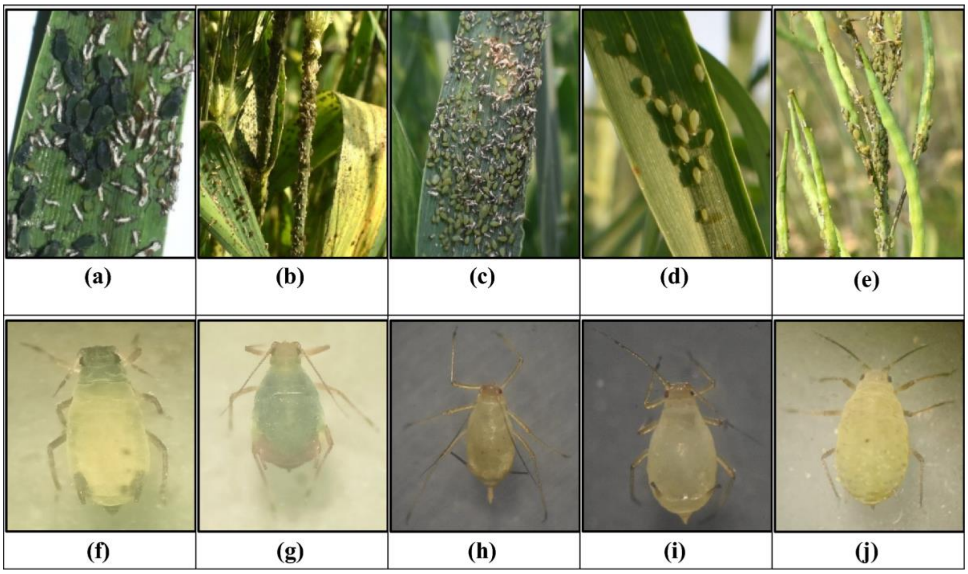
Life Cycle:

- **Egg Stage:** Females lay eggs on young seedlings or near the soil surface. Eggs hatch within 2-3 days.
- **Larval Stage:** After hatching, the larvae bore into the central shoot of the millet plant and feed internally for about 7-10 days. This feeding causes the characteristic deadheart symptom.
- **Pupal Stage:** Pupation occurs in the soil near the base of the plant. The pupal stage lasts 7-10 days.
- **Adult Stage:** Adult flies emerge from the soil, mate, and start the cycle again. The entire life cycle can be completed in about 2-3 weeks, allowing for multiple generations per growing season.

Aphids

Species Affecting Millets

Aphids are small, soft-bodied insects that are significant pests of millet crops, primarily due to their ability to transmit viral diseases.



- **Common Species:**
  - **Green Peach Aphid (*Myzus persicae*):** A polyphagous species that affects a wide range of crops, including millets.
  - **Corn Leaf Aphid (*Rhopalosiphum maidis*):** Commonly infests cereals like maize, sorghum, and millets, feeding on leaves and stems.
  - **Bird Cherry-Oat Aphid (*Rhopalosiphum padi*):** Primarily affects small grains but can also infest millets, particularly in cooler climates.
- **Transmission of Viral Diseases:**
  - Aphids are notorious for their role as vectors of plant viruses. As they feed on plant sap, they can transmit various viral pathogens.
  - **Example of Diseases:**
    - **Millet Mosaic Virus (MMV):** Transmitted by aphids, causing mosaic patterns on leaves, stunted growth, and reduced grain production.
    - **Maize Dwarf Mosaic Virus (MDMV):** Can also infect millets, leading to chlorotic streaks, leaf curling, and overall stunting.
  - The damage caused by viral infections often surpasses the direct feeding damage, leading to significant yield losses.

Armyworms

Types of Armyworms in Millet Fields

Armyworms are another group of destructive pests that affect millet crops, with the most notorious species being the *Fall Armyworm* (*Spodoptera frugiperda*).

Types:

- **Fall Armyworm (*Spodoptera frugiperda*):** A major pest that has spread across Africa, Asia, and the Americas, affecting a wide range of crops, including millets.
- **African Armyworm (*Spodoptera exempta*):** Common in Africa, it primarily feeds on grasses and cereals, including millets.
- **True Armyworm (*Mythimna unipuncta*):** Found in temperate regions, it can cause sporadic damage to millet crops, particularly during outbreaks.

