HARVESTING PROSPERITY:
RICE, MILLETS AND BEYOND- CULTIVATION, VALUE ADDITION AND MARKETING

EDITORS

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PREFACE

Millets, a category of small-seeded grains, have been cultivated for centuries and have played an important role in the food systems of many nations. The nutritional, ecological, and economic value of millets have received increasing attention in recent years. These grains have a stellar reputation for their health benefits due to their abundance of beneficial components including protein, fiber, vitamins, and minerals. Millets are an excellent crop for areas with water constraint and irregular weather patterns because they need less water and show higher tolerance to climate change. Although there are many advantages to growing and eating millets, there have been obstacles that have led to a decrease in their production and use. This reduction may be attributed to a number of factors, including the trend toward monoculture, a lack of knowledge about the health advantages of millets, a scarcity of processing facilities, and insufficient legislative assistance. To emphasize the role of millets in attaining sustainable development objectives, increasing food security, and decreasing hunger, the United Nations has declared 2023 the International Year of Millets.

This book attempts to cover different aspects of advancement in millet research and value addition. This book consists of seventeen chapters on diversified aspects aiming to make the millet farming a profitable venture. The chapters on crop improvement technologies focus on the recent varietal development to mitigate the adverse effects of climate change. Special emphasis is also given on the advances in biotechnological tools like gene editing techniques for development of climate resilient varieties. Information on advancement in production technologies like precise nutrient and water management also elaborated in this book. The modern agronomic practices to make the millet farming climate resilient are also described. Integrated pest and disease management for enhancing the productivity and profitability in an eco-friendly manner is discussed in detail. This book also addresses the recent innovations in millet processing, packaging and value addition.

The editors sincerely acknowledge all the anonymous sources of the information and photographs. The editors firmly believe that the farmers, researchers, educators, extension workers, policy officials, academics, and members of civil society will all find this book to be of great importance.

Editors

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FOREWORD

The millet crops were early domesticated and cultivated on vast acreages in ancient times on the Indian subcontinent. These crops are known for their hardiness and resilience to adverse climatic conditions. Millets were staple food sources for the hardworking people of ancient India, as they were rich sources of fibre, vitamins, minerals, and essential micronutrients necessary for the human body. The nutritional status of millets was evidently mentioned in epic mythologies like 'Ramayan'. However, the popularity and acreage of millet in India have drastically reduced in recent decades due to the introduction of high-yielding varieties of other crops like wheat, maize, and rice. Presently, the millets are grown in an area of ~15 M ha with a production of ~18 Mt in India. Looking back into the nutritional importance of these millets through modern-day scientific shreds of evidence, interest in consuming millets in different ways is increasing among the citizens of the country.

Considering the nutritional importance and the behest of the Government of India, the International Year of Millets is celebrated in the year 2023 to promote millet production and consumption and improve the livelihood of millet-growing farmers. This is a great opportunity for the agricultural scientists and stakeholders in India not only to reorient millet research but also to provide a sustainable vision for nutritional and economic security in the country. There are ample of scope for diversifying the rice area with millet, particularly in the upland areas of many of the eastern states. As millets productivity is a concern, a new achievable target to increase production efficiency in a sustainable direction should be visualized on the occasion of the International Year of Millets. Furthermore, awareness of millets as 'nutri-cereals' should be created across the country. Multigrain products like Rice-Millet, Wheat-Millet and Maize-Millet need to be prepared, validated and promoted. Besides, partnerships between farmers and stakeholders need to be rightly emphasized and materialized for the improvements in form of "farm to food table" scenarios of value-added millet products. Concerted efforts in millets research and dissemination of research outcomes to the stakeholders help meet the nutritional requirements of the growing population in the country.

I believe this book holds great promise for disseminating knowledge on millets and millets-based products. The information on modern high-yielding varieties and myriads of millet products could assist the "Millet Mission" of our country. Publication of this book in the event of the National Millet Expo 2023, jointly organized by the ICAR-National Rice Research Institute, Cuttack and National Institute of Food Technology, Entrepreneurship and Management (NIFTEM-T), Thanjavur, Tamil Nadu encourages students, academicians, scientists, policymakers, and other stakeholders in the area of millets to properly plan to ensure nutritional security of the country. My warmest congratulations and best wishes to all editors, contributors, and other associates for bringing out this valuable publication on the occasion of the National Millet Expo 2023.

Cuttack, Odisha, India

(A.K. Nayak)

October, 2023

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Contents

Importance of Millets in Food Security and Agricultural Sustainability

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Millets are a group of crops cultivated mostly in arid and semiarid ecosystems worldwide and form the mainstay of food and nutritional security for humans in these regions. Around 60% of millet production is concentrated in East and South Asia, 14% in Central Asia and Eurasia, 16% in Africa, and the remaining 10% is shared by the rest of the world. India is the primary producer, contributing approximately 38% of the total millet production. Millets are small-seeded grasses that are hardy and grow well in dry zones as rain-fed crops under marginal conditions of soil fertility and moisture. Millets are coarse grains with high nutritional value, making them crucial crops due to their climate resilience. They contain proteins that boost the body's energy levels and are rich in calcium and iron. Therefore, there is a need to increase millet cultivation to meet the growing demand. The Indian Government has already recognized the importance of millets and declared 2018 as "The Year of Nutri-Cereals." Now, the FAO has proposed 2023 as the International Year of Millets, emphasizing the significance of these crops.

Keywords: Food security, Malnutrition, Agricultural sustainability

Status of food security in India

Food security means ensuring that sufficient food is available for everyone with no barriers to access. India has achieved significant economic growth in recent times and remains one of the fastest-growing economies in the world. However, poverty and food insecurity in India are still areas of concern despite numerous efforts. In 2021, India ranked 101st out of 116 countries on the Global Hunger Index (source: www.drishtiias.com, 2023). Food insecurity can lead to severe health disorders and make it more difficult for children to learn and grow.

The role of human consumption demand is likely to be significant in the development of millets. However, detailed information on the nature of this demand and consumers' preferences for millet products is currently unavailable (Umanath et al., 2018). Major millets such as jowar, ragi, and bajra were consumed at rates of 500g, 20g, and 70g per month, respectively (Sanjiv Kumar et al., 2017). Between 1962 and 2010, India's per capita consumption of millets drastically declined from 32.9 to 4.2 kg (source: www.indiaspend.com). Nowadays, millet consumption has increased due to the rising demand for healthier and gluten-free food products. However, millet production still struggles to meet the needs of the increasing population, mainly due to the following challenges.

- Deteriorating Soil Health
- Invasive weed threats
- Practical difficulty in Procurement
- Climate Change
- Supply Chain Disruption

Millets - Climate Resilient Staple Food Crops

- Less water requirement crop and higher water use efficiency
- Lesser occurrence of pests and diseases
- Contributes significantly to food security
- Suitable for adverse soil & climatic conditions
- Mostly shorter in duration that provide food during lean months of some part of the country
- Some of millets are suitable for a contingency plan
- Lesser input requirements of millets
- Unpredictable weather patterns and water scarcity.

Millets and Soil health

Millets play a vital role in promoting and maintaining soil health. These resilient crops are well-suited for sustainable farming practices, as they do not heavily rely on synthetic fertilizers. Millet cultivation often involves the use of green manures, green leaf manures, household compost, vermicompost, and biofertilizers. These organic and natural inputs enrich the soil with essential nutrients, enhance its structure, and improve its overall health. Moreover, millets' deep root systems help prevent soil erosion, and their pest-resistant nature reduces the need for chemical pesticides, contributing to a healthier and more balanced soil ecosystem. By fostering nutrient-rich, resilient soils, millets not only ensure their own successful growth but also promote sustainable agriculture and long-term soil health. Thus, they are a great boon to the agricultural environment (Sandhya rani *et al.*, 2020).

Millet - The Power house of nutrients

Millets are often hailed as the powerhouse of nutrients. These humble grains are packed with a wealth of essential vitamins and minerals, making them a valuable addition to a balanced diet. Millets are particularly rich in dietary fiber, which aids in digestion and helps regulate blood sugar levels. They are abundant sources of B-vitamins, including niacin, riboflavin, and folic acid, crucial for energy metabolism and overall health (Gopalan *et al.*, 1989). Millets are also renowned for their high content of minerals like iron, calcium, magnesium, and phosphorus, contributing to strong bones and overall vitality. Additionally, millets are gluten-free and offer a healthy alternative for individuals with dietary restrictions or sensitivities. Their impressive nutritional profile establishes millets as a versatile and nutrient-dense choice for promoting well-being and vitality. The following table shows the nutrient content of cereals and millets per 100 g (Nutritive value of Indian foods, NIN, 2007, Longvah *et al.*, 2017)

Table 1. Nutritive value of different millets

Grain (Millet/ cereal)	Carbohydrates (g)	Protein (g)	Fat (g)	Energy (Kcal)	Dietary Fibre (g)	Ca (mg)	P (mg)	Mg (mg)	Zn (mg)	Fe (mg)	Thiamine (mg)	Riboflavin (mg)	Niacin (mg)	Folic acid (mg)
Sorghum	67.7	9.9	1.73	334	10.5	27.6	274	133	1.9	3.9	0.35	0.14	2.1	39.4
Pearl millet	61.8	10.9	5.43	347	11.5	27.4	289	124	2.7	6.4	0.25	0.20	0.9	36.1
Finger millet	66.8	7.2	1.92	320	11.2	364	210	146	2.5	4.6	0.37	0.17	1.3	34.7
Kodo millet	66.2	8.9	2.55	331	6.4	15.3	101	122	1.6	2.3	0.29	0.20	1.5	39.5
Prosomillet	70.4	12.5	1.10	341	–	14.0	206	153	1.4	0.8	0.41	0.28	4.5	-
Foxtail millet	60.1	12.3	4.30	331	–	31.0	188	81	2.4	2.8	0.59	0.11	3.2	15.0

Little millet	65.5	10.1	3.89	346	7.7	16.1	130	91	1.8	1.2	0.26	0.05	1.3	36.2
Barnyard millet	65.5	6.2	2.20	307	-	20.0	280	82	3.0	5.0	0.33	0.10	4.2	-
Wheat	64.7	10.6	1.47	321	11.2	39.4	315	125	2.8	3.9	0.46	0.15	2.7	30.1
Rice	78.2	7.9	0.52	356	2.8	7.5	96	19	1.2	0.6	0.05	0.05	1.7	9.32

Millet and Health benefits

In recent years, millets have garnered significant attention as a nutritional powerhouse and a promising solution to many dietary and health challenges. These ancient grains, often overlooked in modern diets, are reemerging as a staple with an array of remarkable health benefits. However, farmers are not as interested in cultivating millets on a large scale as they are in rice and wheat due to industrialization. Modern lifestyles and dietary habits contribute to various diseases in humans. Proper nutrition can reduce the risk of developing conditions such as hypertension, heart disease, stroke, diabetes, cancer, and more. Millets have resurfaced as a viable solution to living healthy lives and can help decrease the incidence of these lifestyle-related diseases (Venkatesh Bhat *et al.*, 2018). The nutrients present in millets play a crucial role in managing and preventing these diseases.

- **Rich in Protein** – Regulates immune system
- **Rich in Calcium** – Strengthen the bones
- **Rich in Iron** – to make hemoglobin
- **Rich in phytochemicals** - to lower cholesterol
- **Low-glycemic index**-Control Blood Sugar
- **Rich in anti oxidants** - Reduce cancer risk
- **High dietary fiber** - protects against hyperglycemia
- **Phytates** – reduce oxidation stress
- **Phenolics and tannin**- act as antioxidants.
- **Rich in niacin-** helps more than 400 enzyme reactions.
- **Excellent source of beta-carotene** - acts as both an antioxidant and as a precursor to vitamin A
- **Improve Digestive Health** - rich in dietary fiber, both soluble and insoluble.
- **Raise "good" cholesterol levels and lower triglycerides-** to keep your heart healthier.
- **Rich in potassium** - Supports healthy kidney and heart function.

Millets and fodder security

In the realm of sustainable agriculture and livestock management, millets emerge as unsung heroes, quietly but effectively contributing to the crucial aspect of fodder security. These ancient grains, often revered for their nutritional value, hold another hidden treasure their ability to provide a reliable and sustainable source of fodder for livestock. In an era marked by fluctuating climate patterns and growing concerns over food and fodder scarcity, millets have stepped into the spotlight as a valuable solution, safeguarding the well-being of both animals and farmers alike.

Millet cultivation supporting nearly half of India's rural workforce and sustaining 60 percent of the country's cattle population. Beyond contributing to food and nutritional well-being, millets have the potential to play a significant role in bolstering immunity, providing essential fodder, enhancing biodiversity, and safeguarding the livelihoods of farmers. These versatile grains also serve as a nutritious food source for livestock and birds, growing in popularity due to their fast growth, drought resistance, and low input requirements.

Pearl millet, a high-nutrient summer-annual forage crop, enjoys popularity among livestock producers for various uses, including grazing, silage, hay, and green chop. Additionally, it serves as a reliable one-year forage crop option, offering an economical alternative for farmers.

Finger millet stover, rich in minerals, proteins, and digestible fibers, presents a nutritious option for dairy cattle feed and can be effectively utilized for making hay or silage. While seasonal crops like rice and wheat play a vital role in feeding cattle and ensuring food security, millets have emerged as crucial in securing fodder and sustaining livelihoods in today's agricultural landscape.

Millet and its accessibility

In today's ever-evolving landscape of dietary choices and agricultural practices, millets are redefining accessibility to nutritious and sustainable food sources. These resilient grains, often overshadowed by more mainstream crops, are emerging as champions of accessibility, offering a wealth of benefits to diverse communities and regions. Accessibility plays a crucial role in ensuring food security. In India, millet production stands at 180.21 lakh tonnes (APEDA, 2023). However, despite this significant production, the accessibility, such as the average monthly consumption per person in our homes, has historically been limited to just 2-3 kilograms. Recently, there has been a notable increase to 14 kilograms per month. Nonetheless, accessibility remains restricted due to the following reasons

- Lack of awareness about nutritional benefits of millets
- High cost of rice compare to rice

- Limited availability
- Perceived taste
- Agricultural Challenge
- Competition of Rice and Wheat
- Lack of Government support

Millet and Agricultural Sustainability

In the midst of global concerns about climate change, resource conservation, and sustainable agriculture, millets emerge as a beacon of agricultural sustainability. These resilient grains, deeply rooted in traditional farming practices, offer a promising pathway to a more sustainable future and the sustainable development of millet aims to achieve zero hunger. Millets are generally grown using traditional farming methods, which are more sustainable and environmentally beneficial. It plays an important role in providing farmers with a sustainable and reliable source of income. It requires less expenditure, resources, and time when compared to other crops. This makes them an ideal crop for small farmers who may not have the resources to invest in high-input crops.

Way to sustain the millet production and consumption

Developement of biofortified / nutrient rich varieties. Consumption of biofortifies products will reduce malnutrition and improve resistancce to health Vulnerabilities (Dayakar Rao *et al.*, 2018)The following are the some of vailable nutritious varieties in millets

Little millet ATL 1

Foxtail millet ATL 1

Conducting demos through various schemes with all improved technologies

Ragi farmer field

Demo field

Include transplanting techniques in millet cultivation which minimize the weeds problem and provides profuse tillering

Baranyard millet transpalnting

Good crop stand

Adoption of various cropping systems to ensure the higher income

Kodo millet + Black gram

Foxtail millet + Niger

- Promoting seed production techniques by using pelleted seed which give nutrition to the seeds for early vigorus germination.
- Cultivation in non traditional areas and problem soils
- Utilization of Agro-forestries
- Steps taken to introduce millet as a industrial crop
- Development procurement policies like Rice, Wheat to all the millet crops
- Crop diversification is important in the context of persistent poor nutrition and food insecurity
- Governments and the private sector can develop partnerships and expand links with smallholders and farmers' organisation, filling critical gaps along the food system value chain.
- Provide better infrastructure.
- Increase access to financial services for farmers and growing agri-businesses for higher yields or better nutrition.
- Climate-smart agricultural solutions can improve food security and farming resilience by increasing productivity compared to conventional approaches.
- Mobilise young people and empower the women for all the millet cultivation activities.
- More investment is also needed in training and technical works
- Provide agricultural information, via mobile phones and the internet.

Conclusions

Millets stand as indispensable allies in our quest for food security and sustainability. Their remarkable ability to thrive under diverse climatic conditions, low resource requirements, and traditional farming practices positions them as a sustainable solution for feeding a growing global population. Millets offer not just a source of nourishment but also a lifeline to millions of small-scale farmers, bolstering their livelihoods and ensuring economic stability. As we witness the pressing challenges of climate change, resource scarcity, and the need for resilient agriculture, millets emerge as a beacon of hope. Their resilience, adaptability, and nutritional value make them more than just grains; they are the embodiment of a sustainable and secure food future for us all. Embracing millets is not merely a choice; it is a commitment to a healthier, greener, and more secure world.

Way forward

- Increasing awareness and promoting consumption.
- Developing drought-tolerant and biofortified varieties.
- Implementing cost-reduction and resource-use efficiency technologies.

- Establishing a community seed system for quality seed production.
- Conducting demonstrations through various government schemes.
- Providing incentives for nutricereal farming systems that include millets.
- Formulating procurement policies akin to those for rice and wheat.
- Ensuring supply through the Primary Distribution System.
- Raising awareness about the significance of diverse cropping systems.
- Facilitating the availability of seeds and establishing seed banks.
- Implementing crop insurance and crop loan policies, similar to those for other crops.
- Establishing community-level threshing floors and warehouses for storage.
- Developing marketing and processing facilities and providing training for value-added products.
- Ensuring a minimum support price for all millet varieties.

References

Bhat, VB., Rao, DB., and Tonapi, VA. (2018) The story of millet. Karnataka State Department of Agriculture, Bengaluru.

FAO (2005) Food and Agricultural Organization of the United Nations. http//www.fao.org17.

Gopalan, C., Sastry, RBV., Balasubramanian, SC., Rao, NBS., Deosthale, YG., and Pant, KC. (1989) Nutritive Value of Indian Foods. National Institute of Nutrition, Indian Council of Medical Research, Hyderabad, India (Re-printed 2004).

Kumar, S., Kumar, R., Seema., Dhandapani, A., Sivaramane, N., Meena, PC., and Radhika, P. (2017) Food Consumption Pattern in Telangana State – 2017. ICAR-National Academy of Agricultural Research Management, Hyderabad, India. Telangana Statistical Abstract, 2021. Government of Telangana.

Longvah, T., Anantha, RR., Bhaskarachary, K., and Venkaiah, K. (2017) Indian food composition tables 2017. National Institute of Nutrition, Hyderabad, Telangana, India P. 578.

Prashanthi, A., and Reddy, GR. (2023) Millet Status in India - Production and Consumption. Just Agriculture multidisciplinary e-newsletter. APEDA 3(5).

Rani, SY., Triveni, UP., Jamuna, Anuradha, N., Patro, TSSK., Prabhakar., and Tonapi, VA. (2020) An Insight into Organic Farming in Nutri-cereals. All India Coordinated Research Project on Small millets.

Rao, D., B., Bhaskarachary, K., Arlene, GD., Christina, G. Devi, S., and Tonapi, VA. (2017) Nutritional and Health Benefits of Millets. IIMR, Hyderabad.

Rao, D., Bhat, V., and Tonapi VA. (2018) Nutri cereals for nutritional security. IIMR, Hyderabad.

Umanath, MR., Balasubramaniam., and Paramasivam, R. (2018) Millets' Consumption Probability and Demand in India: An Application of Heckman Sample Selection Model. Economic Affairs. 63(4), 1033-1044.

History and Traditional Significance of Millets in Indian Agriculture and Diets

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Abstract

The chapter provides an insight of the history of millets, highlighting its significance as a foremost food crop in different parts of the world. Millets have been cultivated and used as main food crop, with evidence of their use dating back to ancient civilization of India and China. Overtime, millets have been spread to other regions of the world like Africa, Europe and the America. This article is an attempt to bring together the historical and journey of millets in the world as well as in India. It also discusses the speciality of millets in daily diet as they are nutritionally rich and provide number of health benefits due to good levels of protein, fibre and antioxidants mainly its low glycaemic index and gluten free. Millets commonly called as small grains have also played significant role in the culture and tradition around the world in different walks of life. Based on the area grown and its grain size the millets are classified as Major and Minor millet. The Major millet include sorghum and Bajra. While Ragi, fox tail millet, little millet, kodo millet, barynyard millet, proso millet and brown top millet are grouped under minor millets.

Key words: Millet, history, tradition, health benefit

Millets are the oldest crops that mankind ever known. Probably, millets were the first cultivated crops grown among several civilizations of the world. Millets have been staple food for centuries, especially in rural areas of India and were traditionally grown as rainfed crops. They are well suited to the dry climate of the Deccan Plateau in Southern India. Popularly grown millets since ancient times are Sorghum (*Sorghum bicolour (*L.) Moench), Pearl millet (*Pennisetum glaucum* (L.) R.Br.), Finger millet (*Eleusine coracana* L.), Kodo millet (*Paspalum scrobiculatum* L.,), Proso millet or broomcorn millet (*Panicum miliaceum L.),* Barnyard millet (*Echinochloa frumentacea* L.,), Foxtail millet (*Setaria italica.* L.), Little millet (*Panicum sumatrense* L.) and Browntop millet (*Brachiaria Spp*). Vernacular names of these millets in several languages is presented in Table. 1.

Table 1: Vernacular names of millets in different languages

English	Hindi	Marathi	Kannada	Telugu	Tamil	Bengali	Gujrathi	Oriya	Panjabi
Sorghum	Jowari	Jwari	Jola	Jonna	Cholam	Jowar	Jowari	Juara	Jowar
Pearl Millet	Bajra	Bajri	Sajje	Sajja	Kambu	Bajra	Bajri	Bajra	Bajra
Finger millet	Ragi, Mandika, Marwah	Nagli, Nachni	Ragi	Ragulu, Chodi	Keppai, Kelvaragu	Marwa	Nagli, Bavto	Mandia	Mandhuka, Mandhal
Foxtail Millet	Kakum	Kang, Rala	Navane	Korra	Thenai	Kaon	Kang	Kangho, Kangam, Kora	Kangani
Little millet	Kutki, Shavan	Sava, Kutki	Same, Save	Samalu	Samai	Sama	Gajro, Kuri	Suan	Swank
Proso millet	Chena, Barri	Vari	Baragu	Variga	Pani Varagu	Cheena	Chino	Bachari, bagmu	Cheena
Kodo millet	Kodon	Kodra	Harka	Arikelu, Arike	Varagu	Kodo	Kodra	Kodua	Kodra
Barnyard millet	Sanwa, Jhangora	Bhagar	Oodalu	Udhalu, Kodisama	Kuthiraivali	shyama	-	Khira	Swank

Source: http:// www.aicrpsm.res.in and personal communication with growers

The term "Millet" originated from the Latin word "Milum" means grain. Millets belong to group of small seeded grasses, commonly called as "coarse cereals" or "cereals of the Poor" belongs to family Poaceae. Millets can be successfully cultivated with less resources like chemical fertilizers, irrigation and plant protection chemicals. In general millets are climate resilient crops, known for their hardiness and ability to grow in a variety of conditions, arid and semi-arid regions. Millets are gluten free, contain good amount of fibre, essential vitamins and minerals and hence good for digestive system accounting for health benefits. Millets have lower glycemic index which is helpful for people suffering from hyperglycemia and hypertension. Millets were the staple food for centuries, especially in rural areas in India. They were traditionally grown as rainfed crops and were well suited to the dry climate of Deccan Plateau in Southern India. Millet seeds were grounded into flour or as meal with the help of stone tools and cooked in the earthen vessels around 8000 BC.

Origin and Journey of Millets

Millets were indeed first crops being cultivated in Asia and Africa by mankind.

Later they spread throughout the world noted as lifesaving food sources. In Asia, Africa and Europe, millets consumption dates back to pre-historic times, in form of cereal grain and in brewed form. They were among the first crops, grown in "Hoe Age" preceding "Plow Age". Due to the drought resistance and adaptative ability of millets, they were extensively cultivated and majorly used as staple source of food in Africa and Asian cultures. The widespread of millets can be traced through human migration and trade routes. In Asia, millets were introduced to southeast Asia and India, where they occupied prime importance and grown immensely until rice and wheat cultivation perfected.

Millets were majorly originated in Asian and African continents, and grown by local population, thereafter, gradually migrated to other parts of the world. Further, cultivation in those places led to the secondary diversity regions, adaptation and various use options. Current archaeobotanical evidence has proved that fox tail millet (*Seteria italica*) in North China cultivated no later than 8000 BC (Deng *et al.*, 2017). In India, millets cultivation has been mentioned in some old Yajurveda texts, identifying foxtail millet as *priyangava*, Barnyard millet as *annava* and black finger millet as *shyaamaka*, thus indicating that millets consumption was common, pre-dating to Bronze age of India *i.e.* 4,500 BC. Sri Kalidasa, a renowned poet, during 5th Century has mentioned in Abhijnana shakuntala that a ritual of pouring foxtail millet on Shakunthala was performed by sage Kanva while sending her to her husband king Dushanta's court. Sri Kanakadasa, a kannada poet and philosopher, during 16th Century has mentioned about finger millet importance in the novel 'Ramadhanya Charithe'. Similarly, Sri Sarvajna, a Kannada poet, pragmatist and philosopher of the 16th century describes about Sorghum, Ragi, and Foxtail millet. in his vachanas confirms that these were commonly used among the people at that period.

Sorghum (*Sorghum bicolour* (L.) Moench) native to north eastern Africa, with domestication existing around 5,000-8,000 years ago. The Indian Sub-continent with evidence of early cereal cultivation dated 4500 years ago proved to be the secondary center of origin. From its wild ancestor, Sorghum was domesticated more than 5,000 years ago witnessed by the recent evidence at archaeological location, near Kassala in Sudan, dating 3500 to 3000 BC, and is in association with the neolithic Butana group culture.

Bajra (*Pennisetum glaucum* (L.) R.Br.) commonly called as pearl millet originated in north-central Sahelian Africa, around 4500 BC. Being an important cereal crop in West Africa, it is grown widely in east and southern parts of Africa. It has been introduced to Indian sub-continent around 3000 years ago. (Andrews and Kumar 1992, Paschapur *et al.*, 2021). Bajra domestication in Mali was found with old archaeobotanical evidence dated

2,500 BC. In India, well – found archeological pearl millet remains (1000-2200. BC) has been identified at several regions in Gangetic Plains, Deccan Peninsular and in Harappan culture using millets for human consumption. At first, it was introduced to North India, and then to other regions of country, by 1500 BC, spread towards south India as witnessed by the remains of archaeology at Hallur village of Haveri district in Karnataka.

Finger millet (*Eleusine coracana* L.) is an important cereal crop originated in Africa that spread to Asia. It is referred to ragi or korakan(in India) and dagusa (in Ethiopia). Some studies revealed that finger millet was originated at western Tanzania hills, whereas, several botanists referred Ethiopia highlands as the origin. In Asia, upland races that are widespread along the Himalayas of India to Nepal, then to South China, appeared to be its secondary adaptation center. It is staple food for African and South Asian countries and is cultivated 4000 years ago. Finger millet grains discovery in Harappan civilization (2300 BC) said to have connections with African population before 2600 BC.

Foxtail millet (*Setaria italica* L.) was probably originated in China which dates back, more than 8000 years ago (Jiaju and Yuzhi, 1994). Ancestor of the cultivated foxtail millet, green foxtail, belongs to similar species. Foxtail millet journey towards India recovered from early regions of Saurashtra in pre-Harappan civilization times. In Sanskrit, referred as Bhavaji A, Priya Gguka, Rajika etc., It was under cultivation at Shikarpur(Kutch) during Harappan period (2500-2200 BC) and at Punjab, during the late Harappan period (1900-1400 BC)

Proso millet (*Panicum miliaceum L.)* known as common millet, broomcorn millet, the oldest millet and referred as the true-millet in history. It was named as Cheenaka, Kakakangu and Kangu in Sanskrit. Proso millet remains have been found in Gujarat around second millennium's first half BC. Evidences revealed East or central Asia as center of origin, thereafter, the diversity spread in the directions toward Mongolia, China and Eastern Asia. Paschapur *et al.*, 2021, reported proso millet as the third most important millet crop cultivated after bajra and foxtail millet.

Little millet (*Panicum sumatrense* L.) is endemic to india and has different names in several Indian vernacular languages. However, its origin was not documented well. It was domesticated or cultivated throughout India and Srilanka, and grown in neighboring countries 2000 years ago. Indian Eastern Ghats are the little millet domestication places and majorly cultivated in peninsular Indian states like Andhra Pradesh, Karnataka, Tamil Nadu and Kerala. Its relative wild species occur in north India, south eastern Asia. Little millet cultivation paced during 2600 BC, approx. 5% out of total cereal cultivation accounts in the Harappa and Farmana period and Indus valley civilization.

Barnyard millet (*Echinochloa frumentacea* L.,) is said to be native to Central Asia. *Echinochloa crusgalli* was cultivated in Japan, China. and Korea. While, in India, *Echinochloa frumentacea* was in cultivation. Barnyard millet has been cultivated for over 4000 years in India. It is grown widely in east and central Indian regions.

Kodo millet (*Paspalum scrobiculatum* L.,) referred as cow grass, ditch millet or Indian crown grass, was originated from African tropics and travelled to Indian sub-continent by unknown means. In India, cultivation of this crop began over 3000 years ago and is grown widely in the Deccan Plateau and became important food crop in the region.

Brown top millet (*Brachiaria Spp*) was cultivated in South Asia around 3000 BC, and independently cultivated in the south and north westerns of India. By the end of second millennium BC, it was spread to south of Tamil Nadu and Gujarat in north, from Deccan regions. Over the time, this millet was replaced by sorghum, foxtail millet and other millets for higher productivity.

Table 2: Millets: Common names and regions of origin

Sl. No	Common Name	Region of origin
1.	Barnyard Millet	Japan
2.	Brown Top Millet -Pedda sama	South India
3.	Finger Millet – Ragi	East African Highlands
4.	Fox Tail Millet	China
5.	Pearl Millet	West African Savannah
6.	Proso Millet	China
7.	Sorghum- Jowar	African Savannahs
8.	Kodo Millet	India
9.	Little Millet - samai	India especially Peninsula

Ref: Weber and Fuller, 2008

Traditional significance of Millets

Millets have played a tremendous significant role in the culture and tradition of many countries from thousands of years. Few cultural significances are;

a. **Religious and Medicinal Food**: In Hinduism, millets used in offerings to gods and goddesses during festivals and religious ceremonies. In some cultures, millets are used as traditional medicine and healing practices. In traditional Chinese medicine, millets treat a variety of ailments, including digestive problems, urinary tract infections. Millets are also helpful in Ayurvedic medicine in India and have cooling and soothing properties.

b. **Traditional Food**: In India, different millets are being used to make several traditional dishes like roti, chapati etc. commonly referred as "Bhakri".

c. **Farming and harvesting rituals**: Millets are major source of nutrition in some farming communities. In some culture, sowing, harvesting and processing of various millets are celebrated as festivals. These rituals are meant to invoke blessings from the gods and to ensure good reap.

d. **Social and community significance**: In some communities, the sowing, harvesting and processing of millets is celebrated as communal activity that brings people together and strengthen social bonds.

e. **Folklore and stories:** Millets have become a part of many folklore and stories in different cultures.

The Role of Millets in Food security

Food security means when people have physical, social and economic access to sufficient nutritious food and food choices to meet their dietary needs, to lead active and healthy lifestyle. The four pillars of the food security are the **availability of food, access to food, utilization of food** and **food stability**.

Millets are important crop for food security, particularly in areas where climate change and other factors have made traditional crops such as rice and wheat are difficult to grow. It requires less water, which makes them ideal for areas receiving low rainfall. Millets are also more resilient to pests and diseases, requiring less chemical inputs. In addition, millets cultivated by small scale farmers, providing major income source along with food security for rural communities.

Despite many benefits of millets, it is being neglected in recent years in favor of more profitable crops such as rice and wheat. This has led to decline in area of millets cultivation particularly, in India., where millets were once important staple food. To overcome this, organizations such as Millet Network Of India and the International Crops Research Institute for the Semi- Arid Tropics (ICRISAT) are working to promote millet cultivation and consumption.

Importance of consuming millets in diet

The dietary fiber that is there in our food controls the process that release glucose into blood stream from our food. This fiber determines whether glucose should be released in a large quantity at a time or in small quantities over a period of few hours. At present, percentage of fiber in rice and wheat food items is 0.25% - 0.5%. Hence, within 15 to 35 minutes after eating these food items prepared from rice/wheat are converted into glucose and join the bloodstream. For instance, if hundred grams of food is consumed prepared out of rice and wheat 70 grams of it is converted into glucose and joins the bloodstream at a time. Additional, if we have sweets, and food items prepared from Maida (biscuits, Burger, pizza, roti, cake flour), glucose enters the bloodstream at a time in large quantity. It also increases the fat content and causes problem. The problem is more pronounced in diabetic patients leading to various diseases.

Food items made with Maida are converted into glucose within 10 minutes of consumption. and enters the bloodstream. Normally there are only 6 to 7 grams of glucose in our blood (4-5 liters). Food taken if releases the glucose within a span of 10 minutes or 30 to 40 minutes then it is not good for health and risk for patients suffering from various health aliments viz., constipation, fits, piles, triglycerides, high BP, kidney diseases and heart diseases. Hence forward, consuming food and getting habituated to take millets in small quantities release glucose into the blood over a period of 5 to 7 hours in small quantities, thus helps in leading healthy life.

The speciality of millets

The speciality of small millets is that they contain natural fiber. When we eat small millets thrice a day we get 25 to 30 grams of fiber necessary for us (Every person needs 38 grams of fiber per day) through grains. Rest of the fiber are obtained from vegetables and leafy vegetables. Though major cereals have 0.22 - 1.2% of fiber, it lies in the superficial layers and is lost when they are polished. The fiber in small millets will be present throughout the grains in various layers and therefore it is beneficial for health and millets are also referred as Rich millets.

Foods prepared from millets are several and differ from country to country. Some typical dishes of millets are Jowar (Sorghum) roti in Maharashtra, parts of Karnataka, Madhya Pradesh, Uttar Pradesh and Rajasthan; Bajra (Pearl Millet) roti in Punjab, Haryana parts of Uttar Pradesh, Rajasthan and Tamil Nadu and Ragi (Finger millet) mudde (Ragi Ball) in Karnataka, parts of Tamil Nadu and Andhra Pradesh. Barynyard and Little millet found place for niche use, as a bhagar food, consumed during fasting.

Kodo and little millet in Chattisgarh and Madhya Pradesh, finger millet in Odisha, Andhra Pradesh and Uttarakhand, Barnyard Millet in Uttarkhand and Tamilnadu etc., are under successive cultivation, processing and consumption in the tribal areas.

The dehusked grain of small millets is cooked like rice and eaten. In southern parts of India, the grain is processed similar to parboiling of rice. Often, roti and Porridge are made and consumed. It was utilized in preparing flour, used for making pudding or cakes. Another method is to cook cracked grains with vegetables and spices to prepare food similar to curried rice. Fortification with Lysine and heat processing improves protein quality and nutrition.

Fox tail Millet grain is usually cooked whole like rice (millet rice) or made into meal. It is also consumed as stiff porridge called sargati or as leavened bread known as roti after de hulled grain has been milled into flour. Other food products are pudding, breads cakes, Chips, rolls, noodles etc.

Many other traditional foods from millets are made from popped flour mixed with sugar/jaggery/ghee/milk/butter milk and salt. Milled millet is further processed towards various food such as flakes, quick food cereals, ready to eat snacks, supplementary foods, extrusion cooking, malt-based products, weaning foods and more importantly health foods

Finger millet malt is in practice from time immemorial in southern India. It has superior malting properties and the malt has acceptable taste, very good aroma and shelf life.

Traditional foods prepared from barnyard and other millets like Idli, dosa and murukku are very popular in southern zones of India. Sorghum and millets were used to develop various value-added products like biscuits, sweets, vermicelli, ready mixes and multi grain atta.

Millets in Modern foods

Investigation has proved that ready to eat breakfast is highly feasible and 100% acceptable and most feasible. Modern processing technologies provide more options to develop value added modern foods from millets. Processing interventions in post-harvest processing in millets include cleaning, grading, dehulling etc., (Primary Processing) & semolina or suji, flaking, popping, extrusion, baking *etc.*, (secondary) which lead to value addition. Because millets are gluten free it does not make good leavened bread when used alone; Hence it has to be milled and combined with other flours to make delicious breads.

Millets are the future crops

The modernization, industrialization, urbanization has created negative impact on the ecosystem, resulted in global temperature elevation. Cereals like Rice and Wheat are sensitive to increased temperature, cannot sustain the changing climate scenario. Whereas, the millets are climate resilient crops, which can be successfully cultivated under aberrant weather situations. With the aim of satisfying the ever-increasing demand for food for ever increasing population, we need to bring marginal and sub marginal land under cultivation. Under such conditions, millets can be successfully grown by harnessing the natural resources providing greater nutritional security and health benefits.

Conclusion

In conclusion, millets have a rich and long history from the times of human civilization. In recent times the millets have become important owing to their good nutritional values, documented health benefits, versatile environmental adaptation. Millets have played a significant role in human diet for thousands of years and considered as vital crop for food security. Thay have been an important part of the diets and cultures of many societies. Thay are a rich source of nutrients and well suited to grow in low rainfall, marginal lands and under harsh weather conditions. Millets are highly nutritious and sustainable which makes them an ideal crop for marginal and small farmers as source of income and nutritional security. Millets are thus environmentally, ecologically and economically ideal source of food and nutrition.

References

Andrews, DJ and Kumar, KA (1992) Pearl millet for food, feed, and forage. Advances in Agronomy. 48:89-139.

Anonymous, (2018) The story of millets. Published by Karnataka State Department of Agriculture, Bengaluru, India with ICAR-Indian Institute of Millets Research, Hyderabad, India

Deng, Z., Hung, H.C., Fan, X., Huang, Y., and Lu, H. (2018) The ancient dispersal of millets in southern China: New archaeological evidence. The Holocene. 28(1): 34-43.

Jiaju, C and Yuzhi Q. (1994) Recent developments in foxtail millet cultivation and research in China. In: Riley KW, Gupta SC, Seetharam A, Mushonga JN (ed.) Advances in small millets. International Science Publisher, New York; c. p. 101-108.

Paschapur, A., Joshi, D., Mishra, KK., Knat, L., Kumar, A. (2021) Millets for Life: A Brief Introduction; DOI: 10.1007/978-981-16-0676-2_1.

Weber, SA and Fuller, D.Q. (2008) Millets and their role in early agriculture. Pragdhara. 18(69), p.90.

Chapter 03

Millets and their Importance in the Modern World

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Abstract

Millets, ancient and hardy grains, boast a rich heritage in India. They have been precious for millennia for their nutritional value, adaptability to harsh climates, and sustainability. India ranks as the world's largest producer of millets, particularly Pearl Millet (Bajra) and Sorghum (Jowar) grown across states like Rajasthan, Karnataka, and Maharashtra. Millets date back to ancient times, with traces found in the Indus Valley civilization around 5000 years ago. They succeeded in India's diverse climates, offering resilience in the face of erratic rainfall. Apart from their dietary significance, millets are revered in Ayurveda for their medicinal properties, aiding digestion and promoting overall health. Millets require less water, preserve biodiversity, and have a lower carbon footprint compared to other crops. They align with sustainable farming practices, reducing input use and promoting ecological balance. The decline of millets uses can be attributed changing dietary preferences after Green Revolution. However, their resurgence is driven by their nutritional value, adaptability to climate change, and sustainability. Governments and organizations support millet cultivation, acknowledging their role in addressing contemporary challenges like malnutrition, climate change, and shifting dietary patterns.

Introduction

Millets are a group of small-seeded, hardy, annual grasses that belong to the *Poaceae* family. They have been cultivated and consumed by humans for thousands of years, primarily in regions with semi-arid to arid climates. Millets are valued for their nutritional benefits, adaptability to challenging growing conditions, and sustainability. Millets are gaining renewed attention due to their nutritional value and ability to thrive in challenging environmental conditions, making them a promising crop for addressing food security and sustainability concerns, especially in the face of climate change. They are rich in important nutrients like fiber, protein, vitamins, and minerals, and are often gluten-free, making them suitable for people with dietary restrictions or celiac disease.

India holds the distinction of being the world's largest producer of millets, responsible for approximately 19% of the global millet production. In India, the primary millets cultivated are Pearl Millet, commonly known as Bajra, and Sorghum, referred to as Jowar. These two millet varieties, Bajra and Jowar, collectively make up around 19% of the world's millet production. The cultivation of millets in India is widespread across various states. The top ten states engaged in millet cultivation include Rajasthan, Karnataka, Maharashtra, Uttar Pradesh, Haryana, Gujarat, Madhya Pradesh, Tamil Nadu, Andhra Pradesh, and Uttarakhand. These states play a pivotal role in millet production, contributing to approximately 98% of the total millet production in India. Among these states, Rajasthan stands out as a major millet producer, accounting for a substantial 28.61% of the country's total millet production (APEDA, 2023).

Millets have a long and illustrious history in ancient India, go with back thousands of years. These small-seeded grains were among the earliest cultivated crops in the Indian subcontinent and played a significant role in the diets and agriculture of ancient Indian civilizations. Millets have deep roots in ancient Indian agriculture and cuisine, and they have been cherished and cultivated for millennia, contributing to the rich tapestry of India's culinary heritage and agricultural traditions. The declining presence of millets in crop cultivation and household diets can be attributed to several factors. Traditional cultivation methods have resulted in low productivity, discouraging farmers from growing millets. Additionally, the absence of local processing facilities has made millet utilization less convenient. Lack of awareness about the nutritional benefits of millets has further contributed to their decline. However, there is hope for the revival of millets. Rising urban demand for healthier food options, advancements in processing technology, the availability of improved millet varieties, and better agricultural practices offer opportunities to enhance millet cultivation and utilization. Moreover, the potential for accessing irrigation support can significantly increase millet yields, making them a more economically viable option. By addressing these challenges and promoting millets as a nutritious and sustainable crop, we can contribute to achieving nutrition security, resilience in agriculture, and economic stability, particularly among tribal communities who can benefit greatly from millet farming (Venkatesh et al., 2018; ITC, 2023; ICRISAT, 2017; Pokharia et al., 2014 and Hassan et al., 2021). The book chapter delas with information on the millets crops, it importance and connection with ancient India.

Importance of Millets

In ancient India, millets were grown as cereal crops and grains, serving as staple foods for the population. They were well-suited to the Indian climate, particularly their drought-resistant growth adaptations, making them a reliable source of food in regions with erratic rainfall. Millets were a crucial part of the diet until the cultivation of other grains like wheat and rice became more prominent. Millets were not only a dietary staple but also an integral part of Indian culture, as reflected in various folk sayings, travelogues, and religious texts like the Srimad Bhagwat. These ancient grains played a vital role in ensuring food security and nutrition in India's diverse and often challenging environmental conditions.

References to millets can also be found in texts like the Vishnu Purana (450 AD) and Varaha Purana highlighting their importance as a staple food (ITC).

सां का साठी साठ दिन, बरखा बरसे रात दिन। Even in continuous rainfall day and night, Sanwa (Barnyard Millet) and Saathi (a type of rice) can grow within sixty days.

Millets are also referenced in the meeting between Krishna and Sudama in the Srimad Bhagwat, a religious text. When Sudama returns from Dwarka, he is astonished to see his home was resplendent, कै जुरतो नहीं कोदो सवाँ, प्रभु के परताप तैं दाख न भावत affording grains like Kodo and Sanwa (Barnyard millet) was a difficult for him, but now they enjoy a variety of delicacies. Another folk saying illustrates the diverse ways millets are consumed.

मड़ुआ मीन, चीन संग दही, अ कोदो के भात, दूध संग सही।

Fish goes well with finger millet, curd complements proso millet, and for kodo millet rice, milk is the best accompaniment for digestion.

Archaeological excavations in the Indus Valley region have provided intriguing insights into the historical consumption of millets. Traces of this ancient grain were discovered in the area, particularly in sites like Mohenjodaro and Harappa.

These findings suggest that around 5000 years ago, the inhabitants of these ancient civilizations had a diet that included millets, alongside other cereals like wheat and barley. Furthermore, there is evidence indicating that in certain regions within the Indus Valley civilization, small millets might have served as the primary cereals in the diet. This attests to the historical importance of millets as a source of nutrition and sustenance in the early civilizations of the Indian subcontinent (ITC).

Millets have a deep-rooted history in India, with mentions dating back to ancient texts like the Yajurveda, which are believed to have originated around 4,500 BC during the Indian Bronze Age. These grains have been a fundamental component of the Indian diet for millennia, and their cultivation was widespread throughout the country. Millets belong to a diverse group of small-seeded grasses that served as essential cereal crops for human consumption and were also used as fodder for livestock (ICRISAT, 2017). Millets have a rich history as staple cereals and were cultivated and consumed from prehistoric times in various regions, including Asia, Africa, and Europe. They are believed to have been among the earliest crops cultivated, dating back to a period referred to as the "Hoe Age," preceding the "Plow Age" (Venkatesh et al., 2018).

Millet culture thrived in India for centuries and is well-documented in historical records, travelogues, and literature. Its significance in the Indian diet can be traced back to various historical periods. For instance, millets were consumed during the time of Chandragupta Maurya, who ruled from 321-297 BC. The Vijayanagar kingdom, which spanned from 1336 to 1646, also had millets as a dietary staple. During the Mughal rule, particularly under Akbar (1556-1605) and Jehangir (1605-1627), millets continued to be part of the Indian culinary tradition. This historical continuity underscores the enduring significance of millets in India's food culture throughout different epochs (ITC).

Finger millet, known as ragi, has a deep-rooted history in Karnataka, where it served as a staple food during the Neolithic Era. Its cultivation in the region has been traced back to approximately 2300 BC, specifically in Hallur. This historical connection suggests interactions between the people of this area and African cultures. Pearl millet, sorghum, and finger millet also have historical ties to western India from the African shores during the later 3rd millennium BC. Pearl millet was initially prevalent in Saurashtra and gradually spread to South India, where it was recorded as early as 1800 BC. However, it's worth noting that despite this early cultivation and consumption, millets were not prominently documented in Ayurvedic texts until the 14th Century AD. This highlights the rich history and significance of millets in the Indian subcontinent and their interactions with other cultures through trade and agriculture over millennia (ITC).

In different regions of ancient India, specific millet varieties were preferred. For instance, finger millet (ragi) was a staple in South India, especially Karnataka, where it was considered the primary cereal during the Neolithic Era. This grain was not only a source of sustenance but also a cultural symbol, indicating connections between the region's people and African cultures. It's worth noting that African millets found their way to South India, while Indian millet varieties made their journey to Africa, demonstrating the interconnectedness of these ancient civilizations.

Millets in ancient India were not just a source of nutrition but also held cultural and agricultural significance. These hardy and versatile grains were well-suited to India's diverse climates, making them a reliable food source in both favorable and challenging agricultural conditions. The historical records indicate that millets were widely cultivated and consumed across various regions of ancient India. From the plains of the Indus Valley civilization, where millets coexisted with other cereals like wheat and barley, to the southern Deccan Plateau, where finger millet (ragi) reigned supreme, these grains were an integral part of the dietary intake. The ability of millets to thrive in diverse environments made them valuable crops during periods of erratic monsoons and changing climates. In times of drought or poor rainfall, millets often outperformed other cereals, providing a reliable food source for communities. Notably, millets were not just consumed as a primary staple but also found their way into various culinary traditions, giving rise to a rich and diverse repertoire of millet-based dishes. From flatbreads made with pearl millet (bajra) in Rajasthan to the iconic ragi mudde (finger millet balls) in Karnataka, millet-based foods were celebrated for their unique flavors and textures. The cultural significance of millets extended beyond the dining table. They were woven into folklore, rituals, and festivals, reflecting their deep-rooted presence in society. Millets were not merely grains; they were symbols of resilience and adaptability. Today, as the world grapples with issues of climate change and sustainable agriculture, millets are experiencing a resurgence in popularity. Their exceptional nutritional profiles, low water requirements, and ability to thrive in challenging conditions make them a promising crop for the future. Ancient India's reliance on millets in both prosperous and adverse times serves as a testament to the enduring value of these grains (Pokharia et al., 2014 and Hassan et al., 2021).

One of the key reasons for the early cultivation of millets was their ability to thrive in arid and drought-prone regions. Their drought-resistant characteristics made them a vital food source in many African and Asian cultures before advanced irrigation systems were developed. Millets played a crucial role in ensuring food security in areas with unreliable rainfall and limited water resources.

Types of Millets in India

India's significance in the production of millets on a global scale is undeniable. It holds the position of being the largest producer and the second-largest exporter of millets worldwide. This status is underpinned by India's vast semi-arid lands, which constitute over 34% of the country's total land area and are particularly well-suited for millet cultivation. In area coverage, it occupied 17 million hectares of land and with annual production of 18 million tons. This substantial production makes millets a noteworthy contributor, constituting about 10% of India's total foodgrain production. Across various millet-growing regions, one can find the cultivation of at least 4 to 5 different millet species, either as primary crops or in conjunction with pulses, spices, oilseeds, and condiments. This cultivation practice is region-dependent on factors such as the amount of rainfall a region receives and its specific growing conditions. To provide a glimpse of this diversity, consider that pearl millet takes precedence as a primary crop in certain areas, while sorghum assumes the role of an allied crop, especially in the arid regions of Rajasthan. Similarly, finger millet enjoys primary crop status in Gujarat and Tamil Nadu (Saxena et al., 2018).

Millets are classified as (i) Major millets, which constitutes Sorghum (Jowar), Pearl Millet (Bajra), Finger Millet (Ragi/Mandua) and (ii) Minor Millets which constitutes Foxtail millet (Kangani/Kakun), Proso Millet (Cheena), Kodo Millet, Barnyard Millet (Sawa/Sanwa/ Jhangora), Little Millet (Kutki); (iii) Pseudo millets which constitutes Buck-wheat (Kuttu) and Amaranth (Chaulai) Major Millets: These millets play a prominent role in terms of both cultivation and consumption. They include:

- Sorghum (Jowar): Sorghum is a widely grown millet known for its resilience in arid conditions. It's a staple crop in many parts of India and serves as a valuable source of food, fodder, and industrial products.
- Pearl Millet (Bajra): Pearl millet is a crucial millet in India, especially in the arid and semi-arid regions. It's a versatile grain used for various food preparations and is highly nutritious.
- Finger Millet (Ragi/Mandua): Finger millet, commonly known as Ragi or Mandua, is a nutritious millet that's particularly popular in South India. It's prized for its health benefits and is used in various culinary applications.

Minor Millets: These millets, while no less important, have historically played a smaller role in terms of cultivation and consumption. They include:

- Foxtail Millet (Kangani/Kakun): Foxtail millet is a drought-tolerant grain that's grown in several regions of India. It's used in a variety of traditional dishes.
- Proso Millet (Cheena): Proso millet, also known as Cheena, is a small-seeded millet cultivated in some parts of India. It's appreciated for its nutritional value and versatility in cooking.
- Kodo Millet: Kodo millet is a hardy grain that thrives in hilly and upland areas. It's consumed in various forms, such as rice and porridge.
- Barnyard Millet (Sawa/Sanwa/Jhangora): Barnyard millet, known by several regional names, is a minor millet with quick growth characteristics. It's commonly used in fasting foods and traditional dishes.
- Little Millet (Kutki): Little millet, also known as Kutki, is a small-grained millet that's grown in different parts of India. It's used in various culinary preparations, including rice dishes and porridge.

Pseudo millets encompass Buckwheat (Kuttu) and Amaranth (Chaulai). These grains are often grouped with millets due to their similar characteristics and uses in traditional cuisines. Buckwheat is known for its gluten-free nature and is widely used in dishes like pancakes and noodles. Amaranth, on the other hand, is highly nutritious and can be used in various recipes, including porridge and flour-based products. While not true millets, these pseudo millets share some qualities and have found their place in diverse culinary traditions. These millets, major, minor and pseudo have been an integral part of Indian agriculture and diets for centuries. They offer valuable nutrition, adaptability to diverse growing conditions, and sustainability in agricultural practices, making them important components of food security and agricultural resilience in India.