Damage Patterns and Control Measures

Damage Patterns:

- Armyworm larvae are voracious feeders, causing extensive defoliation by consuming leaves, stems, and sometimes even the grains.
- They typically feed during the night and hide during the day, making them difficult to detect early.
- Severe infestations can result in the complete defoliation of plants, leaving only the stems and midribs, which drastically reduces yield.
- In the case of the Fall Armyworm, they can also burrow into the panicles, feeding on developing grains, which further reduces the quality and quantity of the harvest.

Control Measures:

- **Cultural Control:**
  - Early planting to escape peak periods of armyworm infestation.
  - Regular field monitoring to detect early signs of infestation.
  - Use of resistant millet varieties, where available.
- **Biological Control:**
  - Promoting natural predators like parasitoid wasps, birds, and predatory beetles that feed on armyworms.
  - Application of biological pesticides such as Bacillus thuringiensis (Bt) products, which are effective against armyworm larvae.
- **Chemical Control:**
  - When necessary, the application of chemical insecticides like pyrethroids or organophosphates can be used, but these should be applied judiciously to minimize environmental impact.
  - Integrated Pest Management (IPM) practices are recommended, combining multiple control strategies to manage armyworm populations effectively.

Chemical control remains a crucial component of Integrated Pest Management (IPM) for managing insect pests in millet cultivation. While cultural and biological controls are preferred for their sustainability, chemical insecticides are often necessary to protect crops from severe pest outbreaks. The use of chemical control should be carefully managed to minimize environmental impact and the development of pesticide resistance.

1. Shoot Flies

- **Insecticide:** Cypermethrin 10% EC

o **Dose:** 500 ml/ha

o **Application Timing:** Apply at seedling stage when early signs of shoot fly infestation are detected. A follow-up application may be necessary depending on the pest pressure.

o **Effectiveness:** Cypermethrin is a broad-spectrum synthetic pyrethroid insecticide effective against the larvae of shoot flies. It acts by disrupting the nervous system of the insect, leading to paralysis and death.

- **Insecticide:** Dimethoate 30% EC

o **Dose:** 1.5-2.0 liters/ha

o **Application Timing:** Early application during the seedling stage is crucial. Repeat applications may be necessary, depending on pest severity.

o **Effectiveness:** Dimethoate is a systemic organophosphate insecticide that controls shoot flies by inhibiting the cholinesterase enzyme, leading to the accumulation of acetylcholine and subsequent insect death.

2. Aphids

- **Insecticide:** Imidacloprid 17.8% SL

o **Dose:** 150 ml/ha

o **Application Timing:** Apply at the early stage of aphid infestation. Reapplication may be necessary based on pest monitoring results.

o **Effectiveness:** Imidacloprid is a neonicotinoid insecticide that acts on the central nervous system of insects, causing paralysis and death. It is effective against aphids by providing both contact and systemic action.

- **Insecticide:** Thiamethoxam 25% WG

o **Dose:** 100 grams/ha

o **Application Timing:** Apply when aphid populations reach the economic threshold level. Monitor the field regularly for reinfestation.

- **Effectiveness:** Thiamethoxam is another neonicotinoid that disrupts the insect nervous system. It provides quick knockdown effects and long-lasting control of aphids, even at low doses.