Medicinal power of millets: Ayurvedic insights

Millets, often referred to as superfoods, have garnered attention for their potential to address the gut-related illnesses and metabolic disorders. These small-seeded grasses have a rich history as essential cereal crops and fodder. Millets stand out due to remarkable content of protein, fiber, and mineral content, presenting a healthy alternative. The nutritious profile and resilience of millets position them as a promising solution to modern dietary and agricultural challenges (Jena et al., 2023). Millets have been valued not only as a staple food but also for their medicinal and ayurvedic properties in traditional Indian systems of medicine. Here are some of the medicinal and ayurvedic properties of millets are

- Digestive Health: Millets are known to aid in digestion due to their high fiber content. They promote regular bowel movements and help prevent common digestive issues like constipation and indigestion.

- Gluten-Free: Millets are naturally gluten-free grains, making them an excellent choice for individuals who need to follow a gluten-free diet. Gluten is a protein found in wheat, barley, and rye, and it can trigger adverse reactions in people with celiac disease or non-celiac gluten sensitivity. Since millets do not contain gluten, they are a safe and nutritious option for those seeking gluten-free alternatives in their diet. Incorporating millets into your meals can provide essential nutrients without the risk of gluten-related health issues, making them a valuable addition to gluten-free diets (Ashrani et al., 2023).
- Rich in Nutrients: These grains are abundant in complex carbohydrates, providing a sustained source of energy. Additionally, they are a rich source of dietary fiber, supporting digestive health and aiding in weight management. Millets also pack a protein punch, crucial for tissue repair and muscle development. They are abundant in vitamins like niacin, riboflavin, and thiamine, which play vital roles in metabolism. Millets boast an impressive mineral content, including iron for oxygen transport, magnesium for bone health, and zinc for various bodily functions. With antioxidants like ferulic acid and catechins, they protect cells from oxidative stress. Their low glycemic index makes them suitable for diabetics, and their versatility in cooking makes millets a valuable addition to any diet (Hassan et al, 2021).
- Weight Management: These grains are rich in dietary fiber, which promotes a feeling of fullness and helps control appetite, ultimately aiding in weight control. Additionally, millets have a relatively low glycemic index, which means they cause gradual increases in blood sugar levels, helping to prevent sudden spikes and crashes in energy. This stable energy release can contribute to better appetite regulation and reduced cravings for high-calorie snacks. Furthermore, millets are a good source of complex carbohydrates, providing sustained energy, which can support regular physical activity and overall calorie balance, essential for effective weight management. Incorporating millets into a balanced diet can be a smart choice for those looking to achieve and maintain a healthy weight (Kam et al., 2016 and Jena et al, 2023).
- Anti-Inflammatory: Millets have gained recognition for their notable anti-inflammatory properties. They are rich in phenolic compounds, particularly ferulic acid and catechins, which serve as potent antioxidants, safeguarding the body against detrimental oxidative stress. Research in

mice has established a connection between ferulic acid and its ability to promote swift wound healing, provide protection to the skin, and exhibit anti-inflammatory characteristics. These attributes underscore the potential health benefits of including millets in your diet (Liu et al., 2017 and Zduńska et al., 2018).

- Heart Health: Emerging research indicates that integrating millets into one's diet can significantly mitigate the risk of cardiovascular diseases. Studies have revealed that millet consumption can lead to an 8% reduction in total cholesterol levels and contribute to a nearly 7% decrease in BMI (Body Mass Index). Additionally, millets have shown promise in reducing diastolic blood pressure by approximately 5%. Collectively, these positive impacts on cardiovascular health have the potential to substantially lower the risk of heart disease (Jena et al., 2023).
- Antioxidants: Millets are rich in antioxidants, making them a valuable addition to a healthy diet. Antioxidants are compounds that help protect the body's cells from damage caused by free radicals, which are unstable molecules that can harm cells and contribute to various chronic diseases, including cancer and heart disease. The antioxidants in millets, such as phenolic compounds like ferulic acid and catechins, help neutralize free radicals and reduce oxidative stress in the body. Oxidative stress is linked to the aging process and the development of various diseases (Kaur et al., 2019).
- Bone Health: illets are known for their remarkable nutritional profile, which includes an array of essential minerals that are beneficial for promoting and maintaining bone health. These grains are rich in vital minerals like calcium, iron, manganese, magnesium, phosphorus, zinc, potassium, copper, and selenium. Among these, calcium is particularly important for strong and healthy bones, as it plays a key role in bone structure and density, as well as other vital functions in the body. Regular consumption of millets can contribute to enhanced bone strength and a reduced risk of conditions like fractures and arthritis. Certain millets, like finger millet (ragi), are excellent sources of calcium. Adequate calcium intake is essential for maintaining strong and healthy bones (Sahaya et al., 2021).
- Detoxification: Millets play a significant role in detoxifying the body. They are rich in dietary fiber, which aids in the removal of toxins and waste products from the digestive system. The fiber content in millets acts as a natural cleanser for the digestive tract, promoting regular bowel movements and preventing constipation.
- Energy Boost: Millets are an excellent source of energy, making them a valuable addition to your diet for an energy boost. These small-seeded

grains are rich in complex carbohydrates, which are a steady and sustained source of energy for the body. The carbohydrates in millets are slowly digested, leading to a gradual release of glucose into the bloodstream. This results in sustained energy levels, preventing sudden spikes and crashes in blood sugar. It's particularly beneficial for maintaining energy throughout the day, especially for individuals with active lifestyles. Furthermore, millets provide essential vitamins, minerals, and dietary fiber, all of which contribute to overall energy metabolism and vitality. The combination of complex carbohydrates and nutrients in millets makes them an ideal choice for those seeking a natural and lasting energy boost (Gowda et al., 2022).

- Stress Reduction: The small-seeded grains are a rich source of nutrients, including B vitamins, magnesium, and serotonin-producing amino acids like tryptophan. B vitamins, particularly vitamin B6, are essential for the production of neurotransmitters like serotonin, which play a crucial role in regulating mood and reducing stress. Adequate levels of these vitamins can help improve mood and decrease anxiety. Magnesium, another nutrient abundant in millets, is known for its calming effect on the nervous system. It helps relax muscles, reduces tension, and promotes a sense of relaxation, which can be particularly helpful in managing stress. Tryptophan, an amino acid found in millets, is a precursor to serotonin, often referred to as the "feel-good" neurotransmitter. Consuming foods rich in tryptophan can enhance serotonin production, leading to improved mood and reduced stress levels.

Millets: Sustainability in harmony with the environment

Millets, often referred to as the "smart food" or "nutri-cereals," are gaining recognition not only for their nutritional benefits but also for their remarkable contribution to environmental sustainability. Millets are making a positive impact on the environment and that's why they are an eco-conscious choice for both farmers and consumers.

- Drought-Resilient Crops: One of the most significant environmental advantages of millets is their drought tolerance. These hardy crops require significantly less water compared to traditional grains like rice and wheat. In regions prone to water scarcity and erratic rainfall patterns, millets have become a lifeline for farmers. By cultivating millets, farmers can conserve precious water resources, and contribute to water sustainability (Choudhary et al., 2023).

- Biodiversity Preservation: Millets are known to thrive in diverse agro-ecological zones. This adaptability encourages crop diversification, which is crucial for maintaining biodiversity. By planting millets alongside other crops, farmers can create healthier ecosystems, reduce pest infestations, and decrease the need for chemical pesticides. This promotes a balanced and sustainable environment for both flora and fauna (Choudhary et al., 2023).

- Reduced Carbon Footprint: The cultivation of millets generally involves fewer carbon emissions. They mature faster than many other grains, requiring less time in the field and fewer resources. Additionally, millets' ability to thrive in semi-arid conditions means that they are often grown in regions with lower energy-intensive irrigation systems. The carbon footprint (CO_2) of millets is nearly 25% less than wheat and a bit lower than rice (Alexander G, 2023).
- Low Environmental Impact: Millets are less resource-intensive crops. They require minimal synthetic fertilizers and pesticides, reducing the pollution of water bodies and soil. Their reduced demand for water also minimizes the strain on local water sources, making them an excellent choice in areas grappling with water scarcity (UNRIC, 2023).
- Promoting Sustainable Farming: Millet cultivation is closely linked to sustainable and organic farming practices. The promotion of millets encourages a shift towards eco-friendly farming methods, which prioritize long-term ecological balance over short-term gains (UNRIC, 2023).

Millets are more than just a nutritious food source; they represent a sustainable and environmentally conscious choice. By incorporating millets into our diets and supporting their cultivation, we contribute to water conservation, biodiversity preservation, healthier soils, and a reduced carbon footprint.

Millets' Journey: Decline, Revival, and the Path to Food Security

The significance of millets persisted until the cultivation of other major cereal crops like wheat and rice became more widespread and efficient. Despite the shift to these crops, millets remain an important part of the agricultural heritage and dietary traditions in many regions, appreciated for their nutritional value and adaptability to various environmental conditions. With the Green Revolution in the mid-20th century, there was a shift towards high-yield varieties of rice and wheat, which led to a decline in millet cultivation. However, in recent years, there has been a revival of interest in millets due to their nutritional benefits, drought resistance, and suitability for sustainable agriculture. Millets are now being promoted as "nutri-cereals" and "smart food" by agricultural and health organizations.

The decline of millets can be attributed, in part, to the global shift towards monoculture and the promotion of high-yielding cereal crops like rice, wheat, and maize. These crops received more attention and investment due to their higher market demand and yield potential. Further, as societies urbanized and incomes rose, dietary preferences shifted towards processed foods and polished grains, which were often considered more desirable than traditional millet-based diets. Although, being hardy and resilient crops, were sometimes seen as "poor people's food" and were neglected in favor of cash crops and cereals that were easier to market.

Revival of millets represents a shift towards more diverse and sustainable food systems. The nutritional value of millets, including their high fiber content, essential nutrients, and low glycemic index, has gained recognition. They are seen as valuable in addressing malnutrition and diet-related health issues. The crops are well-suited to climate change in conditions. They require less water and are more resilient to drought and heat, making them a valuable crop in regions facing climate challenges. The resurgence of interest in organic and sustainable farming practices has contributed to the revival of millets. They are considered a sustainable crop due to their low resource/input requirements. Several governments and non-governmental organizations (NGOs) have initiated programs to promote millet cultivation. These efforts include research, training, subsidies, and market support to encourage farmers to grow millets. The demand for millets has grown both globally and locally. Internationally, they are gaining popularity as a gluten-free and nutritious grain. Locally, consumers are re-discovering traditional recipes and the health benefits of millets. These crops are versatile and can be used in various forms, from whole grains to flours and processed products. This versatility has expanded their use in cooking and food processing. Governments have formulated policies to promote millets, such as including them in public distribution programs and school feeding schemes. Advocacy campaigns, farmer associations, and nutrition education programs have played a role in raising awareness about millets and their benefits. Thus, millets are increasingly recognized as an essential component of food security and nutrition, offering an opportunity to address some of the challenges posed by climate change and changing dietary patterns.

Research centre associated with millet improvement

IIMR-Hyderabad, the Indian Institute of Millets Research, stands as the nation's premier institute dedicated to millets. Operating under the Indian Council of Agricultural Research (ICAR), this institute has been at the forefront of pioneering research in millet improvement, value chain modeling, capacity building, and entrepreneurship development. One of its most significant contributions has been its unwavering support for the Government of India's plans, particularly through the Department of Agriculture, Cooperation, and Farmers Welfare (DAC&FW). IIMR-Hyderabad played a crucial role in the design and implementation of the sub-mission on Nutri-cereals under the National Food Security Mission (NFSM). This involvement underscores the institute's commitment to enhancing food security and nutritional value for the nation's citizens.

The All India Coordinated Research Project (AICRP) on Sorghum, initiated in 1969, conducts vital research on grain and forage sorghum, focusing on enhancing varieties, technologies, and products. With 21 centers across 11 states and with 17 State Agricultural Universities, this program significantly contributes to sorghum research. The All India Coordinated Research Project on Pearl Millet (AICPMIP), headquartered in Jodhpur, operates 13 AICRP centers and collaborates with 18 public sector cooperating centers along with overseeing 61 coordinated projects, aiming to advance pearl millet research. Previously known as the All India Coordinated Small Millets Improvement Project (AICSMIP), the AICRP on Small Millets operates 14 research centers, including 12 SAU, dedicated to enhancing small millets' research.

Conclusion

Millets, expressing India's rich heritage, are making a remarkable comeback. These resilient grains, deeply rooted in our culture, offer nutrition, adaptability, and sustainability. Their resurgence addresses modern challenges, providing health benefits and eco-conscious farming practices. Millets' gluten-free, nutrient-rich profile aligns with diverse dietary needs. Supported by governments and growing consumer awareness, millet cultivation is rising. Millets symbolize the harmonious blend of tradition and innovation, resilience, and environmental accountability. Involving millets heralds a healthier, greener future, bridging the wisdom of the past with the needs of today.

References

Alexander, G. (2023) Millet for the environment and better nutrition. https://earth911.com/home-garden/millet-for-the-environment-and-better-nutrition/ APEDA 2023. https://apeda.gov.in/milletportal/Production.html.

Asrani, P., Ali, A. and Tiwari, K. (2021) Millets as an alternative diet for gluten-sensitive individuals: A critical review on nutritional components, sensitivities and popularity of wheat and millets among consumers. Food reviews international. 39(6),1-30.

Choudhary, P., Shukla, P., and Muthamilarasan, M. (2023) Genetic enhancement of climate-resilient traits in small millets: A review. Heliyon.25,9(4),e14502. doi:10.1016/j.heliyon.2023.e14502.

Gowda, NN., Siliveru, K., Prasad, PV., Bhatt, Y., Netravati, BP., and Gurikar, C. (2022) Modern processing of Indian millets: a perspective on changes in nutritional properties. Foods. 11(4), 499.

Hassan, ZM., Sebola, NA. and Mabelebele, M. (2021) The nutritional use of millet grain for food and feed: a review. Agriculture and food security. 10,1-14. https://doi.org/10.1186/s40066-020-00282-6.

ICRISAT.(2017) Bringing back millets-the super crop of our ancestors. https://www.icrisat.org/a-short-history-of-millets-and-how-we-are-recognising-their-importance-in-the-modern-context/.

ITC, (2023) Mission millets. https://www.itcportal.com/coffee-table- book.pdf.

Jena, A., Sharma, V. and Dutta, U. (2023) Millets as superfoods: Let thy cereal be thy medicine. Indian Journal of Gastroenterology. 1-4.

Kam, J., Puranik, S., Yadav, R., Manwaring, HR., Pierre, S., Srivastava, RK. and Yadav, RS. (2016) Dietary interventions for type 2 diabetes: how millet comes to help. Frontiers in plant science. 7, 1454.

Kaur, P., Purewal, SS., Sandhu, KS., Kaur, M., and Salar, RK. (2019) Millets: A cereal grain with potent antioxidants and health benefits. Journal of Food Measurement and Characterization. 13,793-806. https://doi.org/10.1007/s11694-018-9992-0

Liu, YM., Shen, JD., Xu, LP., Li, HB., Li, Y.C., and Yi, LT. (2017) Ferulic acid inhibits neuro-inflammation in mice exposed to chronic unpredictable mild stress. International Immunopharmacology. 45, 128-134.

Pokharia, AK., Kharakwal, JS. and Srivastava, A. (2014) Archaeobotanical evidence of millets in the Indian subcontinent with some observations on their role in the Indus civilization. Journal of Archaeological Science, 42,442-455.

Rani, SG., Swaminathan, A., and Vijayaraghavan, R. (2021) Effectiveness of Physical Activity and Finger Millet-Based Food Supplement on Biochemical Parameters and Bone Mineral Density among Premenopausal Women. Evidence-Based Complementary and Alternative Medicine. 1-7.

Saxena, R., Vanga, SK., Wang, J., Orsat, V., and Raghavan, V. (2018) Millets for food security in the context of climate change: A review. Sustainability. 10(7), 2228.

UNRIC 2023. Millets- good for people, the environment, and farmers.

Venkatesh, BB., Dayakar BR., and Tonapi, VA. (2018) The Story of Millets. Karnataka State Department of Agriculture, Bengaluru, India with ICAR-Indian Institute of Millets Research, Hyderabad, India, p.110.

Zduńska, K., Dana, A., Kolodziejczak, A., and Rotsztejn, H. (2018)Antioxidant properties of ferulic acid and its possible application. Skin pharmacology and physiology. 31(6),332-336.

Chapter 04

Crop Diversification and Sustainable Farming with Rice-Millet Cropping Systems: A Climate Change Resilient Strategy

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Abstract

Rice-millet cropping systemshave transformative potential in India to address the multifaceted challenges posed by climate change in the agricultural sector. With a focus on sustainability, climate resilience, and enhanced livelihoods, a comprehensive overview of the current state of agriculture in India in the context of climate change has been presentedand rice-millet cropping systems as an alternative to the current system have been proposed. Drawing from extensive research and case studies across various regions of India, the chapter highlights the diverse agro-climatic zones where rice diversification with millets, including pearl millet, finger millet, sorghum, foxtail millet, and others, can be effectively implemented. It delves into the scientific and practical aspects of these cropping systems,emphasizing their contributions to climate resilience, soil health enhancement, water use efficiency, and nutritional benefits.The chapter presents compelling case studies and success stories from different states in India, showcasing the positive impact of rice-millet cropping

systems on smallholder farmers, women empowerment, nutritional security, and economic viability. It also discusses the challenges faced by farmers in adopting and sustaining these systems, such as yield variability, market access, and pest management.Furthermore, the chapter identifies critical areas for future research and policy directions, including the development of improved millet varieties, promotion of value addition, enhancement of market linkages, and the formulation of a diversificationincentive policy to incentivize crop diversity among poor farmers.Overall, this chapter provides a comprehensive understanding of the potential and challenges of rice-millet cropping systems in India, offering valuable insights for policymakers, researchers, and practitioners working towards sustainable agriculture, food security, and climate resilience in the face of a changing climate.**Keywords**: Rice-millet cropping systems, diversification, agriculture, climate change, sustainability

Introduction

India's agriculture sector faces profound challenges due to climate change. Climate change has resulted in shifts in temperature and precipitation patterns, posing significant risks to crop yields and food security. Rising temperatures can have adverse effects on crops like rice, which is a staple food in India. Studies have demonstrated that higher temperatures can reduce rice yields, impacting food production.The Green Revolution-led agricultural policy lent too much focus to rice and wheat crops which soon became skewed towards excluding bio-diversity principles and crop diversification, resulting in a dominating mono-cropping pattern. It also created ecological threats because of high pesticide and fertilizer consumption and increased production costs. Switching from traditional methods of diversified cropping patterns to mono-cropping has worsened food and nutritional security.

In light of these challenges, the adoption of sustainable farming systems has become imperative. Sustainable agriculture practices encompass a suite of strategies designed to enhance resilience in the face of climate variability. Crop diversification, a central tenet of sustainable farming, holds the potential to bolster resilience significantly.The problems associated with rice monoculture or continuous rice-rice, rice-wheat, and rice-maize cropping systems are multifaceted, including soil degradation, water scarcity, polluted water sources, pest and disease pressures, declining yields, nutritional deficiencies, economic risks, and vulnerability to climate change, and environmental impacts.The diversification of rice with millets in India is vital to enhance climate resilience, reduce risk, improve nutrition, foster soil health, optimize water use, ensure economic sustainability, and promote biodiversity conservation.In the context of India, millets emerge as a key component of climate-resilient agriculture due to their renowned drought tolerance (NAAS, 2013).Sustainable practices prioritize efficient resource utilization, reducing waste, and optimizing inputs. This not only lessens the environmental footprint but also contributes to cost savings for farmers (Kumar & Kumar, 2016). They often incorporate practices like crop rotation and organic farming, leading to improved soil health and fertility (FAO, 2017).This chapter highlights the role of rice-millet cropping systems in addressing climate-related challenges and promoting sustainability. It will explore their contributions to climate resilience, soil health enhancement, and water use efficiency, as well as their nutritional and economic benefits.

Climate change and agriculture in India

Climate change in India is characterized by shifts in temperature and precipitation patterns, as well as an increase in the frequency and intensity of extreme weather events. India has experienced a gradual increase in temperatures, with both maximum and minimum temperatures rising. The Indian monsoon, a crucial factor for agriculture in the country, has exhibited variations. Changes in the monsoon's onset, duration, and intensity can impact crop planting and harvest timings, leading to yield fluctuations.India has witnessed an increase in extreme weather events such as cyclones, droughts, floods, and heatwaves. These events can result in crop damage, soil erosion, and loss of livelihoods for farmers.

Climate change has far-reaching consequences for Indian agriculture. Changes in temperature and precipitation patterns can lead to reduced crop yields. For example, higher temperatures can negatively affect wheat and rice yields, two of India's major staple crops (Lobell and Gourdji, 2012).Altered monsoon patterns can result in water scarcity for irrigation, affecting crop growth. This is particularly critical in regions dependent on rainfall for agriculture. Climate change can create favourable conditions for the proliferation of pests and diseases, posing additional challenges to crop protection (Chakraborty et al., 2016).Indian farmers face several vulnerabilities and risks due to climate change. Crop failures and reduced yields can lead to significant economic losses for farmers, particularly smallholders who rely on agriculture for their livelihoods.Climate change-related disruptions in agriculture can impact food security, as India heavily depends on domestically produced food grains. In regions with severe climate-related challenges, farmers may be forced to migrate in search of alternative livelihoods.

Rice-Millet Cropping Systems

Rice-based cropping system is the backbone of agriculture production in the country. It is important in maintaining the food security of the country and at the same time maintaining the livelihood security of small and marginal farmers. Diversification of rice-rice, rice-wheat, and rice-maize cropping systems to rice-millets cropping systembrings many advantages to the system. It helps in mitigating the challenges posed by climate change by enhancing food security, improving soil health, reducing greenhouse gas emissions, and water demand, and enhancing water productivity and judicious use of other resources (Singh et al., 2010). Diversification of riceinvolves intercropping or rotating rice cultivation with millet crops, such as pearl millet, finger millet, and foxtail millet.An increase in demand for millets in recent times can be successfully met through crop diversification in the existing rice-based cropping systems. Rice and millets stand as the cornerstones of India's agrarian landscape and dietary patterns. Understanding their individual significance is essential to appreciating the role of rice-millet cropping systems in Indian agriculture.Rice is one of the most crucial staple crops globally, and it serves as a primary source of carbohydrates for a significant portion of the Indian population. It is grown extensively in the country and is well-suited to regions with ample water resources. The cultivation of rice has a long history in India and is deeply intertwined with its culture and traditions. It provides a reliable source of food security, particularly in regions with adequate water availability (Khush, 2005).The development of high-yielding, short-duration, and thermal-insensitive rice varieties has paved the way for multiple cropping systems in the country involving a wide range of crops.

Millets are diverse cereal grains known for their resilience in challenging agro-climatic conditions.Important millet crops grown in India are Sorghum (Great millet), Bajra (Pearl millet), Ragi (Finger millet), and small millets viz., Foxtail millet, Little millet, Kodo millet, Proso millet and Barnyard millet. Millets are grown in about 12.45 million ha. with an annual production of 15.53 million tonnes and contribute 10% to the country's food grain basket. Rajasthan has the highest area under millets cultivation (29.05%) followed by Maharashtra (20.67%), Karnataka (13.46%), Uttar Pradesh (8.06%), Madhya Pradesh (6.11%), Gujarat (3.94%) and Tamil Nadu (3.74%) (ASSOCHAM, 2022). They are suitable for harsh, hot, and dry environments.They have a life cycle of 70-100 days and can survive and grow in arid regions, requiring only 350-400 mm of annual rainfall. Some varieties of pearl millet survive at temperatures up to 46°C. Millets are suitable for growing in less privileged undulating terrain with less moisture availability.Besides, they are less labour intensive and require minimal inputs. They have low carbon and water footprint. Barnyard millet provides 10 times more fibre than wheat and is considered to be the fastest-growing crop (six weeks). Similarly, foxtail millet is drought-resistantand is adapted to a wide range of elevations, soils and temperatures, while Kodo millet, another drought-resistant crop is ideal for fallow and infertile lands with pebbles. Little millet is tolerant to both drought and waterlogged conditions. They are nutritionally dense and rich in essential nutrients, making them an excellent source of dietary diversity and nutrition.Millets have a history of cultivation in India dating back thousands of years, making them an integral part of traditional diets (NAAS, 2013). Millets due to their nutrition and hardy attributes have the potential to address the goals and aspirations of these stakeholders at the micro level and contribute to the attainment of larger sustainable developmental goals (SDGs) at the macro level.

The practice of cultivating rice and millets together has historical roots in India's agricultural heritage. With the rising incidences of climatic eventualities, there is growing interest in millet due to increasing vulnerability to the food production system. In order to ensure that soil health is retained, we should focus on growing less extractive crops like millets. They are good for holding water and adding a lot of organic matter for soil health revival. Millets may also act as a check against the rapid depletion of natural resources like groundwater and degrading soil health and also contribute to the attainment of healthy, sustainable, and equitable livelihood.These ancient grains have played a crucial role in ensuring food security, especially in regions prone to erratic rainfall and drought (Reddy et al., 2005). ICAR-National Rice Research Institute has delineated suitable areas for rice in the country at the district level based on the biophysical and weather-dependent variables according to which 207 districts are unsuitable for paddy cultivation (Pathak et al., 2020). These unsuitable districts are located in 15 states but only five states (Punjab, Haryana, Gujarat, Rajasthan, and Uttar Pradesh) constitute 93 percent of these unsuitable rice cultivated areas as well as production, while 21 percent of rice production of the country comes from these regions. However, there might be certain zones in these states where the rice-rice cropping system would prevail. In such zones, rice areas in *rabi* may be liberated and allocated for other crops including millets (Bisen et al., 2023). ICRISAT's 20-year time series data on rice fallows in India suggests that Chhattisgarh has approximately 4.1 Mha of rice fallows, or nearly 35 percent of all rice fallows,compared to Madhya Pradesh and Odisha, which each have nearly 1.8 Mha of rice fallows, or roughly 15 percent of all rice fallows, in Indian states. This indicates a high likelihood of interventions in the aforementioned three states. States with 5 to 8 percent of the overall share include Jharkhand, Maharashtra, and West Bengal, while states with less than 3 percent of the total share include Telangana, Assam, and a few other states. For any short-crop intensification, even 1 percent of the rice crop lying fallow equates to 95,000 hectares, which is a sizeable area (Gumma et al., 2016). Such rice fallow areas provide opportunities to introduce short-duration millets to utilize the residual soil moisture and bring additional income for the farmers. In this context, the experience of ICAR-IIMR indicates that the yield of sorghum in rice fallow ranges between 6-7 t/ha but many constraints are also associated(Chapke et al., 2011).

Diversity in Rice-Millet Cropping Systems Across India: One of the defining features of rice-millet cropping systems in India is their diversity, reflecting the adaptability and ingenuity of Indian farmers. These systems can vary significantly from one region to another, influenced by factors such as climate, soil type, and cultural preferences.In the upland or hilly conditions, rice is intercropped with finger millet or other minor millets. This is commonly practiced in north and north-eastern parts of the country following a rice and intercrop ratio of 3-4:1. In the arid regions of Rajasthan and parts of Gujarat, pearl millet (bajra) takes precedence due to its exceptional drought tolerance. In contrast, the eastern and southern states often incorporate finger millet (ragi) into their cropping systems alongside rice (Choudhary and Prabhakara Setty, 2016).The Salem, Erode, and Dharmapuri districts in Tamil Nadu have been known for both rice and millet cultivation. Intercropping or sequential cropping of rice with finger millet (ragi) is observed in these areas. Some parts of Odisha, including the Kandhamal district, practice mixed cropping of rice and finger millet (mandia). Little millet is widely grown in the hills of the Eastern Ghats and the Chotanagpur Plateau. Certain areas in Madhya Pradesh, such as the Chhindwara district, have seen successful intercropping of rice with pearl millet.The diversity in rice-millet cropping systems also reflects regional dietary preferences and culinary traditions. For example, ragi is a staple in South Indian cuisine, whereas bajra is more prevalent in North Indian dishes.The coexistence of various cropping systems across India showcases farmers' adaptability in selecting crops that best suit their local conditions. It underscores the rich tapestry of agricultural practices and traditions that have evolved over centuries.

Potential regions in India for rice diversification with millets

Rice diversification with millets in India can be considered in various regions across the country, depending on local agro-climatic conditions, soil types, and cropping patterns.

North India

In Punjab, where bajra was cultivated in a large area (around 2 lakh ha) in the 1950's was reduced to a mere 500 ha in 2020. In view of groundwaterover-exploitation in more than 80% of the administrative blocks, millet crops like bajra and ragi may be re-introduced andintercropped with aerobic rice or grown in sequence. Haryana can explore diversification by introducing millets like pearl millet in some regions as in these regions groundwater was over-exploited (Anonymous, 2022). The hilly areas of Himachal Pradesh and Uttarakhand can benefit from diversifying rice cultivation with millets like finger millet and foxtail millet. Some regions in Uttar Pradesh, especially in the Bundelkhand region, can explore intercropping or mixed cropping of rice with millets like finger millet and pearl millet.

Western India

Rajasthan's arid and semi-arid regions, Saurashtra and North parts of Gujarat, and Vidarbha region of Maharashtra can diversify rice cultivation with millets like pearl millet and sorghum.

Central India

Yield of coarse grain crops like pearl millet and sorghum performed better than rice under rainfed conditions in some districts of Central India (Davis et al., 2019).Hence, there exists huge potential for cultivation and promotion of these crops. Rice can also be diversified with minor millets like kodo millet, kutki and little millet as they were grown in large areas in the past in this region.

Southern India

These states have diverse agro-climatic zones, and in some regions, it may be possible to intercrop rice with millets like finger millet, pearl millet, or foxtail millet. Coastal Andhra Pradesh is suitable for intercropping rice with millets like finger millet (ragi) and pearl millet.Regions like Raichur, Bijapur, and Tumkur of Karnataka have scope for cultivating millets alongside rice. Some regions in Kerala, especially in the upland areas, can explore mixed cropping of rice with millets like finger millet and pearl millet. Most of the regions in Telanganaare suitable for diversification of rice with millets like pearl millet and sorghum.

Eastern India

Some parts of West Bengal, parts of Jharkhand especially in the Chotanagpur plateau regions, and southern and eastern parts of Bihar can explore intercropping or mixed cropping of rice with millets like finger millet, little millet, sorghum and pearl millet.

Northeast India

Hilly regions of Northeast India can benefit from diversifying rice cultivationwith millets like finger millet and foxtail millet.

In addition to the above regions, the following areas can be diversified with millets

Finger millet has the highest productivity among the millets in Indiaand is frequently grown in both rainfed and irrigated lands where moisture is limited for rice. It is grown often as the first crop in rotations of shifting cultivation or the second crop after rice

Barnyard millet is cultivated on marginal lands where rice and other crops will not grow well. It is an ideal supplementary crop for subsistence farmers and is also grown as an alternate crop during the failure of monsoons in rice cultivating areas.

Millets can be grown on lands that are no longer suitable for rice cultivation because of the overexploitation of groundwater

In rainfed upland rice areas, rice can be intercropped with suitable millets to reduce risk under aberrant weather conditions

As millets are low water and nutrient-requiring crops, they can be grown in natural farming systems by intercropping with rice or as sequential crops

Rice fallows can be diverted for millet cultivation

Regions where the yield of coarse cereals is higher than rice

In areas where rice-wheat cropping system is practiced, replacing wheat with sorghum improves yield under climate change conditions (Defries et al., 2023).

Advantages of Rice-Millet Cropping Systems: Rice-millet cropping systems offer a range of advantages that make them an attractive and sustainable choice for Indian agriculture.

Climate resilience and adaptability: Rice-millet cropping systems are renowned for their climate resilience and adaptability. Millets, such as pearl millet and finger millet, are inherently drought-tolerant and can thrive in regions with erratic rainfall patterns. This adaptability is crucial in the context of changing climate conditions, which often lead to uncertain and variable precipitation (Krishnamurthy & Serraj, 2017).Temperature rise because of climate change affects the water requirement and evapotranspiration from crop fields leading to higher heat stress. Under such conditions, millets can be a better option for integration into the rice-based cropping system (Davis et al., 2019; Wang et al., 2019). The introduction of short-duration and improved varieties of sorghum can enhance the yield level by 91% (Sonune and Mane, 2018).As millets are C_4 crops, the system helps in reducing the carbon footprint and improves the energy use efficiency compared to rice monoculture.

These millets possess deep root systems that enable them to access water from deeper soil layers, making them better equipped to withstand water stress during dry spells.

Promotes biodiversity: By diversifying crops and promoting mixed cropping, rice-millet cropping systems foster biodiversity and reduce the vulnerability of agriculture to pests and diseases.

Soil health improvement: Rice-millet cropping systems contribute to soil health improvement through various mechanisms. Crop rotation, a common practice in such systems, helps break pest and disease cycles, reducing the need for chemical pesticides. Moreover, the organic matter from millet residues enhances soil fertility and structure (Sharma & Rao, 2006).With low dependence on chemical inputs would put far less pressure on ecosystems.

Water use efficiency: Water scarcity is a significant concern in Indian agriculture, and rice-millet cropping systems are known for their superior water use efficiency. Millets generally require less water than rice and can thrive with limited irrigation (Davis et al., 2019). This efficiency is particularly advantageous in regions facing water constraints and erratic monsoon patterns (Sultana and Naznin, 2012).

Nutritional benefits: Millets are highly nutritious grains, rich in vitamins, minerals, and dietary fiber. They offer a diverse nutrient profile compared to rice, which primarily consists of carbohydrates. Incorporating millets into cropping systems can enhance the nutritional diversity of diets, contributing to improved food security and better health outcomes (Saleh et al., 2013).

Economic viability: Sustainable agricultural practices, including rice-millet cropping systems, have demonstrated economic viability for farmers. Reduced input costs due to lower water and pesticide requirements, coupled with diversified income sources from multiple crops, can enhance the economic sustainability of farming households (Deaton &Dreze, 2009).Moreover, the market for millets has been expanding, driven by increased consumer awareness of their nutritional benefits. This provides farmers with opportunities to access profitable markets.

In summary, rice-millet cropping systems offer a multitude of advantages, including climate resilience, soil health improvement, water use efficiency, nutritional benefits, and economic viability. These advantages position these systems as a sustainable and adaptive choice for Indian agriculture, particularly in the face of changing climate patterns.

Climate-Resilient Practices in Rice-Millet Cropping Systems: Rice-millet cropping systems are known for their climate resilience, thanks to a range of practices that are integral to these systems. This section will delve into each of these practices.

Crop rotation and diversification: Crop rotation and diversification are key climate-resilient practices in rice-millet cropping systems. Crop rotation and diversification in rice-millet cropping systems offer multiple benefits.Farmers often rotate rice with millets like pearl millet, finger millet, or sorghum. This practice disrupts the life cycles of pests and diseases, reducing the need for chemical pesticides. Furthermore, the diverse crop mix enhances soil health, reduces soil erosion, and contributes to improved resilience against changing climate conditions (Kumar & Ladha, 2011).Intercropping of millets with legumes enhances soil fertility by adding organic matter and fixing atmospheric nitrogen, reducing the need for synthetic fertilizers (Giller &Cadisch, 1995).

Water management strategies: Effective water management is essential in rice-millet cropping systems, particularly in regions with water scarcity. Farmers employ various strategies to optimize water use.Implementing rainwater harvesting systems, such as rooftop rainwater collection and farm ponds, helps capture and store rainwater for irrigation during dry periods (Sharma et al., 2014; Bhunya& Tyagi, 2018).Implementing efficient irrigation methods like drip irrigation or sprinkler irrigation to minimize water wastage (Kaur & Singh, 2016). Alternate wetting and drying (ADW) allows for intermittent drying and wetting of rice fields and reduces water usage in rice cultivation (Bouman et al., 2007).

Pest and disease management: Rotating rice with millets disrupts the life cycles of pests and diseases specific to rice, reducing the need for chemical pesticides. For instance, the fall armyworm, a common rice pest, has different host preferences than millets (Gressel & Hanafi, 1993).Integrated pest and disease management practices are crucial in rice-millet cropping systems. Farmers often adopt biological control methods, such as releasing beneficial insects or using disease-resistant crop varieties. These practices reduce the reliance on chemical pesticides and contribute to a healthier environment (Altieri, 1999).

Organic and sustainable farming practices: Many farmers practicing rice-millet cropping systems embrace organic and sustainable farming practices. This includes the use of organic fertilizers, cover cropping, and reduced tillage. Organic practices enhance soil health, reduce greenhouse gas emissions, and promote biodiversity, all of which contribute to climate resilience (Reganold& Wachter, 2016; Tripathi & Singh, 2019).

These practices collectively contribute to the climate resilience of rice-millet cropping systems by conserving resources, reducing environmental impact, and enhancing overall sustainability. They empower farmers to adapt to changing climate conditions while maintaining agricultural productivity and ecosystem health.

Table 1. Case Studies and Success Stories of Rice-Millet Cropping System in India

Region	Success story
Andhra Pradesh	**Enhanced yield andimproved livelihoods**:In Andhra Pradesh, the adoption of rice-millet cropping systems has led to remarkable outcomes. For instance, in the Anantapur district, farmers have successfully embraced sustainable farming practices, including the cultivation of pearl millet alongside rice. This practice has resulted in a substantial increase in overall crop yields and improved soil health (Anitha & Reddy, 2018).
Karnataka	**Empowering women farmers**: In Karnataka, rice-millet cropping systems have had a transformative impact on women farmers. By integrating finger millet cultivation alongside rice in rainfed areas, women have not only increased their incomes but also played a pivotal role in ensuring household food security. This success story highlights the empowerment of marginalized communities through millet-based farming practices (Aruna & Sandhya, 2018).
Odisha	**Improved resilience in coastal areas**: In the coastal regions of Odisha, rice-millet cropping systems have significantly enhanced climate resilience. By intercropping rice with drought-tolerant millets such as sorghum and finger millet, farmers in vulnerable areas have successfully mitigated the risks associated with cyclones and erratic monsoons. This approach has led to not only improved livelihoods but also greater food security (Kishore & Ananth, 2019).
Telangana	**Enhancing nutritional security**: In Telangana, the promotion of rice-millet cropping systems, particularly the cultivation of pearl millet alongside rice, has led to improved nutritional security. Pearl millet, rich in micronutrients and dietary fiber, has been integrated into the diet of local communities. This dietary diversification has not only improved nutrition but also contributed to reduced food insecurity (Shalander et al., 2016).

Maharashtra	**Sustainable farming and income generation**: In Maharashtra, a state in western India, smallholder farmers have adopted rice-millet cropping systems to enhance sustainability and income. By cultivating finger millet alongside rice, they have reduced production costs, increased yields, and diversified their income sources. This approach has not only improved their financial well-being but also contributed to soil health and water conservation (Zade &Gangare, 2018).
Tamil Nadu	**Climate-resilient farming**: Farmers in Tamil Nadu have embraced rice-millet cropping systems as a climate-resilient farming strategy. By cultivating drought-tolerant millets like foxtail millet alongside rice, they have mitigated the risks associated with monsoon variability. This approach has led to consistent yields even in adverse weather conditions, contributing to improved food security (Janila et al., 2015).

These additional case studies from different regions of India further illustrate the positive outcomes of rice-millet cropping systems. They showcase the adaptability of these systems to various agro-ecological conditions and their potential to improve nutrition, increase income, and enhance climate resilience for smallholder farmers in India.

Challenges Faced by Rice-Millet Cropping System Farmers in India:

Yield variability: Indian farmers practicing rice-millet cropping systems often contend with significant yield variability, primarily driven by unpredictable rainfall patterns and limited access to improved seeds and modern agricultural technology.

Inefficient seed supply chain: Supply chain of small millet seeds other than ragi is inefficient

Minimumsupportprice(MSP)forfewmillets:Itisavailableonlyforpearlmillet, finger millet and sorghum. Other minor millets are not included under MSP.

Sorghum effect: The nutrient status of the soil is exhausted by fast-growing cereal like sorghum. Its crop residue has a wide C:N ratio and takes a long time to decompose because of which soil nitrogen is temporarily immobilized ausing temporary deficiency of nitrogen in the soil for the succeeding crop. To reduce the sorghum effect, 25% more nitrogen is applied at the time of the first fertilizer dose of the succeeding crop.

Market access challenges: Limited market access and price fluctuations for millet grains can pose significant hurdles for Indian farmers seeking to sell their produce and earn a sustainable income (Sultana & Dhar, 2018).

Availability of other fine cereals at incentivized prices: Fine cereals such as Rice and Wheat have been made available at incentivized prices through PDS, MDM, WCD, and other public-funded feeding/nutritional programs

Processing Issues: Apart from ragi and jowar, other types of millets have tough seed coats and need more processing. The efficiency of current machinery is low with the recovery of 70–80% of grain and the remaining being the un-hulled and broken grains. One type of dehuller unit is not suitable for all the millets, as their morphological features differ mainly in size, shape husk content and nature (ASSOCHAM, 2022).

Pest and Disease Management: Effectively managing pests and diseases in millet crops without relying on excessive chemical inputs presents a significant challenge to farmers (Singh &Irungbam, 2018).

Future Research and Policy Directions in India:

Improved varieties for Agro-ecological zones: Research efforts should be directed toward breeding high-yielding and climate-resilient millet varieties tailored to India's diverse agro-ecological zones (Bidinger et al., 2007).

Emphasis is needed on all millets: There are no restrictions to promote a particular crop. But ragi is gaining popularity due to its easy processing facility and community adaptability. So, in this way, we are again entering into another kind of monoculture and risking our agro-biodiversity. There should be a parallel policy of promoting small millets along with major millets in domestic and international markets.

Promoting value addition: Since the processing of millets involves hardships, proper processing and value additions will be effective in creating more demand among consumers. Policies and interventions should encourage value addition to millet products, promoting their consumption and commercialization (Gowda et al., 2007).

Enhancing market linkages:Developing efficient market linkages and ensuring fair prices for millet farmers are essential to improve their economic well-being (Kumar & Pal, 2009).

Diversification Incentive Policy: Incentivise poor farmers to increase their crop diversity to reduce the sensitivity of rice to rainfall variability (Davis et al., 2019).Additionally, empowering millet farmers with Guaranteed Buy-

Back and a Bonus Above the MinimumSupport Price not only enhances their financial security but also fosters millet cultivation, offering benefits to both farmers and consumers.

MSP for all millets: Expanding the Minimum Support Price (MSP) to include all millet cropswould promote agricultural diversity and support small-scale farmers in cultivating a wider range of nutritious grains.

Gaps in Knowledge and Research Needs in India:

Sustainability Assessment: Further research is required to comprehensively assess the long-term sustainability of rice-millet cropping systems in India, considering their impact on soil health and water resources (Sharma & Sreelatha, 2008).

Climate-resilience research: Research should prioritize the development of climate-resilient farming practices and technologies tailored to India's varied agro-climatic regions (Taneja & Wani, 2009).

Farmers' capacity building : Efforts should be made to enhance the capacity of Indian farmers, particularly smallholders, in adopting and adapting to sustainable rice-millet cropping systems (Kumar & Saini, 2013).

Addressing these challenges and focusing on these specific research and policy directions tailored to the Indian context will be crucial for harnessing the potential of rice-millet cropping systems for sustainable agriculture, food security, and livelihood improvement in India.

Conclusion

In summary, the chapter highlights the vital role of rice-millet cropping systems in addressing climate change challenges in Indian agriculture. It emphasizes diversifying rice cultivation with millets like pearl millet, finger millet, sorghum,etc. to enhance climate resilience, considering specific regions and agro-climatic conditions. These systems offer benefits like climate resilience, soil health improvement, efficient water use, nutritional diversity, and economic viability. They incorporate climate-resilient practices like crop rotation, water management, pest control, and organic farming. Case studies showcase their positive outcomes, despite challenges like yield variability, market access issues, and pest management. Policy recommendations focus on millet cultivation, value addition, market connections, and diversification incentives. Further research is essential for sustainability, climate resilience, farmer capacity, and knowledge gaps. In conclusion, rice-millet cropping systems provide a sustainable solution for India's agriculture, addressing yield variability, market access, and pest management. Collaborative research, government policies, farmer education, and public awareness can promote their adoption as a resilient, nutritious, and climate-ready approach to agriculture.

References

Altieri, M.A., 1999. The ecological role of biodiversity in agroecosystems. Agriculture, Ecosystems & Environment, 74(1-3), pp.19–31.

Anitha, K. and Reddy, S.M., 2018. Conservation agriculture-based millet cropping systems for higher productivity, profitability, and sustainability in rice fallows of Anantapur district. Journal of Community Mobilization and Sustainable Development, 13(2), pp.193-197.

Anonymous., 2022. https://www.weforum.org/agenda/2022/05/ancient-crop-india-waterfood-crisis/

Aruna, R and Sandhya, G. 2018. Impact of integrated rice and finger millet cultivation on food security and women's livelihood in rainfed regions of Karnataka. International Journal of Agriculture and Biology, 20(10), 2242-2247.

ASSOCHAM, 2022. MILLETS The Future Super Food for India.

Bhunya, P.K.and Tyagi, N.K., 2018. Harnessing rainwater for sustainable agriculture: A review. Journal of Water Management Modeling, 26, C405.

Bidinger, F.R., Yadav, O.P. and Sharma, M.M., 2007. Millets in marginal environments of India: Identifying options for better livelihoods. In Proceedings of the International Crop Science Congress, 3, pp.1-6.

Bisen, J., Goud, B.R., Mondal, B., Saha, S. and Nayak A.K., 2023. Can Rice Facilitate Revival of Mighty Millets? Policy Brief 1, ICAR-National Rice Research Institute, Cuttack.

Bouman, B.A.M., Lampayan, R.M. and Tuong, T.P., 2007. Water management in irrigated rice: Coping with water scarcity. Los Baños (Philippines): International Rice Research Institute.

Chapke, R.R., Rakshit, S., Mishra, J.S. and Patil J.V., 2011. Factors Associated with Sorghum Cultivation under Rice Fallows. Indian Research Journal of Extension Education, 11 (3), pp. 67-71.

Choudhary, M.R. and Prabhakara Setty, T.A., 2016. Combining millets with rice and wheat: A viable option for improved food and nutritional security. International Journal of Agriculture, Environment and Biotechnology, 9(6), pp.1229–1235.

Davis, K., Chhatre, A., Rao, N.and Defries, R., 2019. Sensitivity of grain yields to historical climate variability in India. Environmental Research Letters. 14. 064013. 10.1088/1748-9326/ab22db.

Davis, K., Chhatre, A., Rao, N., Ghosh-Jerath, S., Mridul, A., Poblete-Cazenave, M., Pradhan, N. and DeFries, R., 2019. Assessing the sustainability of post-Green

Revolution cereals in India. Proceedings of the National Academy of Sciences. 116. 201910935. 10.1073/pnas.1910935116.

Deaton, A. and Dreze, J., 2009. Food and nutrition in India: Facts and interpretations. Economic and Political Weekly, 44(7), pp. 42–65.

Deep, M., Kumar, R.M., Saha, S. and Singh, A., 2018. Rice-based cropping systems for enhancing productivity of food grains in India: decadal experience of AICRP. Indian Farming 68(01), pp.27–30.

Defries, R., Liang, S., Chhatre, A., Davis, K., Ghosh, S. and Rao, N., 2023. Climate resilience of dry season cereals in India. Scientific Reports, 13, pp. 9960. 10.1038/s41598-023-37109-w.

FAO, 2017. The State of Food and Agriculture: Leveraging Food Systems for Inclusive Rural Transformation. Retrieved from http://www.fao.org/3/a-i7658e.pdf

Giller, K.E., and Cadisch, G., 1995. Future benefits from biological nitrogen fixation: An ecological approach to agriculture. Plant and Soil, 174(1-2), pp.255–277.

Gowda, C.L.L., Rai, K.N. and Reddy, B.V.S., 2007. Pearl Millet and Sorghum Improvement for Food Security in Rainfed Semi-Arid Tropics of Asia and Africa. Genome, 50(4), pp. 329-337.

Gressel, J. and Hanafi, A., 1993. Lessons from the management of rice pests on rotated fields. Crop Protection,12(4), pp. 304–313.

Gumma, M.K., Thenkabail, P.S., Teluguntla, P., Rao, M.N., Mohammed, I.A. and Whitbread, A.M., 2016.Mapping rice-fallow cropland areas for short-season grain legumes intensification in South Asia using MODIS 250 m time-series data. International Journal of Digital Earth, 9(10), pp. 981-1003.

IPCC, 2021. https://www.ipcc.ch/2022/05/05/ipcc-wgi-final-report-materials-online/

Janila, P., Ravikiran, K.T. and Srinivas, T., 2015. Farmers' Participatory Evaluation of Rice and Pearl Millet Based Cropping Systems for Enhancing Food Security and Income in Tamil Nadu. Indian Journal of Hill Farming, 28(2), pp. 67-70.

Kaur, G. and Singh, M., 2016. Evaluation of drip and sprinkler irrigation for sustainable production of rice (*Oryza sativa* L.). Indian Journal of Agricultural Sciences, 86(5), pp. 576–582.

Khush, G.S., 2005. What it will take to feed 5.0 billion rice consumers in 2030. Plant Molecular Biology, 59(1), pp. 1–6.

Kishore, A. and Ananth, D., 2019. Diversified cropping systems in rainfed rice areas of coastal Odisha: A climate-resilient approach. Journal of Agro-meteorology, 21(1), pp. 53-58.

Krishnamurthy, L. and Serraj, R., 2017. Pearl millet and climate change: Significance, opportunities, and potential impacts. Frontiers in Plant Science, 8, pp. 1961.

Kumar, R. and Kumar, S., 2016. Sustainable Agriculture: A Review. Journal of Ecology andthe Natural Environment, 8(4), pp. 52–63.

Kumar, R. and Pal, D.K., 2009. Indian millets: Current status and future outlook. Journal of Arid Environments, 73(2), pp. 183-193.

Kumar, S. and Ladha, J.K., 2011. Direct seeding of rice. Advances in Agronomy, 111, pp. 297–413.

Kumar, S. and Saini, J.P., 2013. Farmer's training and sustainable agricultural practices: A case study of West Bengal. International Journal of Research in Commerce, Economics and Management, 3(2), pp. 67-70.

Lobell, D.B. and Gourdji, S.M., 2012. The Influence of Climate Change on Global CropProductivity. Plant Physiology, 160(4), pp. 1686–1697.

Ministry of Earth Sciences, 2018. Assessment of Climate Change overthe Indian Region. Retrieved fromhttps://moes.gov.in/hi/documents/reports/assessment-climate-change-over-indian-region

NAAS, 2013. Millets: Future of Food andFarming. Retrieved fromhttp://naasindia.org/Millets_Future_of_Food_and_Farming.pdf

Pathak, H., Tripathi, R., Jambhulkar, N.N., Bisen, J.P. and Panda B.B., 2020. Eco-regional Rice Farming for Enhancing Productivity, Profitability and Sustainability. NRRI Research Bulletin No. 22, ICAR-National Rice Research Institute, Cuttack 753006, Odisha, India,pp 28.

Reddy, B.V.S., Ramesh, S., Reddy, P.S. and Gowda, C.L.L., 2005. Millets: A Solution to Agrarian and Nutritional Challenges. Journal of SAT Agricultural Research, 1(1), pp. 1–15.

Reganold, J.P. and Wachter, J.M., 2016. Organic agriculture in the twenty-first century. Nature Plants, 2(2), pp. 15221.

Saleh, A.S.M., Zhang, Q., Chen, J. and Shen, Q., 2013. Millet grains: Nutritional quality, processing, and potential health benefits. Comprehensive Reviews in Food Science and Food Safety, 12(3), pp. 281–295.

Shalander, K., Garg, K.K. and Raja, R., 2016. Promoting Nutritional Security through Pearl Millet-based Rainfed Farming Systems in India. International Crops Research Institute for the Semi-Arid Tropics (ICRISAT).

Sharma, A.R. and Rao, B.V., 2006. Organic matter, microbial biomass and enzyme activities in a sandy loam soil under pearl millet (*Pennisetum glaucum* L.)-wheat (*Triticum aestivum* L.) cropping system. Plant and Soil, 283(1-2), pp. 37–47.

Sharma, A.R. and Sreelatha, T., 2008. Soil quality, productivity and energy dynamics under different cropping sequences in alfisols of semi-arid India. Journal of SAT Agricultural Research, 6(1), pp. 1-8.

Sharma, A., Chakravarty, A. and Goyal, S., 2014. Impact of rainwater harvesting on groundwater recharge in arid to semiarid region of Bikaner district, Rajasthan, India. Environmental Monitoring and Assessment, 186(10), pp. 6853–6864.

Singh, A.S. and Irungbam, J.S., 2018. Assessment of losses in major millet crops in the farms of Churachandpur district, Manipur. International Journal of Fauna and Biological Studies, 5(4), pp. 19-24.