***3*. Armyworms**

- **Insecticide:** Chlorantraniliprole 18.5% SC
  - **Dose:** 150-200 ml/ha
  - **Application Timing:** Apply at the onset of armyworm infestation when larvae are small and feeding on the foliage.
  - **Effectiveness:** Chlorantraniliprole is an anthranilic diamide insecticide that causes muscle paralysis in insects by activating the ryanodine receptors. It provides excellent control of armyworms with minimal impact on non-target organisms.
- **Insecticide:** Lambda-Cyhalothrin 5% EC
  - **Dose:** 300 ml/ha
  - **Application Timing:** Best applied when the first signs of armyworm activity are observed in the field. A second application may be required depending on the severity of the infestation.
  - **Effectiveness:** Lambda-cyhalothrin is a pyrethroid insecticide effective against a broad range of pests, including armyworms. It works by disrupting the sodium channels in the nervous system, leading to rapid knockdown and death.
- **Insecticide:** Spinosad 45% SC
  - **Dose:** 75-100 ml/ha
  - **Application Timing:** Apply during early larval stages of armyworms for optimal control. Monitor crops regularly to determine the need for additional treatments.
  - **Effectiveness:** Spinosad is a naturally derived insecticide that targets the nicotinic acetylcholine receptors in the insect nervous system. It is particularly effective against caterpillars and has a relatively low impact on beneficial insects.

Data Summary

Insect Pest	Insecticide	Active Ingredient Concentration	Dose	Application Timing	Effectiveness
Shoot Flies	Cypermethrin 10% EC	10%	500 ml/ha	Seedling stage	High effectiveness, fast knockdown

Shoot Flies	Dimethoate 30% EC	30%	1.5-2.0 liters/ha	Early seedling stage	Systemic action, broad-spectrum control
Aphids	Imidacloprid 17.8% SL	17.8%	150 ml/ha	Early aphid infestation	Systemic and contact action, long-lasting
Aphids	Thiamethoxam 25% WG	25%	100 grams/ha	At threshold level	Quick knockdown, effective at low doses
Armyworms	Chlorantraniliprole 18.5% SC	18.5%	150-200 ml/ha	Early larval stages	Excellent control, minimal non-target impact
Armyworms	Lambda-Cyhalothrin 5% EC	5%	300 ml/ha	First signs of activity	Broad-spectrum, fast-acting
Armyworms	Spinosad 45% SC	45%	75-100 ml/ha	Early larval stages	Low impact on beneficials, effective on caterpillars

Monitoring and Early Detection of Insect Pests

Effective pest management in millet cultivation relies heavily on timely monitoring and early detection of insect pests. This proactive approach allows for the implementation of control measures before pest populations reach damaging levels, thereby minimizing yield losses and reducing the need for chemical interventions.

Field Scouting Techniques

Field scouting is the cornerstone of early pest detection and involves systematically inspecting millet fields to assess pest presence and population levels.

- **Systematic Sampling:** Divide the field into sections and inspect a representative sample of plants from each section. This ensures a comprehensive assessment of the pest situation across the entire field.
- **Visual Inspection:** Check for visible signs of pest activity, such as damaged leaves, stems, or grains. Look for symptoms specific to different pests, like deadhearts caused by stem borers or honeydew and sooty mold associated with aphid infestations.

- **Use of Tools:** Magnifying lenses, sweep nets, and beat sheets can aid in detecting small or elusive pests like aphids and armyworm larvae.

Regular Monitoring Practices

Regular monitoring is essential to track pest populations over time and to detect early stages of infestation.

- **Frequency:** Conduct field scouting at least once a week, and increase the frequency during peak pest activity periods, such as early crop growth stages or during favorable weather conditions for pest proliferation.
- **Record Keeping:** Maintain detailed records of pest observations, including the number of pests, the extent of damage, and the locations of infestations. This data helps in making informed decisions on when and how to intervene.
- **Threshold Levels:** Establish economic threshold levels (ETLs) for different pests. When pest populations exceed these thresholds, timely action is required to prevent economic damage.

Identifying Early Signs of Infestation

Early signs of pest infestation are often subtle but can provide critical warning signals.

- **Deadhearts:** The early symptom of shoot fly and stem borer infestation, where the central shoot of the millet plant withers and dies.
- **Frass and Boring Holes:** Small piles of frass (insect excrement) near holes in the stem or leaves are indicative of stem borer activity.
- **Sticky Leaves:** A sign of aphid infestation, where honeydew secreted by aphids causes leaves to become sticky and attract sooty mold.
- **Chewed Leaves:** Ragged or skeletonized leaves often point to armyworm activity, particularly if caterpillars are found nearby.