Singh, R.D., 2010. Food security for increasing rural livelihood under limited water supply through adoption of diversified crops and crop sequences. In *Resource Conservation Technologies for Food Security and Rural Livelihood*; Khan, A.R., Singh, S.S., Bharti, R.C., Srivastava, T.K., Khan, M.A., Eds.; Agrotech Publishing Academy: Udaipur, India, pp. 342–355.

Sonune, S.V. and Mane, S., 2018. Impact of climate resilient varieties on crop productivity in NICRA village. Journal of Pharmacognosy and Phytochemistry. https :// doi. org/10.30954 /0424-2513.3.2018.9

Sultana, R. and Dhar, A.R., 2018. Constraints in producing and marketing of millets in the major producing states of India. International Journal of Current Microbiology and Applied Sciences, 7(3), pp. 198-209.

Sultana, R. and Naznin, H.A., 2012. The role of millets in food security in India. Food Security, 4(2), pp. 227–236.

Taneja, K.K. and Wani, S.P., 2010. Improving Livelihoods and Natural Resource Management in India: Beyond the Green Revolution. Journal of SAT Agricultural Research, 8, pp. 1-13.

Tripathi, G. and Singh, A. 2019. Impact of organic farming on soil health, crop productivity, and economics: A review. Agroecology and Sustainable Food Systems, 43(11), pp. 1303–1333.

Wang, J., Vanga, S.K., Saxena, R., Orsat, V. and Raghavan, V., 2018. Effect of Climate Change on the Yield of Cereal Crops: A Review. *Climate*, 6, pp. 41. https://doi. org/10.3390/cli6020041

Zade, P.B.and Gangare, D.S., 2018. Profitability and Resource Productivity of Rice-Millet Crop Rotation in Rainfed Rice Fallow of Vidarbha Region of Maharashtra. International Journal of Current Microbiology and Applied Sciences, 7(2), pp. 2018-2025.

Area, Production and Productivity of Millets in World and India

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Abstract

Millets are considered a climate-resilient crop and have a Pharmaceutical value making them highly valuable crops in recent times. Millets are mostly consumed by developing, arid and semi-arid regions of the world . However, during the recent past due to the versatile benefits of millets, it has become popular in urban area also. Asia and African continent alone account for 97 percent of total millet production (27.5 M.t.) According to the USDA estimate, the largest area decline in millet was observed in Asia (148%) and the lowest reduction in area was observed in Africa . The area under millet cultivation for the last 60 years dropped to the tune of 26 percent from 1960 to 2020, whereas millet production in the world has improved by 36 percent and the productivity level increased from 575 ka/ha to 900 kg/ha in 2018. India shares more than 80 percent of Asia and 20 percent of the global production. In India, millet production is confined to arid , semi-arid regions and tribal regions where rainfall is low and erratic. Among the millets, pearl millet being the drought-escaping plant accounts for more than 56% of total millet production in India. Mostly produced from Rajasthan, Uttar Pradesh, Gujarat, Madhya Pradesh and Haryana. Among the minor millets, finger millet ranks first in minor millet production of 1.79 M.t from the cropped area of 1.17 M.ha with productivity of 1530 Kg/ha. More than 90% of total finger millet production comes from Karnataka, Uttarakhand, Maharastra, Tamil Nadu, Odisha and Andra Pradesh State. The remaining 10 % of the total minor millet is produced from kodo millets and others. As per the Indian Scenario, a quantum increase of 73% was achieved in the last 73 years in millet productivity. Among the

millets, Finger Millet recorded the highest productivity of 1591 kg/ha, Pearl Millet (1130 kg/ha) and Sorghum (883 kg/ha, Fig 3) ranked second and third position respectively. Higher productivity may be achieved by use of Hybrids, fertilizer responsive varieties and adoption of improved production technologies. Millet farmers livelihood may be improved by value addition of their produces.

Introduction

Millets are broadly grouped into major and minor millets viz., Sorghum, Pearl Millet, Finger Millet, Proso Millet, Fox tail Millet, Kodo Millet, Barnyard Millet. Millets are mostly consumed by developing, arid and semi-arid regions of the world (McDonough *et al.*, 2000). In the world, more than 93 countries are involved in millet production, whereas only 7 countries have more than 1 million cultivation areas and consume more than 97 percent of millet production.

The area under millet cultivation for the last 60 years dropped to the tune of 26 percent from 1960 to 2020, whereas millet production in the world has improved by 36 percent, and the productivity level increased from 575 ka/ha to 900 kg/ha in 2018 (Meena *et al.*, 2021). According to USDA estimates, among the continents, Asia and Africa alone account for 97 percent of total millet production (27.5 M.t.) whereas the Australian continent contributes the least production of 0.003 Million tonnes with a share of 0.13 percent of global millet production. Chandra *et al.*, (2021) reported that pearl millet share 50 percent of the world millet production. FAOSTAT 2021 reveals that the average productivity of millet is 1229 kg/ha. Indian average productivity is 10 kg higher than world productivity. India shares more than 80 percent of Asia and 20 percent of the global production (Ministry of Agriculture and Farmers Welfare 2022). During 2019 alone, the African continent shared major production of the millet of nearly 50 M. ha. followed by America, Asia with a total area of 13.8 M. ha. and production of 8.63 M.t. In India, millets are mostly consumed by tribal states viz. Madhya Pradesh, Jharkhand, Odisha, Rajasthan, Karnataka and Uttarakhand (Sood et al., 2019). However, during the recent past due to the versatile benefits of millets, it has become popular in urban areas. According to the estimate, the largest area decline in millet was observed in Asia (148%) and the lowest reduction in area was observed in Africa (Fig 1). The area reduction in millet may be due to a lack of high-yielding varieties, shifting to the cultivation of commercial crops, lack of government policies unaware of value addition and low productivity. Millets are considered a climate-resilient crop and have a Pharmaceutical value making them highly valuable crops in recent times. Although millets have high nutritional value, the area under millet production is drastically reduced or remains stagnated as compared to cereal crops. In this chapter status of millet area, production and productivity in the world and India are discussed.

Millets area Scenario

According to FAO statistics, millet scenarios are given as small millets and pearl millet as one category (Fig 1) and Sorghum (Fig 2) is another category. In the Indian scenario, all the Major millets (Sorghum, Pearl millet) and Minor millets (Finger millet) are given. (India stat 2020: Fig 3). In the world, only seven countries viz., India, Niger, Sudan, Nigeria, Mali, Burkina Faso and Chad have more than 1 M. ha. Millet area and more than 25 countries have less than 1 lakh ha area. Among the countries, India has the highest area of 15.29 M. ha followed by Niger (7.03 M. ha), Sudan (3.75 M. ha), Nigeria (2.7 M. ha) and Chad (1.2 M. ha). India shares nearly 27% of the global millet area according to FAO STAT 2018. Among the continents, Asia ranks first in the area with 27.1 M.ha followed by Africa, Europe, America and Australia with 11.8, 4.0, 2.6 and 0.02 M.ha respectively based on baseline data of 1961 data. Recent statistics revealed that Africa ranks first in an area of 48.9 M.ha followed by Asia (16.2 M.ha), Europe (0.8 M.ha) and America (0.53 M.ha). Among the African continent, west Africa recorded the highest area of 14.3 M.ha followed by North Africa (3.0 M.ha). West Africa alone contributes nearly 44 % of the world's millet area (Fig 1, FAO STAT 2018).

Among the Asian countries, India shares more than 80 % of the millets area USA and Argentina are the major countries that cultivate millets in America. Among Europe Ukraine, Poland and France are the largest millet area grower. Worldwide area and Asia under millet have come down to the tune of 25 and 148 % respectively (Fig 1). The decline in millet area in Asia is mainly due to the lower yield of millets during the 1960s whereas in African continents 42% increase in area was observed. Among the African continents, West Africa recorded the highest degree of 5.5 M.ha was increased from 2016-2018 (Fig 1). Sorghum is cultivated in more than 105 countries of which 10 countries are having more than 10 lakh ha cultivated area viz., Sudan, India, Nigeria, Niger, America, etc., and 37 countries have less than 1 lakh ha area. Among the continents, Africa alone contributes more than 70% of the cultivated area followed by Asia and America. Sudan ranks first in world area with 71 lakh ha followed by Nigeria (61.2 lakh ha) and India (49 lakh ha). However, during the last 50 years, the Sorghum area decreased at the rate of 1.5 M.ha per decade in the world. However in African continents, for the last 58 years from 1961 to 2018, there was a gradual increase in sorghum area to the tune of 44%. The increase in sorghum area is mainly due to hot weather that prevailed during the last decades which in turn resulted in the replacement of water-loving crops such as maize to drought tolerant crops like minor millets and sorghum.

Fig. 1. World millet area and production excluding sorghum.

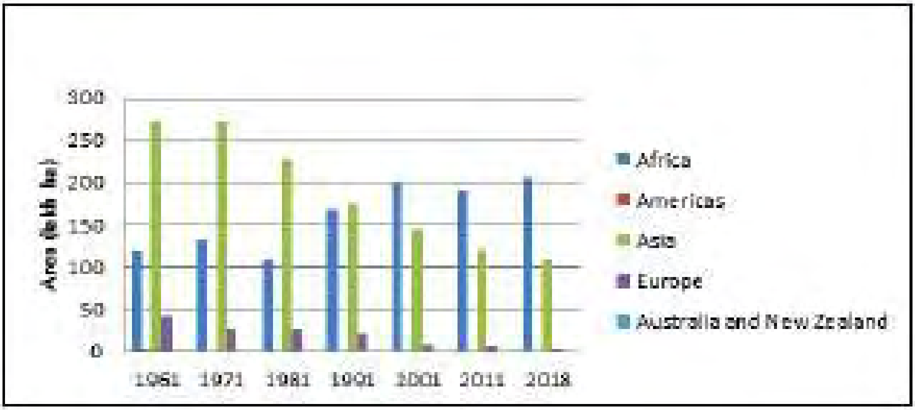

Fig 1a: World millets (Excluding sorghum) area

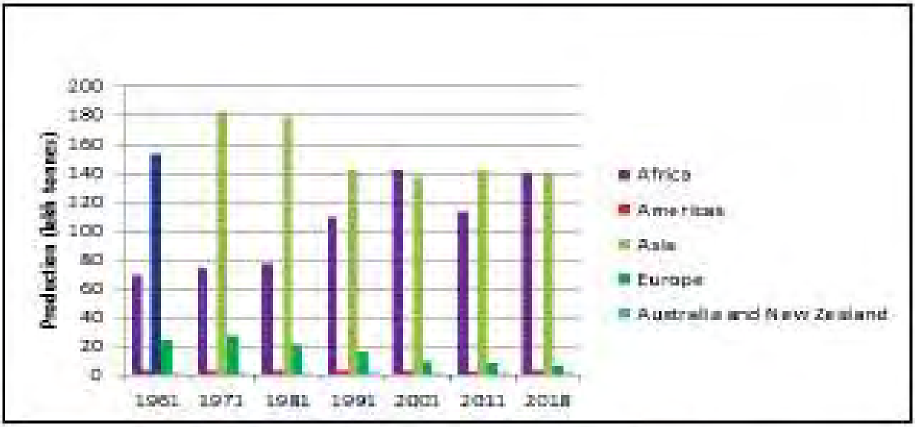

Fig 1b: World millets (Excluding sorghum) production

World Millet Production Scenario:

Around 97 % of the millet is produced and consumed by developing countries alone and a small fraction only from developed nations. From 1961 to 1963 among the countries, Asia had the highest production of millets (13.2 M.t) followed by Africa (6.9 M.t), Europe (2.3 M.t), America (0.32 M.t) and Australia (0.03 M.t) (Fig 1b). Asia alone contributes more than 38% of world millet production. Among the Asian countries, 3 countries India, China and Nepal contribute major millet production.

Fig. 2. World Sorghum area and production by continents

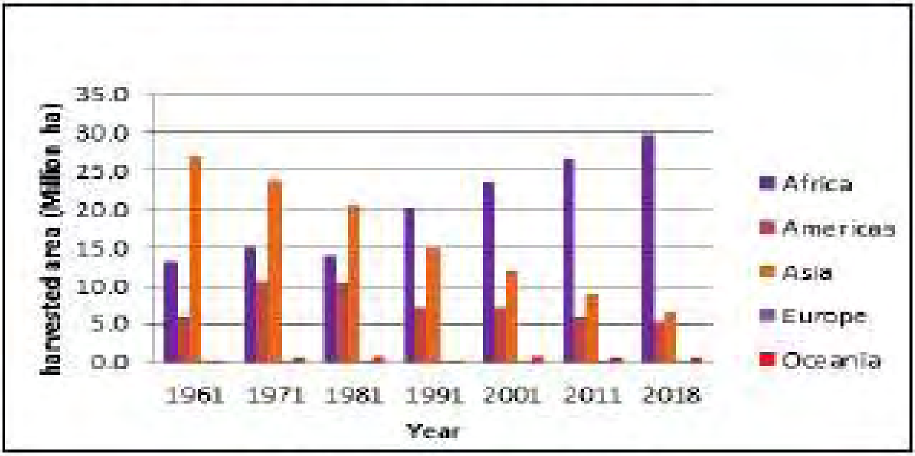

Fig 2a: World sorghum area Million ha

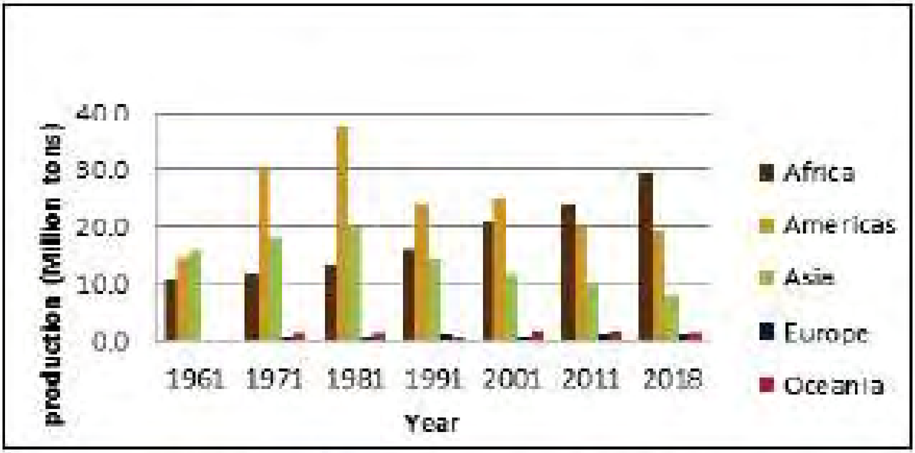

Fig 2b: World sorghum Production Million tonnes

As per FAO Statistics 2018, the major share of millet production comes from African continents. The main reason is due to the prevailing hot climate suitable for millet production and millets are the main stable crops. The major millet-producing African countries are Nigeria, Sudan, Mali, Guinea and Ghane. The United States of America is the main country in millet production on North American continents. Argentina has having highest production in South America. Major millet production comes from hot and drier regions of Europe shares 90% of the region's total.

During, 61 years from 1961 onwards gradual increase in millet production was noticed among African countries, especially West Africa. However, there was a gradual decrease in millet production was observed in other parts of the world. During 2016-18 highest millet production was achieved in Africa (14 M.t) followed by Asia (13.9 M.t), and Europe (0.62 M.t). Major increases in millet production in African countries are mainly due to prevailing dry climatic conditions. Farmers have shifted their maize area to millet production. In Asian countries till 1980, the millet production was higher and thereafter continuous decline in production was observed mainly due to reduced millet area, especially in India and China (Fig 3). Whereas in Australia, there was no change in millet production and remained constant from 1961 to 2018.

World sorghum production during 2018, was only 59.3 M.t. Among the countries, the United States of America ranks first in the production of (9.27 M.t) followed by Nigeria (6.8 M.t). Africa contributes more than 23% of total

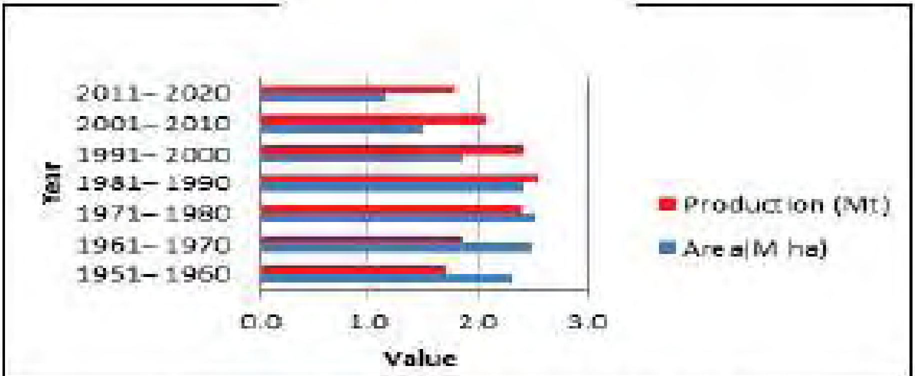

Fig 3a: Area, Production of Finger millets in India

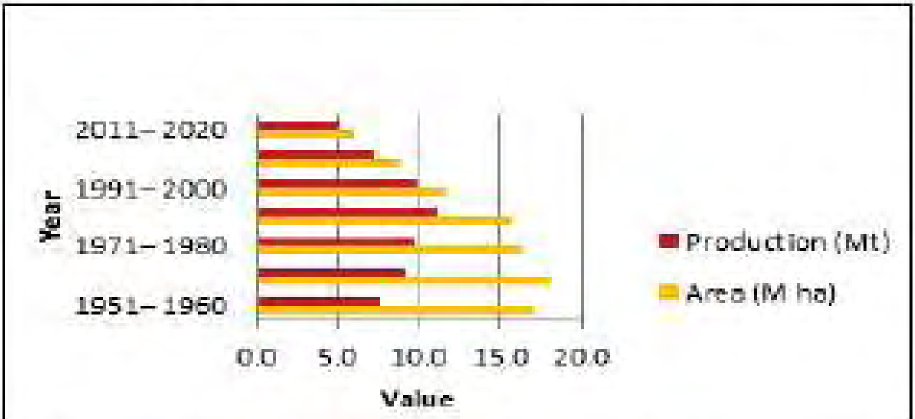

Fig 3b: Area, Production of Sorghum in India

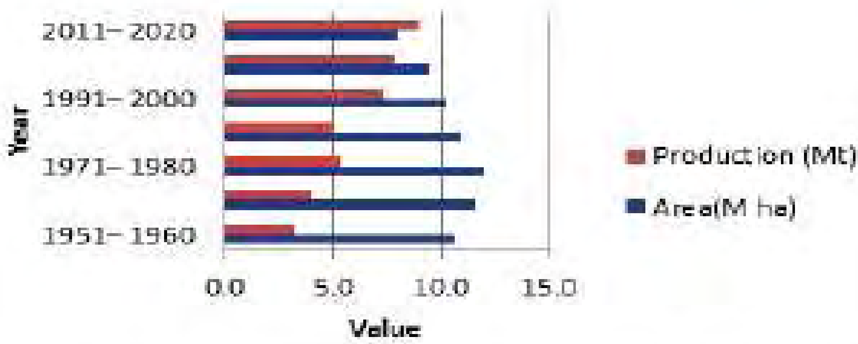

Fig 3c: Area, Production of Pearl Millet in India

sorghum production produced from Nigeria, Sudan, Ethiopia Mali and Niger. Among African countries, Nigeria ranks first in sorghum production followed by Argentina, Brazil, Mexico and the United States. Among Asian countries, more than 89% of total sorghum grains are produced from India and China (FAO STAT 2018). France, Italy, Albania, Spain and Ukraine are the major producing countries among Europe countries. There was a gradual increase in world sorghum production from 40.66 M.t to 73.2 M.t from 1961 to 1981 with a 44% increase in sorghum production. However, there was a gradual decline in sorghum production by 19% mainly due to a decrease in cropped area by 8% from 1981 to 2018. From 1961 onwards, production increased in African continents and gradually declined in other parts of the world. Mainly Asian countries especially India and China regarded a negative growth rate in production due to a sharp decline in cultivated area. During the 1950's with 17 M.ha of total cropped area produced 7.65 M.t of Sorghum and drastically reduced to 6 M.t from 6 M.ha (Fig 3). Overall, there was a reduction in total cropped area but the global production of Sorghum increased from 24.9 M.t to 29. M.t. The increase in Sorghum production was achieved mainly due to good agronomic management practices and the cultivation of high-yielding varieties led to an increase in productivity.

In India, millet production is confined to arid and semi-arid regions where rainfall is low and erratic. Among the millets, pearl millet being the drought-escaping plant accounts for more than 56% of total millet production in India. Mostly produced from Rajasthan, Uttar Pradesh, Gujarat, Madhya Pradesh and Haryana. Among the minor millets, finger millet ranks first in minor millet production of 1.79 M.t from the cropped area of 1.17 M.ha (Fig 3) with productivity of 1530 Kg/ha. More than 90% of total finger millet production comes from Karnataka, Uttarakhand, Maharastra, Tamil Nadu, Odisha and Andra Pradesh State. The remaining 10 % of the total minor millet is produced from kodo millets and others.

World Millet Productivity Scenario:

During the last seven decades (1961-2018) millet productivity increased by 36%. The highest increase in productivity was achieved in Europe from 583 to 1517 kg/ha (62%) and the second highest was from Asia from 562 to 1276 kg/ha (56%), America from 1233 to 2166 kg/ha (44%) (Fig 4).

Fig 4: Millets (except sorghum) productivity

Interestingly in Africa, the productivity level increased during the 1960s and reached its highest level during the 1980s and gradually declined in the 1990s. During 2003, the productivity level increased to the tune of 18.6 % as compared to the 1960's (Fig 4) and again the productivity level declined. However, the productivity level from 1963 to 2018 increased by 40% and 69% in Eastern Africa and South Eastern Asia respectively. During 2018, Eastern Asia alone recorded the highest productivity of 2308 kg/ha. According to FAO STAT 2018, the highest millet productivity was achieved in Mexico, Uzbekistan, Austria and Switzerland at 15.7, 6.76, 4.4 and 4.0 t/ha respectively.

As per the Indian Scenario, a quantum increase of 73% was achieved in the last 73 years in millet productivity (Fig 3). Among the millets, Finger Millet recorded the highest productivity of 1591 kg/ha, Pearl Millet (1130 kg/ha) and Sorghum (883 kg/ha, Fig 3) ranked second and third position respectively. Higher productivity achieved in Indian millet was due to the development of fertilizer-responsive varieties, higher fertilizer use efficiency and adoption of improved production technologies. Improvement in the productivity of sorghum was due to evolving improved sorghum hybrids and high input management practices among sorghum-grown countries. In India, Sorghum is grown in varied soil types, rainfall and different seasons. Rainy season sorghum out yielded sorghum productivity over post-rainy season crop (Rakshit and Wang, 2016) Among the Asian countries, China ranked first in productivity of 4500 kg/ha followed by India. Whereas in the world, Oman recorded the highest productivity of 28000 kg/ha, followed by Jordan at 22100 kg/ha.

Table 1: Area, Production and Productivity of Millets in India (2021-2022)

State/ UT	Area (Million ha)				Production (Million tons)				Productivity (t/ha)			
	Jowar	Bajra	Ragi	Small millets	Jowar	Bajra	Ragi	Small millets	Jowar	Bajra	Ragi	Small millets
AndhraPradesh	0.8	0.3	0.8	0.1	0.41	0.06	0.41	0.01	3.17	1.78	3.17	0.79
Bihar	0.0	0.0	0.0	0.1	0.00	0.00	0.00	0.00	1.07	1.13	1.07	0.62
Chhattisgarh	0.0	0.0	0.0	0.0	0.00	0.00	0.00	0.00	0.83	0.45	0.83	0.75
Gujarat	0.4	4.5	0.4	0.5	0.06	1.06	0.06	0.03	1.35	2.37	1.35	0.58
Haryana	0.2	4.8	0.2	0.1	0.02	1.12	0.02	0.02	0.53	2.32	0.53	1.88
HimachalPradesh	0.0	0.0	0.0	0.0	0.00	0.00	0.00	0.00	0.00	0.56	0.00	0.87
Jammu&Kashmir	0.0	0.0	0.0	0.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Jharkhand	0.0	0.0	0.0	0.3	0.00	0.00	0.00	0.02	0.71	0.62	0.71	0.79
Karnataka	6.2	1.5	6.2	0.0	0.90	0.17	0.90	0.00	1.20	1.16	1.20	1.22
Kerala	0.0	3.4	0.0	0.9	0.00	0.87	0.00	0.08	1.45	2.53	1.45	0.86
MadhyaPradesh	1.2	5.3	1.2	0.4	0.22	0.48	0.22	0.02	1.94	0.90	1.94	0.40
Maharashtra	16.5	0.0	16.5	0.4	1.75	0.00	1.75	0.02	1.04	0.62	1.04	0.51
Odisha	0.1	0.0	0.1	0.1	0.00	0.00	0.00	0.00	0.63	0.65	0.63	0.63
Rajasthan	6.2	37.4	6.2	0.2	0.59	3.75	0.59	0.03	0.86	1.00	0.86	1.18
TamilNadu	4.0	0.6	4.0	0.0	0.43	0.16	0.43	0.00	0.74	2.62	0.74	0.00
Telangana	0.7	0.0	0.7	0.1	0.16	0.00	0.16	0.01	1.54	0.82	1.54	0.71
UttarPradesh	1.7	9.0	1.7	0.5	0.28	1.95	0.28	0.07	1.58	2.16	1.58	1.56
WestBengal	0.0	0.0	0.0	0.0	0.00	0.00	0.00	0.00	0.54	0.43	0.54	1.13
Other	0.0	0.2	0.0	0.5	0.00	0.01	0.00	0.06	0.82	0.75	0.82	1.16

Concerning the Indian state's Millet production as per the Ministry of Agriculture and Farmer's Welfare 2022, Sorghum scenario, the highest area, production was observed in Maharashtra and productivity was observed in Madhya Pradesh (Table 1). There was a gradual decline in the area from 22.31 to 16.49 lakhs ha with a decline of 26% in the area was noticed. The decline in productivity was observed in Madhya Pradesh from 2.112 to 1.9 t/ha during 2016 to 2021. In case of Bajra, the highest area and production was observed in Rajasthan and the highest productivity was observed in Tamil Nadu (Table 1). There was a gradual decline of 11% in the area observed and the productivity level was increased in Tamil Nadu from 2.3 to 2.6 t/ha. The highest area and production in Ragi was observed in Karnataka and productivity was in Tamil Nadu. There was a gradual increase in area from 0.78 to 0.85 Million ha in Karnataka whereas productivity decreased from 3.7 to 3.01 t/ha. In the case of small millets, the highest area and production were noticed in Madhya Pradesh and productivity was highest in Gujarat. There was a gradual decline in the area from 0.148 to 0.89 Million ha in Madhya Pradesh and a Quantum jump in productivity was observed from 1.21 to 1.988 t/ha (Table 1)

Constraints in Millet Production:

- Drought is considered the main constraint in millet production in African continents (Matanyaire, 1996)
- Nonavailability of seeds in time. Most of the time farmers purely depend on the local market and informal seed chains for their seeds
- Millets are mostly grown in marginal and sub-marginal lands, low fertility soil or problematic soil leads to low yield
- Mostly they are grown under rainfed situations, crop failure has become a common phenomenon and low yields due to terminal drought (Patil 2007)
- Millets are mostly grown by resource-poor farmers which leads to low input use efficiency and lower yield
- Farmers use landraces local varieties leads to lower yields.
- Lack of marketing facilities
- Unlike other crops, mechanization is not practiced as the grain size is very small to realize a higher yield
- Lack of Minimum support price for millets as compared to other crops
- Millet areas are replaced by high-value crops due to high monetary return (Seetharam, 2015)
- Lack of subsidy for millet growers
- Lack of agro-industries to promote value addition.

Way forward

- Importance may be given to growing millets in fertile lands rather than marginal and sub-marginal lands
- Big farmers may be encouraged to grow millets in the larger area
- Small and marginal farmers may be motivated to grow millet by giving incentives
- Setting up agro-industries for value addition at the village level
- Farmers especially women may be empowered by way of capacity building
- Millet production may be increased by complete mechanization
- Integrated nutrient management practices followed to increase production
- Millets may be included in ration shop

- Award may be given to the best millet farmer for achieving the highest yield in millet at the district, State and National level

Conclusion

The importance of millet raising demand of consumer to fit into the regular diet. Thus the area under the millet cultivation have to be increased so that the demand of consumer should be fulfilled.

References

Chandra, AK., Chandora, R., Sood, S., and Malhotra, N. (2021) Global production, demand, and supply. In Millets and Pseudo Cereals. Woodhead Publishing. P7-18.

FAO. Special Report, (2020) FAO Crop and Food Supply Assessment Mission (CFSAM) to the Republic of the Sudan. 2021.:https://doi.org/10.4060/cb9122en

FAOSTAT (2018) Production-yield quantities of millets in world + (total) 1962–2018. http://www. fao.org/faostat/en/data/QC/visualize.

INDIASTAT(2020) Statistical information about India. https://www.Indiastat.com/agriculturedata/2/stats.aspx.

Matanyaire,. CM (1996) Pearl millet production system(s) in the communal areas of northern Namibia: priority research foci arising from a diagnostic study. In: Leuschner K, Manthe CS (eds) Drought-tolerant crops for southern Africa. In: Proceedings of the SADC/ICRISATregional sorghum and pearl millet workshop, pp 25–29.

McDonough, CM., Rooney, LW., Serna-Saldivar,SO. (2000) The millets, food science and technology: Handbook of cereal science and technology, 2nd edn. CRC Press, Boca Raton, FL, pp 177–210.

Meena, R.P, Joshi, D., Bisht, JK., Kant, L. (2021) Global Scenario of Millets Cultivation. In Millets and Millet Technology. Springer, Singapore. pp 33-50.

Ministry of Agriculture & Farmers Welfare. (2022) National Conference on Kharif Campaign 2022 Ministry of Agriculture and Farmers Welfare, 1-45. https://agricoop.nic.in/sites/default/files/Crops.pdf

Patil, SL. (2007) Performance of sorghum varieties and hybrids during post-rainy season underdrought situations in Vertisols in Bellary, India. Journal of SAT Agricultural Research.5:1–3.

Rakshit, S., Wang, YH. (2016) The Sorghum genome. Springer International Publishing, Singapore, pp 284.

Seetharam, A. (2015) Genetic improvement in small millets. In: Tonapi VA, Patil JV (eds) Millets: ensuring climate resilience and nutritional security. Daya Publishing House, New Delhi, pp 649.

Sood, S., Joshi, DC., Chandra, AK., and Kumar, A. (2019) Phenomics and genomics of finger millet: currentstatus and future prospects. Planta.250:731–751.

Chapter 06

Potential of Millets as a Nutri-cereal in the Context of Changing Climate

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Abstract

In the twenty-first century, climate change, water scarcity, rising food prices, population growth, and other socioeconomic effects are considered serious risks to agriculture and global food security, particularly for the world's poorest residents in arid and sub-arid countries. Scientists and nutritionists are challenged by these effects to examine the feasibility of growing, processing, and consuming alternative food sources to eradicate hunger and poverty. Cereal grains are the primary source of food worldwide and play a vital role in the global diet. Millet is a significant source of carbohydrates and proteins for people living in the semi-arid tropics of Africa and Asia and is one of the most drought-resistant crops. Moreover, millet grain is currently attracting increasing interest from food scientists, technologists, and nutritionists because of its significant contribution to national food security and potential health advantages. This paper reviewed recent advancements in the research that has been conducted to date in the area of nutritional value and potential health advantages of millet grains. Even in the event of global warming and extreme temperature scenarios, millets are climate change-tolerant and have huge potential to produce greater economic advantages in marginal conditions than other cereals. The food insecurity problem can be solved by millet production, which is also covered in this chapter.

Keywords: Millet, nutrient, fiber, phytochemicals, health benefits, sustainability.

Malnutrition

Malnutrition is a significant issue in the modern world owing to climate change and growing food supply insecurity in developing and developed nations (Unicef et al. 2018). According to Organization et al. (2018), malnutrients refer to a person's inability to obtain sufficient nutrients or excess consumption of nutrients. There are 821 million malnourished individuals (those who experience chronic food insecurity) in the globe, according to (Organization and others 2018). Similarly, 109 billion overweight individuals and 462 million underweight adults exist worldwide. According to Unicef et al. (2018), 20 million infants are born underweight, and one-third of pregnant women experience anemia. In the Indian context, rural and urban populations of children (under five years), adolescent females, pregnant women, and breastfeeding mothers have relatively high malnutrition rates (Striessnig and Bora 2020). The seriousness of the situation is demonstrated by the fact that more than 65% of the children (under the age of five) died because of malnutrition in 2017. In the same year, the percentages of anemic teenage girls and low birth weight babies were 21.4% and 54.4%, respectively. In developing countries, malnutrition has a serious negative impact, particularly on poor populations. Globalization and industrialization have had a significant impact on people's eating habits, which has led to weakened immunity to noncommunicable diseases (Singh et al. 2018). Economically deprived individuals may experience significant difficulties with regard to food and nutrition security due to a lack of resources to avoid malnutrition as a result of the global economic slowdown (Ahirwar and Mondal 2019). According to (Harding et al. 2018), a significant portion of the population in South Asian nations lacks essential vitamins and micronutrients in their diet. Severe micronutrient and vitamin deficiencies can cause serious health problems, such as stunted mental and physical development and even death. These flaws ultimately result in the weak performance of the most vulnerable members of society, which impedes the economic development of emerging nations (Bhandari and Banjara 2015).

Epidemiological examinations carried out across the nation revealed that 43.8% of the population lacked sufficient quantities of zinc, particularly Orissa, Uttar Pradesh, Madhya Pradesh, and Karnataka, which have the highest zinc deficiency rates (Striessnig and Bora 2020). Obesity is also a consequence of malnutrition. It is well recognised that the main contributors to India's rising obesity rates include a sedentary lifestyle, unhealthy eating patterns, and an overreliance on fast food. By 2040, (Luhar et al. 2020) predicted that overweight and obesity would affect 30.5% of both men and women. Obesity is associated with diabetes, heart disease, cancer, osteoarthritis, and liver and kidney problems, and cancer is a serious illness. In addition, it is known to have detrimental effects on reproductive health. The quality of life is affected by obesity, which is a persistent risk factor for disease and mortality. Diabetes and heart diseases are the most prevalent and harmful effects of obesity, respectively. Furthermore, the prevailing COVID 19 pandemic is devastating and has made the situation of nutrition security poorer in India and throughout the world (Tripathy et al. 2017). The current situation necessitates greater focus on human health and immunity as a matter of lifetime. Millets appear to be the best alternative staple food for maintaining food security and boosting immunity in these circumstances.

Millet

Millet refers to small-seeded grains compared with cereals belonging to the Poaceae family. millet, sometimes referred to as nutri-cereals, and an indispensable component of millions of people's diets. India is the world's largest producer of millet following China and Nigeria, which is extensively grown in arid and semi-arid parts of the globe and supplies 41% of global output (Kumar et al. 2020). Millets are commonly planted because they can survive in challenging growth conditions, such as drought, high temperatures, and low soil fertility (Maitra 2020). Major and minor millets are two broad categories of millet. The major millets include finger millet (*Eleusine coracana*), sorghum (*Sorghum bicolor*), and pearl millet (*Pennisetum glaucum*). Foxtail millet (*Setaria italica*), proso millet (*Panicum miliaceum*), barnyard millet (*Echinochloa colona*), little millet (*Panicum sumatrense*), browntop millet (*Urochloa ramosa*), and kodo millet (*Paspalum scrobiculatum*) are among the minor millets. Compared with several other important grains (including wheat, rice, and maize), millet has a higher nutritional profile in terms of protein, minerals, vitamins, dietary fiber, and phytochemicals, such as ferulic acid and phytic acid (Chauhan et al. 2018). In addition, it has better digestibility than cereal grains such as maize and contains high concentrations of vital amino acids (leucine, isoleucine, arginine, threonine, and valine) (Sharma et al. 2021). Since millet is non-glutinous, it is safe for people diagnosed with celiac disease and gluten allergy. It is also easy to digest, non-acid-forming, and nonallergenic. In addition, millets have proven to be effective in both preventing and treating a number of diseases, including type II diabetes and cardiovascular disease (Allai et al. 2022). Diets with millets as staples ensured the survival and nourishment of ancient people and provided various health benefits, as shown in Fig 1. They are widely used in food, feed, fodder, and fuel. These are used as flour, partially broken, or as a whole grain in various local recipes.

Figure 1. Health benefits of millets

Role of millets to address nutrient deficiency

Food and nutrition security is defined as "all people at all times having physical, social, and economic access to food that is consumed in sufficient quantity and quality to meet their dietary needs and food preferences that allow healthy and active life'(Unicef et al. 2018). The three factors determining nutritional security are (1) simple access to enough food, (2) care and feeding practices, and (3) hygiene and excellent health for every sector of society (Unicef et al., 2018). According to (Hwalla et al. 2016), nutritional insecurity is an extreme concern for society that is heavily reliant on diets high in carbohydrates yet lacking in important vitamins and minerals. The nutrient composition of the millet is tabulated in Table 1. To promote nutritious eating and prevent malnutrition, supplementing diets high in carbohydrates with foods high in micronutrients and vitamins would be an appropriate approach. Millets have great potential to serve as substitutes for cereals to maintain food and nutritional security in the majority of the world because they are one of the greatest sources of micronutrients, dietary fiber, vitamins, and phytochemicals with a variety of medicinal benefits (Konapur et al. 2014). It has become more popular to consume millets in the form of numerous functional food products because of their great nutritional value. The consumption of millet in the form of various functional food products has gained popularity owing to its superior nutritional value.

According to (Saleh et al. 2013), millets are a significant source of protein and carbohydrates for people living in the semi-arid tropical regions of Asia and Africa. According to (Li et al. 2018), rice, wheat, finger millet, and sorghum are the main sources of starch in Indian diet. Millets have a carbohydrate content that is comparable to that of main cereals, ranging from 60.9 to 72.6 g/100 g. According to (Ramakrishnan et al. 2022), finger millet contains 72% carbohydrates, the majority of which are slow-digesting starch and resistant starch, both of which aid in preventing constipation and decreasing blood sugar. The slow-digesting and inexpensive pearl millet starch ranges from 62.8 to 70.5 g/100 g, can be used to produce functional food products that are suitable for infants as well as those with diabetes and obesity (Lokeswari et al. 2021). Similar to other grains, foxtail millet has a high carbohydrate content (60.9 g/100 g), making it an excellent source of energy for the elderly, children, and pregnant or nursing (Abbas et al. 2013). In addition, inactive individuals greatly benefit from the slow-digesting carbohydrate profile (Chauhan et al. 2018). The greatest advantage of millet protein is that it is gluten-free compared to wheat, making it ideal for patients with celiac disease. In comparison to milled rice (6.8%), foxtail millet, barnyard millet, pearl millet, and sorghum contain 12.3%, 12.0%, 11.6%, and 10.4% protein, respectively (Konapur et al. 2014). Millet protein quality is superior to that of other cereals because pearl, foxtail, and finger millet contain higher levels of essential amino acids such as methionine and cystine. Millets have a good fatty acid profile and are rich in mono- and polyunsaturated fatty acids. According to (Lokeswari et al. 2021), pearl millet has a high oil content (up to 4.2%) and is composed of 50% unsaturated fatty acids. The three main fatty acids found in finger millet are oleic (49%), linoleic (25%), and palmitic acids, which lower the risk of duodenal ulcers. According to (Nani and Krishnaswamy 2021), finger millet malt is a well-known traditional weaning diet with high energy and low viscosity. Weaning food reportedly contains 18.37% protein and 398 kcal per 100 g when made from 30% of each of foxtail millet and barnyard millet flour (Abedin et al. 2022)we looked at foxtail millet in Bangladesh and analyzed its nutritional value, functional and physical characteristics. In addition, methanol, ethanol, and acetone: water: acetic acid (70: 29.50: 0.50. To help prevent protein and calorie deficiencies, millet might be a perfect addition to a cereal-based diet.

Table 1. Nutritional composition of Millets

Food	Rice (brown)	Wheat	Maize	Sorghum	Pearl millet	Finger millet	Foxtail millet	Common millet	Little millet	Barnyard millet	Kodo millet
Protein, g	7.9	11.6	9.2	10.4	11.6	7.7	11.2	12.5	9.7	11	9.8
Fat, g	2.7	2	4.6	3.1	4.8	1.5	4	3.5	5.2	3.9	3.6

Ash, g	1.3	1.6	1.2	1.6	2.2	2.6	3.3	3.1	5.4	4.5	3.3
Crude fiber, g	1	2	2.8	2	2.3	3.6	6.7	5.2	7.8	13.6	5.2
Carbohydrates, g	76	71	73	70.7	67	72.6	63.2	63.8	60.9	55	66.6
Energy, kcal	362	348	358	329	363	336	351	364	329	360	353
Ca, mg	33	30	26	25	42	350	31	8	17	22	35
Fe, mg	1.8	3.5	2.7	5.6	11	3.9	2.8	2.9	9.3	18.6	1.7
Thiamin, mg	0.41	0.41	0.38	0.38	0.38	0.42	0.59	0.41	0.3	0.33	0.15
Riboflavin, mg	0.04	0.1	0.2	0.15	0.21	0.19	0.11	0.28	0.09	0.1	0.09
Niacin, mg	4.3	5.1	3.6	4.5	2.8	1.1	3.2	4.5	3.2	4.2	2

Micronutrients and traces of minerals are nutrients that the body needs in very small amounts to complete vital metabolic processes and to build resistance to various diseases. Finger millet contains a high amount of iron and is an abundant source of calcium (344 mg/100 g). According to (Nani and Krishnaswamy 2021), finger millet has a calcium level that is up to 10 times greater than that of brown rice, wheat, or maize and three times that of milk, making it the greatest source of calcium among cereals. Iron (8.0 mg/100 g), phosphorus (296 mg/100 g), zinc (3.1 mg/100 g), and magnesium (137 mg/100 g) are abundant in pearl millet (Ramakrishnan et al. 2022). Little millet contains high levels of zinc (3.7 mg/100 g) and iron (9.3 mg/100 g). The micronutrients such as iron (5.0 mg/100 g), zinc (3.0 mg/100 g), and phosphorus (280 mg/100 g) are all abundant in barnyard millet as well (Renganathan et al. 2020). Calcium is a necessary element for bone mineralization, cell signaling, and homeostasis. Calcium intake in India's rural and urban populations is much lower than the daily amount recommended for healthy adults. One long-term strategy to combat calcium deficiency in underdeveloped nations is to supplement diets with millet-based foods that are high in calcium instead of cereals that are high in carbohydrates. When families cannot afford enough milk and milk products or when people are lactose sensitive, finger millet grains can serve as an effective calcium dietary supplement. Aside from finger millet, pearl millet, foxtail millet, kodo millet, and barnyard millet are excellent calcium sources. Phosphorus is abundant in millet grains and is necessary for the synthesis of ATP molecules that supply energy during several metabolic pathways (Harinarayan et al. 2007). Pearls, fingers, and foxtail millet are excellent sources of phosphorus. A major malnutrition issue that affects approximately 2.36 billion people worldwide is anemia caused by iron deficiency. According to (Renganathan et al. 2020), approximately 89 million anemic children under the age of five are found in India. Excellent sources of iron include pearls, proso, barnyards, and finger millet. One sustainable and effective method to lower the risk of micronutrient-related illnesses, including anemia, is the biofortification of staple foods with iron-rich millet. For example, pearl millet, which is the greatest source of iron among millets, may be a dietary supplement to combat iron deficiency (Finkelstein et al. 2015). Zn is another essential element for maintaining good health. It plays a crucial role in the biosynthesis and metabolism of vital proteins, lipids, and nucleic acids, which are crucial for maintaining reproductive functions, boosting immunity, healing wounds, and other complementary actions in the human body (Maxfield et al. 2022). In developing countries, zinc deficiency negatively affects children, adolescent girls, and pregnant women. Almost all millets, including proso, finger, foxtail, and pearl millet, have high zinc concentrations, which are essential for sustaining the body's regular physiological processes (Shankaramurthy and Somannavar 2019). Mg is an additional vital component that supports metabolic and physiological functions. According to studies (Chauhan et al. 2018), adequate dietary magnesium consumption lowers the risk of heart attack, atherosclerosis, respiratory issues, and migraine. Kodo millet has the highest concentration of magnesium among the millets (147 mg/100 g), followed by finger millet (137 mg/100 g), and little millet (133 mg/100 g) (Farzana et al. 2022). The B vitamins thiamine, riboflavin, niacin, and folic acid are also abundant in millets and are used for healthy brain function, including energy production, nucleic acid synthesis, and the synthesis of certain neurochemicals (Sarita and Singh 2016). Little millet, pearl millet, and foxtail millet have very high concentrations of important vitamins. Pearl millet, sorghum, and kodo millet are good sources of folic acid, which is essential for pregnant women. Sorghum, finger millet, little millet, pearl millet, and kodo millet have folate contents of 39.42, 36.11, 34.66, 36.20, and 39.49 g/100 g, respectively compared to 9.32 g/100 g for milled rice (Malik et al. 2023). A healthy diet rich in folic acid lowers the risk of anemia, neurological abnormalities, and cardiovascular disease. Millet often contains a substantial number of essential vitamins and minerals that can aid in reducing deficiency disorders, thus contributing to the alleviation of malnutrition.

Nutraceutical properties of different millets

Barnyard millet

It contains a high amount of both soluble and insoluble dietary fiber, easy-to-digest protein, and perhaps the most significant micronutrients, including iron (Fe) and zinc (Zn), which are associated with a number of positive health effects. Due to its low and slowly digesting carbohydrate content, barnyard millet is a natural gift for today's inactive human population. Oleic, palmitic, and linoleic acids are the most prevalent fatty acids (Renganathan et al. 2020). Additionally, it exhibits considerable oxidative degradation of amylase, which encourages the production of more resistant starches. The phenolic compounds in millet are listed in Table 2. Barnyard millet is effective in treating biliousness, constipation, and allergic conditions, such as atopic dermatitis (Kumari et al. 2021). It can potentially be advised for individuals with cardiovascular disease and diabetes mellitus because it is most effective at decreasing blood glucose and cholesterol levels. Additionally, it is believed to be excellent at preventing cancer, anti-inflammatory, antibacterial, and capable of healing wounds (Bhatt et al. 2022). Barnyard millet has a high iron concentration, which makes it beneficial for pregnant women with anemia.

Finger millet

Finger millet is an important millet crop for feed and fodder. It is an excellent source of protein, fiber, calcium, iron, and other minerals, and is a gluten-free cereal. Finger millet is thought to be a great source of fiber, which is used to prevent constipation and act as a laxative. A finger millet-based diet has been suggested for people with diabetes, liver disease, asthma, heart issues, excessive blood pressure, and other issues (Devi et al. 2014). It consists of low fat content, probably due to the presence of unsaturated fatty acids. It can help fight the high prevalence of anemia due to its high calcium and iron content. Its seed coat contains an enormous quantity of phytochemicals, dietary fiber, polyphenols, and micronutrients, particularly calcium (SK and Sudha 2012). The seed coat of millet has anti-cancer and anti-diabetic properties owing to its high polyphenol content. Finger millet grains are preferred by children, pregnant women, and nursing women and contain essential amino acids such as methionine, tryptophan, and lysine. The whole grain of finger millet has hypoglycemic and hypocholesterolemic properties, as well as antitumorogenic, antidiarrheal, anti-inflammatory, atherosclerogenic, anti-microbial, and antiulcerative capabilities (Thapliyal and Singh 2015). It is also beneficial for preserving youthful skin. Finger millet is a dynamic crop with many important uses in sustainable farming, food security, and human health. As the demand for food increases, finger millet is likely to play a larger role in feeding people globally.

Pearl millet

Compared to other common cereals, it is a healthier and wonderful source of calories, carbohydrates, crude fiber, soluble and insoluble fiber, proteins (8–19%), antioxidants, and fat (3–8%), with enhanced intestinal absorption

(Nambiar et al. 2011). Additionally, it contains a lot of minerals (2.3 mg/100 g), including potassium, phosphorus, magnesium, iron, zinc, copper, and manganese, and vitamins like thiamine, riboflavin, and niacin. Niacin in grains provides the ability to decrease cholesterol. It is an extremely nourishing food that is non-acid-forming, non-glutinous, high in fiber, and contains a number of nutraceuticals. Phytates, polyphenols, and other substances increase the antioxidant activity (Malik 2015). Pearl millet is used to treat gallstones, migraines, and respiratory problems. It has anti-inflammatory, anti-cancer, anti-diabetic, and antioxidant properties (Gupta et al. 2022). Pearl millet has anti-allergic and anti-ulcerative properties that are used to increase hemoglobin levels, constipation-relieving, weight loss, bone growth and development, protection against cardiovascular illnesses, control of blood pressure, and celiac disease (Gupta et al. 2022).

Foxtail millet

Foxtail millet is a rich source of carbohydrates, dietary fiber, proteins, vitamins, and minerals. Foxtail millet contains high amounts of iron, beta-carotene, a precursor of vitamin A, and other nutrients (Sharma and Niranjan 2018). Because it has a low glycemic index, it is used to make a dessert called burfi, which is an excellent dish for patients with diabetes. Yellow-seeded foxtail cultivars have medicinal applications such as stomachics, astringents, digestive aids, and emollients. In addition, it is used to treat dyspepsia, poor digestion, and abdominal food stagnation. White seeds are used to treat cholera and fever, whereas green seeds are used as diuretics that increase masculinity. In India, foxtail millet is frequently made into porridge, used to produce rotis, and is utilized in a variety of dishes. Additionally, it is used to produce rawa, bread, and puffy snacks (Sadygova et al. 2019).

Foxtail millet has several health benefits, including the prevention of cancer, hypoglycemic and hypolipidemic effects, treatment of dementia, maintenance of cholesterol levels, antiproliferative activity, antilipidemic activity, reduction of inflammation, anti-aging, improvement of overall digestive health, improvement of kidney functionality, and assistance in the development of body tissue and energy metabolism (Andersen and Nepal 2017).

Proso millet

Proso is composed of many vitamins and minerals including copper and magnesium. In addition, it improves the glycemic responses and plasma levels. Proso millet contains abundant lecithin, which benefits the nervous system. It contains many essential amino acids, including methionine and cysteine, as well as B-complex vitamins, folic acid, P, Ca, Zn, and Fe (Kalinová 2007). It has a low glycemic index and reduces the incidence of type 2 diabetes mellitus. Proso millet could potentially be beneficial in preventing cancer, heart disease, diabetes, and liver disease. This millet has a low glycemic index and is useful in the treatment of type 2 diabetes and cardiovascular diseases. It aids in lowering cholesterol and high blood pressure levels, as well as in the prevention of cancer, heart disease, obesity, liver damage, and celiac disease. Additionally, it slows the aging process and provides protection from degenerative disorders that develop with age (Kalinová 2007).

Little millet

It is a refreshing millet that is suitable for people of all ages. Its high fiber content helps to prevent the buildup of body fat. It is especially beneficial for diabetics, whose blood glucose levels frequently increase (postprandial) after consuming other grains, especially rice and wheat. It helps avoid constipation and addresses all stomach-related disorders (Guha et al. 2015). It is also advantageous for women who struggle with irregular menstrual cycles. Increased consumption of millet also lowers the body mass index (BMI). It is an excellent source of antioxidants like polyphenols, phenolic compounds, tannins, and flavonoids which are crucial for preserving health and preventing diseases like diabetes, heart disease, and obesity that are linked to sedentary lifestyles. These antioxidants greatly decrease low-density lipoprotein (LDL) cholesterol levels, which can clog arteries and increase the risk of heart attack and other heart problems. It also contains a considerable amount of bioactive nutraceutical ingredients, such as phenols, carotenoids, and tocopherols, which are crucial for maintaining optimal health, delaying aging, and treating metabolic disorders. Additionally, it helps in the treatment of common gastrointestinal problems such as flatulence, bloating, constipation, and irregular bowel movements. Furthermore, they support the overall health of the body's internal organs (Rani et al. 2017).

Kodo millet

Kodo millet is excellent for strengthening the nervous system and contains high levels of calcium, iron, potassium, magnesium, zinc, niacin, pyridoxine, and folic acid (Bunkar et al. 2021). Daily consumption of kodo millet may be extremely beneficial for postmenopausal women with heart disease symptoms, including high blood pressure and cholesterol levels. Kodo millet has a wide range of positive health effects, including anti-diabetic, anti-oxidant, anti-microbial, anti-obesity, anti-cholesterol, anti-mutagenic, anti-oestrogenic, anti-carcinogenic, anti-inflammatory, anti-hypertension, and antiviral activities. It is effective in treating heart attacks, atherosclerosis, migraines, blood pressure, aging, and asthma (Deshpande et al. 2015).