Use of Traps and Pheromones

Traps and pheromones are valuable tools in monitoring and managing pest populations, especially for moths and other flying insects.

Trap Placement and Maintenance

- **Placement:** Install traps at strategic locations in the field, such as along the edges and in the center, to capture a representative sample of the pest population. For stem borers and armyworms, pheromone traps should be placed at a height of 1-1.5 meters.

- **Maintenance:** Regularly check traps for captured insects and replace lures as needed. Clean or replace sticky or water traps to maintain effectiveness.

Interpreting Trap Data

- **Trap Counts:** Monitor the number of insects caught in traps over time. Sudden increases in trap counts can indicate an impending infestation.
- **Correlation with Field Observations:** Compare trap data with field scouting results to validate pest presence and assess the need for control measures.
- **Thresholds:** Establish thresholds for action based on trap counts. For instance, catching a specific number of moths in pheromone traps may signal the need for insecticide application.

5. Case Studies in Millet Pest Management

Successful IPM Programs in Millet Cultivation

Several Integrated Pest Management (IPM) programs have been successfully implemented in millet cultivation, combining cultural, biological, and chemical control methods.

Case Study 1:

- **Location:** Sahel Region, Africa
- **Pest Target:** Pearl Millet Stem Borer
- **IPM Strategies:** Early planting, use of resistant varieties, and biological control using parasitoids.
- **Outcome:** Significant reduction in stem borer damage and increased millet yield by 20-30%.

Case Study 2:

- **Location:** Rajasthan, India
- **Pest Target:** Shoot Fly and Aphids

- **IPM Strategies:** Seed treatment with Imidacloprid, intercropping with legumes, and timely application of neem-based insecticides.
- **Outcome:** Reduced pest pressure and decreased reliance on chemical insecticides by 40%.

Lessons Learned from Field Trials

- **Timely Intervention:** Early detection and timely control measures are critical for minimizing pest damage.
- **Diversified Approaches:** Combining multiple control strategies, including cultural practices and biological controls, is more effective than relying solely on chemical treatments.
- **Community Participation:** Engaging local farmers in IPM programs through training and demonstration trials enhances adoption and effectiveness.

6. Future Trends in Millet Pest Control

Advances in Pest Control Technologies

- **Precision Agriculture:** The use of drones and remote sensing technologies for real-time pest monitoring and targeted pesticide application is gaining traction in millet cultivation.
- **Biopesticides:** Development of new biopesticides derived from natural organisms, such as bacteria, fungi, and plant extracts, offers environmentally friendly alternatives to chemical insecticides.
- **Digital Tools:** Mobile apps and decision support systems are being developed to assist farmers in identifying pests, monitoring infestations, and choosing appropriate control measures.

Role of Genetically Modified Millets

- **GM Millets:** Research is underway to develop genetically modified millet varieties with built-in resistance to key pests, such as stem borers and aphids. These GM crops could significantly reduce the need for chemical insecticides.
- **Regulatory and Ethical Considerations:** The adoption of GM millets will depend on regulatory approvals, public acceptance, and the consideration of potential ecological impacts.

Sustainable Practices and Organic Pest Management

- **Organic Practices:** Increasing interest in organic millet production has led to the adoption of sustainable pest management practices, such as the use of organic fertilizers, biopesticides, and crop rotation.
- **Sustainable Pest Control:** Emphasis on conservation of natural enemies, habitat management, and reduced pesticide use aligns with the principles of sustainable agriculture and long-term environmental health.

7. Conclusion

Effective pest management in millet cultivation requires a combination of monitoring, early detection, and integrated control measures. Regular field scouting, the use of traps, and the timely application of targeted insecticides are essential for managing pest populations. Integrated Pest Management (IPM) approaches that combine cultural, biological, and chemical controls offer the most sustainable and effective solutions. The adoption of integrated pest management strategies is crucial for the long-term sustainability of millet cultivation. By reducing reliance on chemical insecticides and promoting the use of biological and cultural control methods, farmers can protect their crops, enhance yield stability, and contribute to environmental conservation. The future of millet pest management lies in the continued development of innovative technologies, sustainable practices, and the integration of traditional knowledge with modern science.

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