Sorghum

Sorghum is a grain that contains polysaccharides such as carbohydrates, proteins, lipids, vitamins, fiber, and minerals, making it rich in nutrients for human health and nutrition (Nani and Krishnaswamy 2021). Kafirins are the primary prolamins of sorghum proteins. Among these minerals, phosphorus, potassium, and zinc constitute the majority of sorghum. Sorghum is rich in phytochemicals such as phytosterols, policosanols, and phenolic compounds, which are beneficial to the body. Sorghum is popular among obese and diabetic individuals because it contains a resistant starch. Sorghum can be beneficial in treating diseases, such as obesity, diabetes, celiac disease, dyslipidemia, cardiovascular disease, cancer, heart disorders, maintenance of cholesterol levels, bone health, hypertension, and anemia. The grain also has antioxidant, anti-inflammatory, antibacterial, antithrombotic, and anticancer properties (Kane-Potaka et al. 2021).

Table 2: Phytochemical content of millets and its properties.

S. No.	Phytochem-icals	Source	Examples	Properties
1a	Phenolic acids	Seed coat/ bran layers	Hydroxycinnamic acids—protocatechuric acid and vanillic acid Hydroxybenzoic acids—ferulicacid, caffeic, coumaric acid, and sinapic acid	Antioxidant, anti-fibrotic, antiviral, anti-atherosclerotic, antibacterial, antiaging, anticancer
1b	Flavonoids	Seed/ seed coat	Quercetin, Catechin and its derivatives (Gallocatechin, Epicatechin, and Epigallocatechin), vitexin, tricin, luteolin, myricetin	Antioxidant, anti-inflammatory, antimutagenic effects, antiaging as well as cardiovascular disease-preventive properties

1c	Condensed tannins	Seed coat of brown finger millets	Polymers of flavan-3-ols	Anticancer, anti-ulcer, gastroprotective, and hypocholesteraemic properties, avoiding UTI
2	Carotenoids	Seed/ seed coat	β-Carotene, lutein, zeaxanthine	Antioxidant
3	Phytosterols	Bran layers	β-Sitosterol, campesterol, stigmasterol	Cardiovascular disease-preventive properties
4	Bioactive peptides	Total protein	Specific peptide sequences	Antioxidant, antihypersensitive, immunomodulatory, antidiabetic, anticarcinogenic

Environmental sustainability of important millets

In addition to their health benefits, millets are environmentally beneficial because they are pest-resistant, tolerant of a wide range of climates and moisture levels, and require only a small amount of synthetic fertilizer to thrive. Because they only require a small amount of moisture for growth, they can even survive in areas that are prone to drought. Millets are C4 carbon sequestering plants that assist in reducing atmospheric CO_2 levels, in addition to being water efficient. Millets are a reliable and sustainable source of income for small and marginal farmers because of the small investment required for their production (Sharmili et al. 2021).

Millets are a significant crop with an extensive history that is renowned for its resilience in times of adversity, minimal input needs, and high nutritional content. They are essential for environmental sustainability and food security. One of the earliest foods consumed by humans was millet, which may have been the first cereal grain to be domesticated for use in households. Small-seeded millets are drought-tolerant grasses that thrive in arid environments with poor soil fertility and water availability (Yang et al. 2022). Millets stand out, in part, because of their short growth seasons.

With rising agricultural costs, climate change, and a growing global population, millet is known to have significant promise for food and nutritional security. Millets are appropriate for use in both rain-fed and desert environments because they thrive in a variety of agroclimatic zones. Millets are suitable for cultivation in regions with water constraints, because they can resist drought and require little rainfall. They also require minimal amounts of synthetic fertilizers and pesticides and are highly resistant to insects, pests, and diseases. In addition, their capacity to thrive in less-than-ideal soil types may make them a tempting option for small-scale farmers who lack access to high-quality input and fertile land. Millets are versatile crops that can be used in various ways to support sustainable agriculture, human nutrition, and health (Pandey and Bolia 2023). Millets will probably take on greater significance as the world's population grows and more people become dependent on the food source.

Sorghum

Sorghum frequently has lower production costs than other significant cereal crops such as maize, including the cost of fertilizer, seeds, chemicals, and land rent, and generates more net revenue. Sorghum probably surpassed maize because of its effective water usage and high harvest index under water stress (Maitra and Duvvada 2020). It requires less water, which makes the effective use of marginal lands and expands the farmer's income at a lower production cost.

Pearl millet

It is especially advantageous because it has significant potential to generate better economic returns under challenging conditions and is nutrient-rich and climate-resilient. It is a popular crop farmed over 30 million hectares of land in the dry and semi-arid tropical regions of Asia and Africa, where 90 million people live in poverty and provide staple food. India generated 9.22 million metric tons of pearl millet over a land area of 7.55 million hectares. Haryana, Madhya Pradesh, and Tamil Nadu were the top three producers of pearl millet. Pearl millet is mostly grown in arid, salty, and hot climates because of its intrinsic capacity to endure conditions with inconsistent and erratic rainfall patterns (Dube et al. 2021). It also provides various advantages, including rapid growth, drought resilience, low input requirements, and a general absence of biotic and abiotic restrictions.

Finger millet

Finger millet is a vital crop for farmers in arid and semi-arid regions owing to its high drought tolerance and capacity to flourish under challenging conditions. This requires less pesticides and fertilizers. This is an advantage for immense deserts because they can grow on low-fertility soils and do ot require synthetic fertilizers. It can withstand storage pests for up to 10 years, providing year-round food security or even in an instance of crop failure (Maitra et al. 2020b). The main states producing finger millet are Gujarat, Karnataka, Uttarakhand, Maharashtra, Tamil Nadu, Odisha, and Andhra Pradesh.

Little millet

Little millet initially originated in Southeast Asia, although it has now grown across India, particularly in Madhya Pradesh, Orissa, Jharkhand, and Uttar Pradesh. This quick-growing crop has a short lifespan and can withstand both drought and water. Marginal lands and tribal areas are mainly used for cultivation (Guha et al. 2015).

Foxtail millet

The second-most produced millet in the world is foxtail millet, which provides six million metric tons of food to millions of people. It grows largely on marginal or depleted soils in temperate, subtropical, and tropical Asia and southern Europe. Foxtail millets continue to play an important role in global agriculture. The cultivation of foxtail millet is also said to be environmentally friendly because it requires less water and fertilizer than other crops, making it an ideal crop for sustainable farming and fighting against climate change. Even though foxtail millet has moderate drought tolerance, because of its early maturity, droughts may occasionally not affect it. Owing to its rapid growth, it is suitable for cultivation as a catch crop for a limited time (Maitra et al. 2020a). It is an adaptable crop that can flourish in a variety of soil types and can withstand challenging weather patterns, such as drought and extreme heat. Public and corporate organizations are promoting foxtail millet as a superior nutrient-dense option to other major grains such as rice and wheat to improve nutrition and food security, particularly in rural and water-stressed areas.

Proso millet

The crop proso millet has limited requirements and no reported diseases that can harm its growth. Proso millet is an excellent intercrop between two crops that requires a lot of water and herbicides because of its shallow root system and tolerance to atrazine residues. Proso millet grows most effectively in warm climates. Owing to its high level of drought resilience, it can be grown in areas with low rainfall. It can handle a specific volume of stagnant water. Proso millet is a distinctive crop that has a brief growing season and can withstand dryness, making it a viable rotational crop in semi-arid locations (Yuan et al. 2021). The soil types can range in texture from sandy loam to clay loam, although coarse sand should not be used.

Kodo millet

Kodo millet is widely cultivated in humid areas throughout the tropical and subtropical regions of the world. Owing to its high drought resistance, it can be grown in areas with erratic and infrequent rainfall. Key crops promote environmental sustainability and human well-being. Owing to its versatility, low input needs, and high nutritional content, it is an essential source of food for populations worldwide (Vetriventhan and Upadhyaya 2019).

Barnyard millet

Barnyard millet is a widespread crop that has been grown for many years in Asia, particularly in India, China, Japan, and Korea. It is the fourth most extensively cultivated millet, providing food security to many poor people worldwide. It is a short-lived crop that can survive in unfavorable environmental conditions with minimal maintenance, while tolerating a variety of biotic and abiotic stressors. When the monsoon season fails in areas where rice and other important crops are cultivated, it provides a great alternative and supplemental crop for impoverished farmers (Maithani et al. 2023). Despite the enormous nutritional and agronomic advantages of barnyard millet, this crop is underappreciated because of ignorance.

Browntop Millet

Small-seeded annual grass, known as browntop millet, is grown as a grain crop, especially in dry subtropical and tropical soils. They can be produced in damaged soils with very little water. Additionally, it is used as a cover crop in plantation groves to reduce soil erosion and boost straw production. It is grown between commodity crops as an optional crop that has a rapid growth rate. Owing to its ability to store significant amounts of Zn and Pb in the root and stem tissues, it is essential for the removal of pollutants from polluted soils (Maitra 2020). Therefore, browntop millet has a lot of potential for lowering hunger, enhancing nutrition, and achieving sustainability goals.

Conclusions

Malnutrition is an important national and international health challenge. In many nations, under- and overnutrition exist simultaneously. India has one of the highest malnutrition rates worldwide. In light of pervasive malnutrition and climatic fluctuations, there is an imminent need to expand food grain production. Millet crops are among the most cost-effective alternative. Millets are a rich source of multiple vital nutrients compared with polished and refined wheat. Millets contain a significant amount of dietary fiber and phytochemicals, which may have a preventative effect on a number of degenerative diseases, including obesity, type 2 diabetes, cardiovascular disease, and cancer. It is important to commercialize millet food products and increase the public's understanding of the benefits of including millet in one's diet through nutrition education. As a result, including millet in the diet, both traditionally and via the use of novel food products, can have a number of positive effects on preserving an individual's health and nutrition. The potential of millet to address issues related to nutrition, food security, and sustainable agriculture is highlighted. Millets are resistant to drought, and nutritious crops have several advantages, from encouraging biodiversity to boosting environmentally friendly agriculture. However, millets continue to face difficulties in marketing, processing, and cultural acceptance. To overcome these obstacles, technology, effective promotional techniques, regulations, and international collaboration can be very important. Future strategies are needed to emphasize promoting millets as environmentally conscious agricultural products, expanding access to improved varieties, stimulating international scientific and technological collaboration, and providing favorable circumstances for processing and marketing. Therefore, millet may greatly contribute to long-term nutrition and food security.

References

Abbas, M. A., Taha, M. O., Zihlif, M. A., & Disi, A. M. (2013). β-Caryophyllene causes regression of endometrial implants in a rat model of endometriosis without affecting fertility. European Journal of Pharmacology. 702, 12–19.

Abedin, M. J., Abdullah, A. T. M., Satter, M. A., & Farzana, T. (2022). Physical, functional, nutritional and antioxidant properties of foxtail millet in Bangladesh. Heliyon. 8, e11186.

Ahirwar, R., and Mondal, P. R. (2019). Prevalence of obesity in India: A systematic review. Diabetes & Metabolic Syndrome: Clinical Research & Reviews. 13, 318–321.

Allai, F. M., Azad, Z., Gul, K., & Dar, B. N. (2022). Wholegrains: A review on the amino acid profile, mineral content, physicochemical, bioactive composition and health benefits. International Journal of Food Science & Technology. 57, 1849–1865.

Andersen, E. J., and Nepal, M. P. (2017). Genetic diversity of disease resistance genes in foxtail millet (Setaria italica L.). Plant Gene. 10, 8–16.

Bhandari, S., and Banjara, M. R. (2015). Micronutrients deficiency, a hidden hunger in Nepal: prevalence, causes, consequences, and solutions. International Scholarly Research Notices. 2015.

Bhatt, D., Rasane, P., Singh, J., Kaur, S., Fairos, M., Kaur, J., Gunjal, M., Mahato, D. K., Mehta, C., Avinashe, H., and others. (2022). Nutritional advantages of barnyard millet and opportunities for its processing as value-added foods. Journal of Food Science and Technology. 1–13.

Bunkar, D. S., Goyal, S. K., Meena, K. K., & Kamalvanshi, V. (2021). Nutritional, functional role of kodo millet and its processing: a review. International Journal of Current Microbiology and Applied Sciences. 10, 1972–1985.

Chauhan, M., Sonawane, S. K., Arya, S. S., and others. (2018). Nutritional and nutraceutical properties of millets: a review. Clinical Journal of Nutrition and Dietetics. 1, 1–10.

Deshpande, S. S., Mohapatra, D., Tripathi, M. K., and Sadvatha, R. H. (2015). Kodo millet-nutritional value and utilization in Indian foods. Journal of Grain Processing and Storage. 2, 16–23.

Devi, P. B., Vijayabharathi, R., Sathyabama, S., Malleshi, N. G., & Priyadarisini, V. B. (2014). Health benefits of finger millet (Eleusine coracana L.) polyphenols and dietary fiber: a review. Journal of Food Science and Technology. 51, 1021–1040.

Finkelstein, J. L., Mehta, S., Udipi, S. A., Ghugre, P. S., Luna, S., Wenger, M. J., Murray-Kolb, L. E., Przybyszewski, E. M., & Haas, J. D. (2015). A randomized trial of iron-biofortified pearl millet in school children in India. The Journal of Nutrition. 145, 1576–1581.

Guha, M., Sreerama, Y. N., and Malleshi, N. G. (2015). Influence of processing on nutraceuticals of little millet (Panicum sumatrense). In Processing and impact on active components in food. 353–360.

Gupta, V., Singh, A. P., and Gupta, N. (2022). Importance of pearl millet and its health benefits. Just Agriculture E-Magazine. 2, 2582–8223.

Harding, K. L., Aguayo, V. M., & Webb, P. (2018). Hidden hunger in South Asia: a review of recent trends and persistent challenges. Public Health Nutrition. 21, 785–795.

Harinarayan, C., Ramalakshmi, T., Prasad, U., Sudhakar, D., Srinivasarao, P. V. L. N., Sarma, K. V. S., & Kumar, E. G. T. (2007). High prevalence of low dietary calcium, high phytate consumption, and vitamin D deficiency in healthy south Indians. The American Journal of Clinical Nutrition. 85, 1062–1067.

Hwalla, N., Labban, S., and Bahn, R. A. (2016). Nutrition security is an integral component of food security. Frontiers in Life Science. 9, 167–172.

Kalinová, J. (2007). Nutritionally important components of proso millet (Panicum miliaceum L.). Food. 1, 91–100.

Kane-Potaka, J., Anitha, S., Tsusaka, T. W., Botha, R., Budumuru, M., Upadhyay, S., Kumar, P., Mallesh, K., Hunasgi, R., Jalagam, A. K., & others. (2021). Assessing millets and sorghum consumption behavior in urban India: A large-scale survey. Frontiers in Sustainable Food Systems. 5, 680777.

Konapur, A., Gavaravarapur, S. R. M., Gupta, S., and Nair, K. M. (2014). Millets in meeting nutrition security: issues and way forward for India. Indian J. Nutr. Diet. 51, 306–321.

Kumar, S. R., Sadiq, M. B., and Anal, A. K. (2020). Comparative study of physicochemical and functional properties of pan and microwave cooked underutilized millets (proso and little). Lwt. 128, 109465.

Kumari, P., Kajla, P., and Kaushik, D. (2021). Barnyard Millet—Composition, Properties, Health Benefits, and Food Applications. In Handbook of Cereals, Pulses, Roots and Tubers. 149–156.

Li, W., Gao, J., Saleh, A. S. M., Tian, X., Wang, P., Jiang, H., and Zhang, G. (2018). The modifications in physicochemical and functional properties of proso millet starch after Ultra-High pressure (UHP) process. Starch-Stärke. 70, 1700235.

Lokeswari, R., Sharanyakanth, P. S., Jaspin, S., and and Mahendran, R. (2021). Cold Plasma Effects on Changes in Physical, Nutritional, Hydration, and Pasting Properties of Pearl Millet (Pennisetum Glaucum). IEEE Transactions on Plasma Science. 49, 1745–1751.

Luhar, S., Timæus, I. M., Jones, R., Cunningham, S., Patel, S. A., Kinra, S., Clarke, L., and Houben, R. (2020). Forecasting the prevalence of overweight and obesity in India to 2040. PloS One. 15, e0229438.

Maithani, D., Sharma, A., Gangola, S., Bhatt, P., Bhandari, G., and Dasila, H. (2023). Barnyard millet (Echinochloa spp.): a climate resilient multipurpose crop. Vegetos. 36, 294–308.

Maitra, S. (2020). Potential horizon of brown-top millet cultivation in drylands: A review. Crop Research. 55, 57–63.

Maitra, S., and Duvvada, S. K. (2020). Sorghum-based intercropping system for agricultural sustainability. Indian Journal of Natural Sciences. 10, 20306–20313.

Maitra, S., Pine, S., Shankar, T., Pal, A., and Pramanick, B. (2020). Agronomic management of foxtail millet (Setaria italica L.) in India for production sustainability: A review. International Journal of Bioresource Science. 7, 11–16.

Maitra, S., Reddy, M. D., and Nanda, S. P. (2020). Nutrient management in finger millet (Eleusine coracana L. Gaertn) in India. International Journal of Agriculture, Environment and Biotechnology. 13, 13–21.

Malik, S. (2015). Pearl millet-nutritional value and medicinal uses. International Journal of Advance Research and Innovative Ideas in Education. 1, 414–418.

Malik, S., Bayati, M. B., Lin, C.-H., and Krishnaswamy, K. (2023). Sustainable processing of Greek yogurt acid-whey waste to develop folic acid encapsulated millet powders. Sustainable Food Technology. 1, 437–454.

Nambiar, V. S., Dhaduk, J. J., Sareen, N., Shahu, T., & Desai, R. (2011). Potential functional implications of pearl millet (Pennisetum glaucum) in health and disease. Journal of Applied Pharmaceutical Science. 62–67.

Nani, M., and Krishnaswamy, K. (2021). Physical and functional properties of ancient grains and flours and their potential contribution to sustainable food processing. International Journal of Food Properties. 24, 1529–1547.

Pandey, A., and Bolia, N. B. (2023). Millet value chain revolution for sustainability: A proposal for India. Socio-Economic Planning Sciences. 101592.

Ramakrishnan, S. R., Antony, U., and Kim, S. J. (2022). Non-thermal process technologies: Influences on nutritional and storage characteristics of millets. Journal of Food Process Engineering, November. 1–13.

Rani, Y. S., Triveni, U., and Patro, T. (2017). Integrated Nutrient Management for Enhancing the Soil Health, Yield and Quality of Little Millet (Panicum sumatrense). International Journal of Bio-Resource and Stress Management. 8, 26–32.

Renganathan, V. G., Vanniarajan, C., Karthikeyan, A., and Ramalingam, J. (2020). Barnyard millet for food and nutritional security: current status and future research direction. Frontiers in Genetics. 11, 500.

Sadygova, M. K., Anikienko, T. I., Bashinskaya, O. S., Kondrashova, A., and Kuznetsova,

L. I. (2019). Foxtail millet (panicum italicum) as a perspective raw material for the production of healthy products. Ernahrung. 43, 51–58.

Saleh, A. S. M., Zhang, Q., Chen, J., and Shen, Q. (2013). Millet grains: nutritional quality, processing, and potential health benefits. Comprehensive Reviews in Food Science and Food Safety. 12, 281–295.

Sarita, E. S., and Singh, E. (2016). Potential of millets: nutrients composition and health benefits. Journal of Scientific and Innovative Research. 5, 46–50.

Shankaramurthy, K. N., and Somannavar, M. S. (2019). Moisture, carbohydrate, protein, fat, calcium, and zinc content in finger, foxtail, pearl, and proso millets. Indian Journal of Health Sciences and Biomedical Research Kleu. 12, 228–232.

Sharma, N., and Niranjan, K. (2018). Foxtail millet: Properties, processing, health benefits, and uses. Food Reviews International. 34, 329–363.

Sharma, R., Sharma, S., Dar, B. N., and Singh, B. (2021). Millets as potential nutri-cereals: a review of nutrient composition, phytochemical profile and techno-functionality. International Journal of Food Science & Technology. 56, 3703–3718.

Sharmili, K., Yasodha, M., Rajesh, P., Rajendran, K., Thankappan, S., and Minithra, R. (2021). Millet and pulse-based intercropping system for agricultural sustainability-A review. Crop Research. 56, 369–378.

Singh, M., Prasad, C. P., Singh, T. D., and Kumar, L. (2018). Cancer research in India: Challenges & opportunities. The Indian Journal of Medical Research. 148, 362.

SK, M., and Sudha, K. (2012). Functional and phytochemical properties of finger millet (Eleusine coracana L.) for health. International Journal of Pharmaceutical, Chemical and Biology Sciences. 2, 431–438.

Striessnig, E., and Bora, J. K. (2020). Under-five child growth and nutrition status: spatial clustering of Indian districts. Spatial Demography. 8, 63–84.

Thapliyal, V., and Singh, K. (2015). Finger millet: potential millet for food security and powerhouse of nutrients. International or Research in Agriculture and Forestry. 2.

Tripathy, J. P., Thakur, J. S., Jeet, G., Chawla, S., Jain, S., Pal, A., Prasad, R., and Saran, R. (2017). Prevalence and risk factors of diabetes in a large community-based study in North India: results from a STEPS survey in Punjab, India. Diabetology & Metabolic Syndrome. 9, 1–8.

Vetriventhan, M., and Upadhyaya, H. D. (2019). Variability for productivity and nutritional traits in germplasm of kodo millet, an underutilized nutrient-rich climate smart crop. Crop Science. 59, 1095–1106.

Yang, J., Zhang, D., Yang, X., Wang, W., Perry, L., Fuller, D. Q., Li, H., Wang, J., Ren, L., Xia, H., and others. (2022). Sustainable intensification of millet--pig agriculture in Neolithic North China. Nature Sustainability. 5, 780–786.

Yuan, Y., Liu, C., Gao, Y., Ma, Q., Yang, Q., and Feng, B. (2021). Proso millet (Panicum miliaceum L.): A potential crop to meet demand scenario for sustainable saline agriculture. Journal of Environmental Management. 296, 113216.

An Analysis of Yield and Related Traits in Pearl Millet Hybrids Released for Cultivation in India

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Abstract

Pearl millet is one of the important millets cultivated in India. In pearl millet, more than 167 hybrids are released for cultivation in India. Though, yield and related traits are well known in pearl millet hybrids, the relationship between yield and year of release, days to flowering, fodder yield, Fe and Zn content and other related traits are known. In this analysis, we attempted to understand the yield relationship with other traits in pearl millet hybrids. This analysis showed ~ 58 out of 167 pearl millet hybrids were released in the last decade. Further, on an average, four hybrids were released per year in the last five decades. The average yield of pearl millet hybrids was found to be ~3000 kg/ha. The yield increase of the pearl millet hybrids due to breeding approach was found to be 27 kg/ha/year. Besides, every one day increase in days to flowering after 50 days increases the yield of hybrids by 37 kg/ha. Interestingly, the highest coefficient of determination of 0.502 was observed between yield and fodder yield in pearl millet hybrids. Additionally, the mean Fe and Zn content in pearl millet hybrids was found to be ~48 and ~38 ppm, respectively. In general, increase in

yield of hybrids increases the Fe content in pearl millet hybrids. Thus, targeting the fodder yield breeding in pearl millet hybrids has the potential to increase the mean yield by more than 4000 kg/ha.

Keywords : Yield, linear regression, coefficient of determination, Fe and Zn content, fodder yield

Introduction

Pearl millet is one of the important millets cultivated in India. In pearl millet, more than 167 hybrids are released for cultivation in India. Pearl millet is cultivated in an area of about ~ 7 Mha and it is the fourth important food crops in India next to rice, wheat, and maize (AICRP, Pearl Millet; http://www.aicpmip.res.in/). However, the average productivity of pearl millet in India is only 1243 kg/ha. There is an urgent need to improve the yield of pearl millet in India (Yadav and Rai, 2013). Especially, genetic and cytoplasmic diversification of pearl millet hybrids is an important avenues for yield improvement (Yadav et al, 2021). There are several high yielding and disease resistant cultivars are developed in pearl millet in India (Yadav et al, 2012). However, low yield and yield gap are the major concerns of pearl mill hybrids in India (Murty et al, 2007). The details of the pearl millet hybrids and varieties released through AICRP in india is reported by Tara Satyavathi et al (2018). In this analysis, the relationship between yield and other traits were analyzed and summarized.

Methodology

Linear regression analysis was performed using the data analysis option in MS Excel. The data used for the analysis is reported by Tara Satyavathi et al (2018). The data was taken from AICRP on pearl millet.

Pearl millet hybrids released for cultivation

There are more than 167 pearl millet hybrids has been released for cultivation in India. One of the first hybrids were released in the year 1950 with 95 days duration and compact ear heads. Based on the availability of the yield information, 37 hybrids were leased between 1969 and 1990. Further, in the last three decades, >125 pearl millet hybrids were released for cultivation in India (Fig.2). Moreover, most number of hybrids were released in the last decades numbering ~58. In the year 1997, 2012, and 2018, hybrids released for cultivation were 9, 11, and 9, respectively. On an average, 4 hybrids were released per year in the last five decades (Fig. 1 and 2).

Fig.1 Pearl millets hybrids released for cultivation in India from 1969 to 2018.

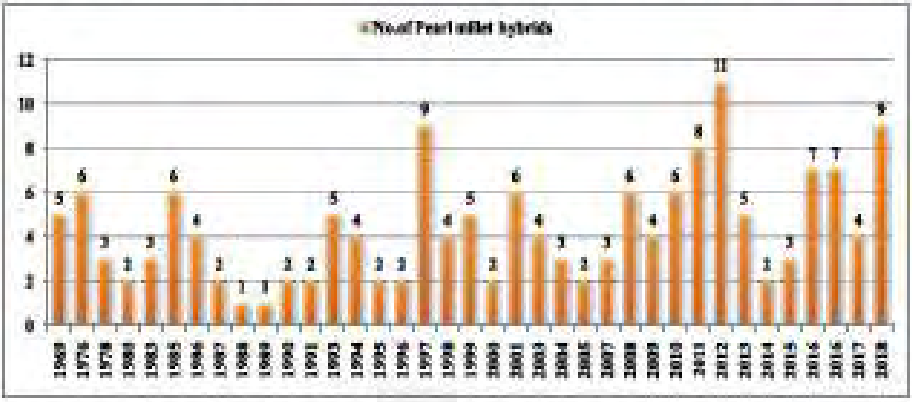
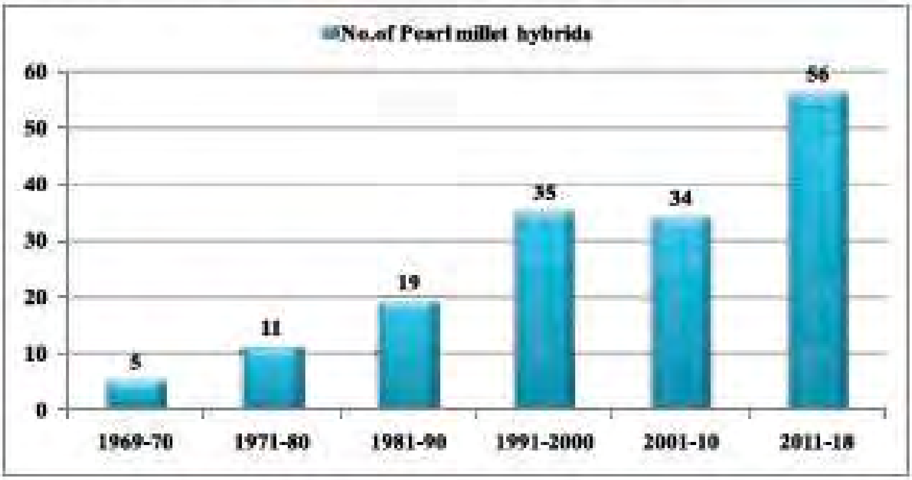


Fig. 2 Decade-wise release of pearl millet hybrids in India



Year of release and yield relationship in pearl millet hybrids

This analysis was performed only from the year 1985 onwards as yield data is available only for the hybrids released during and after 1985. The regression coefficient for year of release and mean yield of pearl millet hybrids is 0.184. The average yield of pearl millet hybrids was found to be ~3000 kg/ha. The yield ranged from 1683 to 5497 kg/ha. Five year analysis showed that the mean yield increased from 2588 kg/ha in 1985-1900 to 3483 kg/ha in 2016-18 with an increase of about 25.68%. The yield increase of the pearl millet hybrids due to breeding approach was found to be 27 kg/ha/year. Further, 19% yield improvement out of 25.68% was achieved in the last two decades in pearl millet hybrids improvement programs (Fig.3a and 3b).

Fig. 3a Relationship between yield and year of release of pearl millet hybrids

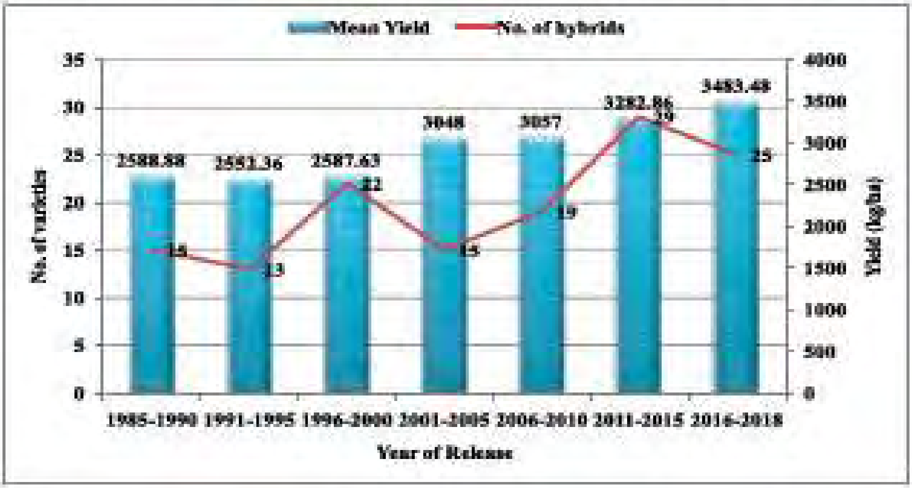
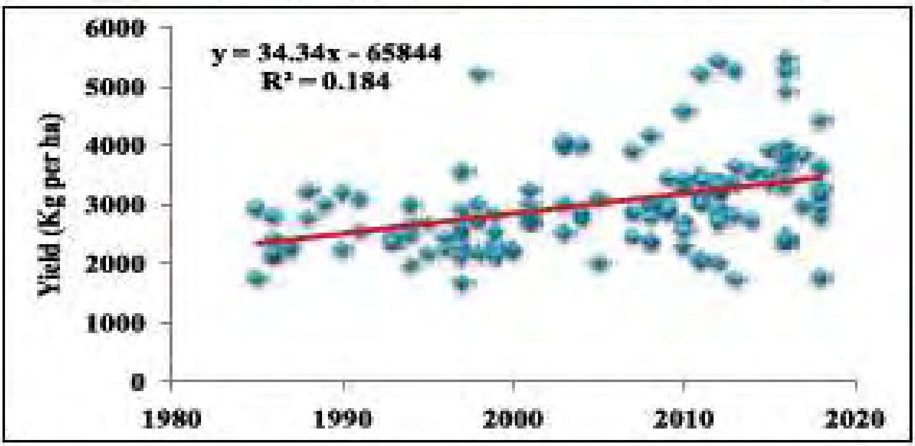


Fig. 3b Relationship between yield and year of release of pearl millet hybrids



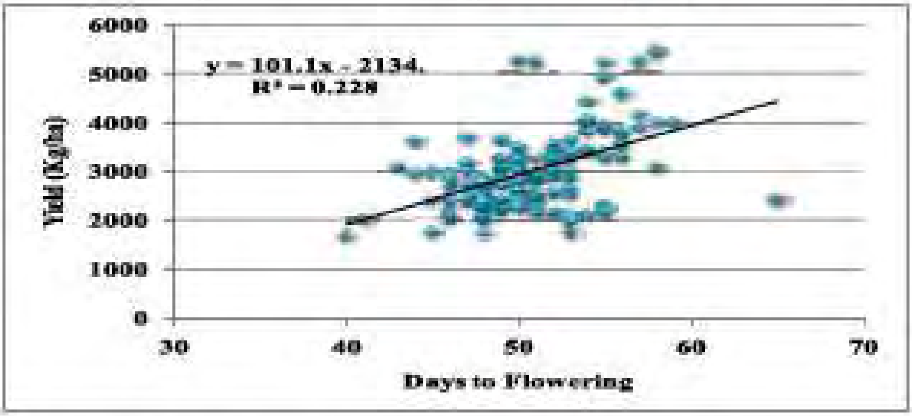
Relationship between yield and days to flowering in pearl millet hybrids

Days to flowering are an important trait in pearl millet hybrids which decides the yield per hectare. The days to flowering in pearl millet ranged from 40 to 65 days. The mean number of days to flowering in pearl millet was found to be 50.81. The mean yield of the hybrids with the days to flowering between 40 and 50 was found to be 2737.64 kg/ha. Similarly, mean yield of hybrids with days to flowering between 51 and 65 was found to be 3263.92 kg/ha. This indicates an increase in the flowering duration of two week significantly increases the yield by 526 kg/ha. This corresponds to every one day increase in days to flowering after 50 days increases the yield of hybrids by 37 kg/ha. The coefficient of determination for yield and days to flowering was found to be 0.228 (Fig. 4).

Relationship between yield and days to maturity in pearl millet hybrids

Days to maturity are also an important trait in pearl millet hybrids which decides the yield per hectare. The days to maturity in pearl millet ranged from 62 to 98 days. The mean number of days to maturity in pearl millet hybrids was found to be 80.96. The mean yield of the hybrids with the days to maturity between 60 and 75 was found to be 2819.75 kg/ha. Similarly, mean yield of hybrids with days to flowering between 76 and 98 was found to be 3028.84 kg/ha. This indicates an increase in the flowering duration of three weeks significantly increases the yield by 209 kg/ha. This corresponds to every one day increase in days to flowering after 75 days increases the yield of hybrids by 9.95 kg/ha. The coefficient of determination for yield and days to flowering was found to be 0.149 (Fig. 5).

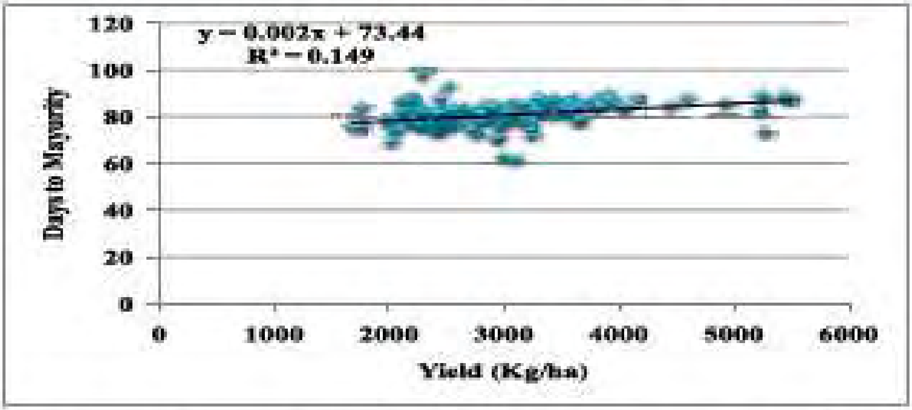
Fig. 4 Relationship between yield and days to flowering of pearl millet hybrids



Relationship between yield and fodder yield in pearl millet hybrids

The mean fodder yield in pearl millet hybrids was found to be 66 q/ha. The range of fodder yield varied from 28 to 117 q/ha. The coefficient of determination between yield and fodder yield was 0.502 indicative of very high R2 value among the traits studied for yield relationship. Interestingly, a perfect correlation exists between the fodder yield and grain yield in pearl millet hybrids. For example, hybrids with fodder yield of > 100 q/ha showed the highest mean grain yield of 4168 kg/ha. This corresponds to the ~1.8 fold increase in the grain yield for 2.75 fold increase in the fodder yield in pearl millet hybrids. Similarly, the highest correlation of determination was also obtained and found to be 0.994 (Fig.6a and 6b).

Fig. 5 Relationship between yield and days to maturity of peal millet hybrids



Relationship between yield and Fe and Zn contents in pearl millet hybrids

The mean Fe content in pearl millet hybrids was found to be 48.28 ppm. The Fe content ranged between 38-77 ppm. The relationship between the Fe content and yield of pearl millet hybrids as the coefficient of determination was found to be 0.075. However, in general an increase in the yield is associated with increase in the Fe (ppm) content in the mille hybrids. For example, 9 hybrids with Fe content between 51 and 60 ppm was found to have the highest mean yield of 3442 kg/ha. However, this data needs to be validated in large number of pearl millet hybrids. The mean Zn content in pearl millet hybrids was found to be 38.33 ppm. The Zn content ranged between 27-48 ppm. The relationship between the Fe content and yield of pearl millet hybrids as the coefficient of determination was found to be 0.018.

Fig. 6 a Relationship between yield and fodder yield of pearl millet hybrids

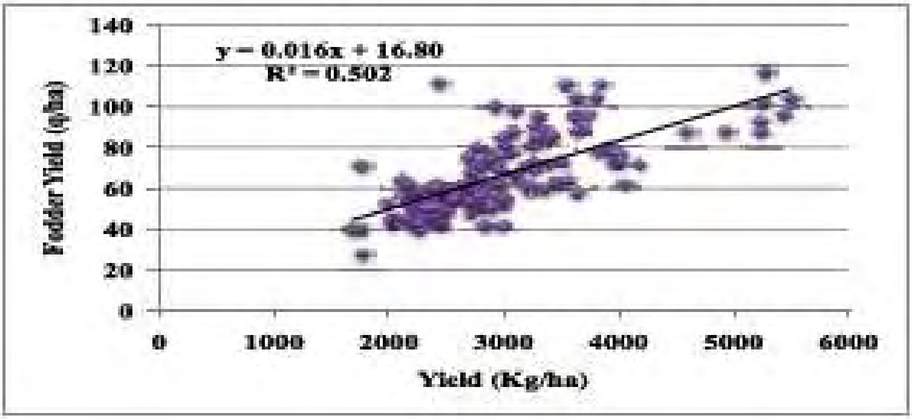


Fig. 6 b Relationship between yield and fodder yield of pearl millet hybrids

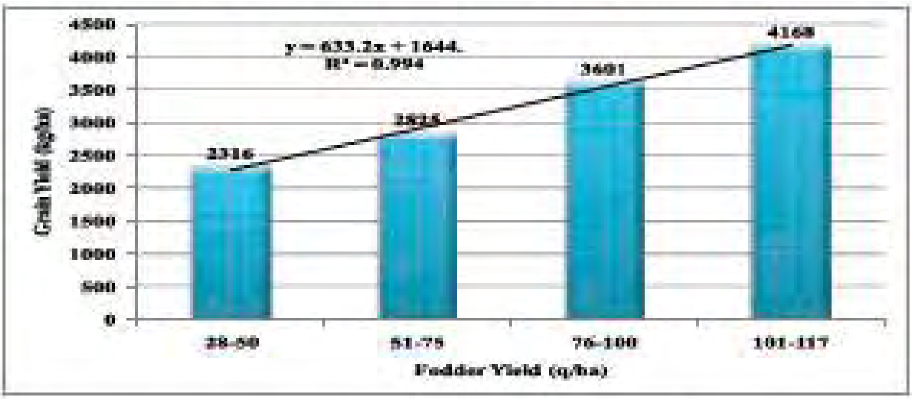


Fig. 7 a Relationship between yield and Fe (ppm) content of pearl millet hybrids

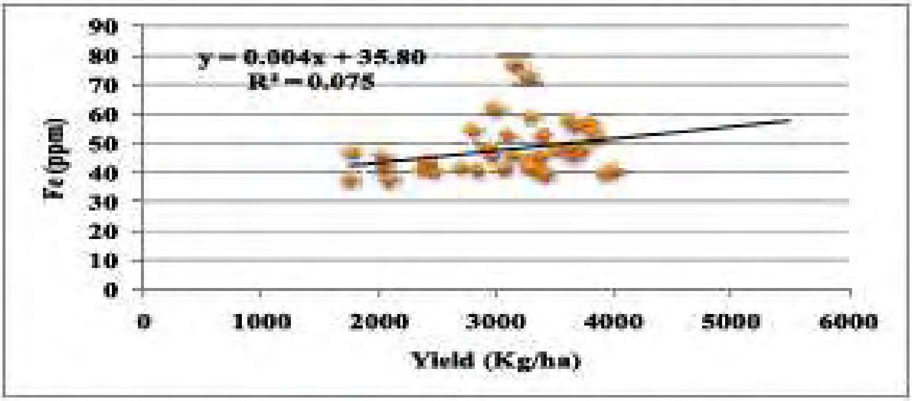


Fig. 7 b Relationship between yield and Fe (ppm) content of pearl millet hybrids

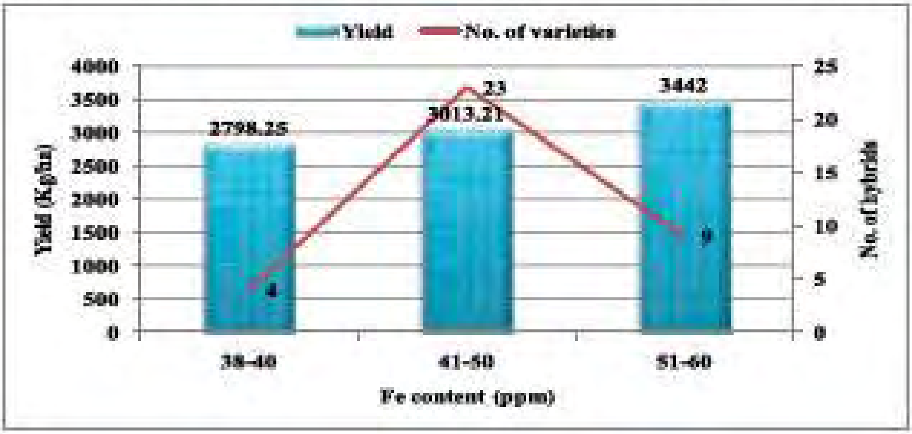
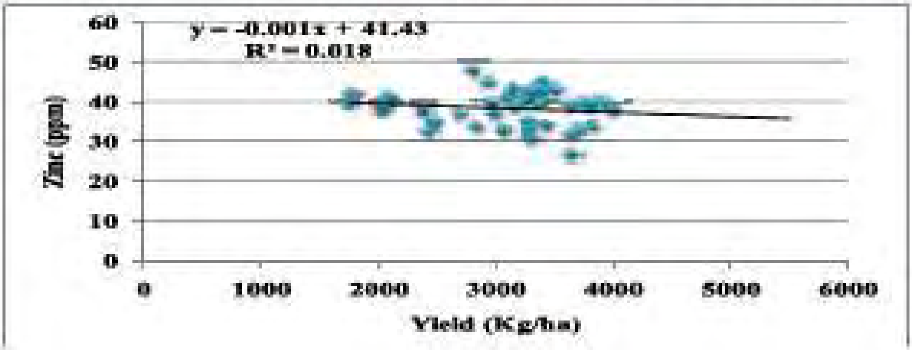


Fig. 8 Relationship between yield and Zn (ppm) content of pearl millet hybrids



Conclusion

In this analysis, few insights have been obtained related to the relationship between the yield and other related traits in pearl millet hybrids. Especially, fodder yield was found to be highly correlated with the grain yield in pearl millet hybrids. This indicates the breeding strategies targeting the source strength would provide higher enhancement in yield of pearl millet hybrids. Further, high Fe content was also found to be positively correlated with the yield of pearl millet hybrids. However, this requires further analysis using large number of datasets. Next to fodder yield, increasing the days to flowering was found to be positively associated with the grain yield of pearl millet hybrids. Thus, increase the source capacity and days to flowering are an important target trait for improvement of yield in pearl millet hybrids. Further, the importance of sink strength relationship to yield may be explored further for the development of ideal pearl millet hybrid with high grain and fodder yield with high Fe and Zn content.

References

Yadav, O. P., and Rai, K. N. (2013). Genetic improvement of pearl millet in India. Agricultural Research, 2, 275-292.

AICRP on pearl millet. http://www.aicpmip.res.in/

Yadav, O. P., Gupta, S. K., Govindaraj, M., Sharma, R., Varshney, R. K., Srivastava, R. K., ... & Mahala, R. S. (2021). Genetic gains in pearl millet in India: insights into historic breeding strategies and future perspective. Frontiers in Plant Science. 12, 396.

Yadav, O. P., Rai, K. N., Rajpurohit, B. S., Hash, C. T., Mahala, R. S., Gupta, S. K., ... & Raghvani, K. L. (2012). Twenty-five years of pearl millet improvement in India. ICAR.

Murty, M. V. R., Singh, P., Wani, S. P., Khairwal, I. S., & Srinivas, K. (2007). Yield gap analysis of sorghum and pearl millet in India using simulation modeling No. 37.

Tara Satyavathi C, Kandelval V and others (2018) Pearl Millet Hybrids and Varieties. ICAR-All India Coordinated Research Project on Pearl Millet, Mandor, Jodhpur, India.142.

Chapter 08

Water management options for higher production and profitability of millet production system

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Abstract

Millets are short duration crops adopted to various ecologies and tolerant to abiotic and biotic stresses thus considered as climate resilient under the scenario of climate change. It is grown as sole crop or as inter crop in uplands, marginal land and well suited for rice fallows, various agroforestry system. Most of the millets are highly nutritious and considered as 'Miracle Grains or Nutri-cereals'. Being climate resilient, millets will play a major role to meet future demands of food and feed, for the growing population and livestock. As water is becoming a scarce natural resource, it is imperative to adopt appropriate water management practices to enhance productivity of millets per drop of water used in production. Better water management in terms of optimum sowing window, appropriate sowing or planting methods, seed treatment, suitable irrigation methods, irrigation schedule and need based drainage facilities will enhance the millet production on sustainable basis which will contribute tremendously to the food, feed, fodder and fuel demand of our country without degrading our natural resources.

Millets are a group of food crops which consumes less water for growth and development as compared to other cereals which are well adopted to rainfed ecosystem. On the basis of grain size, millets are grouped as large and small millets. Jowar (*Sorghum bicolor*) and Bajara (*Pennisetum glaucum*) comesunder large millets, whereas Finger millet (*Eleusine coracana*), Little millet (*Penicumsumatrense),*Foxtail millet (*Setariaitalica*), Proso millet *(Panicum miliaceum)*, Barnyard millet(*Echinochloafrumentacea)*, Kodo millet(*Paspalum scrobiculatum*)and Brown-top millet (*Brachiariaramosa; Panicum ramosum*) are categorizedas small millets.Buck wheat (*Fagopyrumesculentum*), Grain Amaranthus (*Amarantuscaudatus; Amaranthus cruntus*) and Quinoa (*Chenopodium quinoa*) are alsorecognised as pseudo millets by virtue of their food and nutritional values.

Being short duration and tolerant to various abiotic stresses, millets are cultivated in plains as well as in undulating terrains, where major food crops like rice and maize could not be raised economically. It is grown as sole crop or as inter crop under rice based cropping system, rice fallow, marginal land and under agroforestry system. In India it is grown in 13.8Mha area with annual production of 17.3mt of grains which contributes to about 6% of total food grain production of the Country. India contributes to 80 and 20 % of total production of millets in Asia and World, respectively. Millets are cultivated under varying agroclimatic zones from Jamu & Kashmir of north, Tamil Nadu in south, Gujrat in west and in several north eastern Indian states. Contribution of Rajasthan, Maharashtra, Uttar Pradesh and Karnataka to total millet production in India are 27,15,14 and 13%, respectively. Area under millets, production and productivity in India are presented in Table 1.

Most of the millets are highly nutritious, non-glutinous, non-acid forming and easily digestible thus considered as 'Miracle Grains or Nutri-cereals' and gaining popularities as part of human foods for nutritional security under changing climatic conditions (Table 2). It has tremendous potential for value addition as human food, animal feed and industrial raw materials. Being climate resilient, millets will play a major role to meet future demands of food and feed, for the growing population and livestock. As water is becoming a scarce natural resource, it is imperative to adopt appropriate water management practices to enhance water use efficiency, water productivity, land productivity and farm income under different millet production system. Knowledge on climatic requirement, growing ecologies, water requirement of crops with their critical growth stages for water stress, cropping system are essential to develop an optimum water management strategy for sustainable millet production.Better water management in terms of optimum sowing window, appropriate sowing or planting methods, seed treatment, suitable irrigation methods, irrigation schedule and need based drainage facilities will enhance the millet production on sustainable basis which will contributetremendously to the food, feed, fodder and fuel demand of our country without degradingour natural resources.

Table 1 : Area, Production and Productivity of different millets in India (2021-22)

Millets	Area (mha)	Share of total (%)	Production (mt)	Share of total (%)	Productivity (kg/ha)
Bajra	7.65	56.13	10.86	60.29	1420
Sorghum	4.38	32.13	4.81	26.71	1099
Ragi	1.16	8.51	1.99	11.05	1724
Other Small millets	0.44	3.23	0.35	1.95	781
Total	13.63	100.00	18.01	100.00	1321

Table 2 : Nutritional value of different millets (per 100 g of dry weight)

Millets	Protein (g)	Fibre (g)	Minerals (g)	Iron (mg)	Calcium(mg)
Sorghum	10.0	4.0	1.6	2.6	54.0
Bajra	10.6	1.3	2.3	16.9	38.0
Finger millet	7.3	3.6	2.7	3.9	344.0
Foxtail millet	12.3	8.0	3.3	2.8	31.0
Kodo millet	8.3	3.0	2.6	0.5	27.0
Little millet	7.7	7.6	1.5	9.3	17.0
Barnyad millet	11.2	10.1	4.4	15.2	11.0
Teff	13.0	8.0	0.85	7.6	180.0
Brown top millet	11.5	12.5	4.2	0.65	0.01
Proso millet	12.5	2.2	1.9	0.80	14.0

Climatic requirement of millets

Millets are preferably cultivated under hot and dry climate but it can also be grown in areas having moderate rainfall. Most of the millet crops prefers tropical and subtropical climate, whereas foxtail millet also grown in temperate region. In India millets are grown from mean sea level in plains to high altitudes of hilly regions up to 2700m. Comparative crop duration, temperature, rainfall and water requirement of millets are tabulated in Table 3

Table 3 : Comparative crop duration, water requirement and optimum temperature of millets

Crop	Duration (days)	Water requirement (mm)	Rainfall (mm)	Optimum temperature (oC)
Rice	90-130	900-2500	700-2000	27-30
Maize	100-120	400-600	250-1800	20-30
Wheat	110-`135	400-600	125-1000	15-25
Sorghum	100-125	300-400	400-1000	21-28
Pearl millet	80-95	250-300	250-700, 1500	25-30
Finger millet	90-130	250-300	500-1000	25-30
Barnyard millet	45-60	250-300	250-600	25-30
Proso millet	60-90	250-300	250-600	25-30
Foxtail millet	70-90	250-300	250-600	25-30
Kodo millet	100-140	250-300	500-600	25-30
Little millet	70-110	250-300	250-600, 1500	25-30
Quinoa	75-85	250-325	700-1500	8-35

Growing seasons of millets in India

Millets are mostly grown in *kharif* season under rainfed ecology. Some of millets like Jowar, Little millet and Finger millets grown as rabi crop under residual soil moisture and/or under irrigated lands. Bring short duration and tolerate to high temperature, millets can also be grown during summer season under assured irrigation. Among the Indian states in Rajasthan all most all the millets are grown in several agroclimatic and cropping systems. Next to Rajasthan, Maharashtra and Tamil Nadu states are also popular for several millet varieties. Finger millet is most dominant crop inKarnataka, Uttarakhand and Odisha. Different millet growing States and seasons in India are tabulated in Table 4. Millets grown on Odisha, growing seasons, varieties and crop establishment methods are reflected in Table 5.

Table 4 : Major millet growing states and seasons in India

Crop	Major growing states	Season
Pearl millet	Rajasthan, Uttar Pradesh, Maharashtra, Haryana, Gujrat, Tamil Nadu, Odisha (negligible)	Kharif Summer
Jowar	Maharashtra, Karnataka, Rajasthan, Tamil Nadu, Uttara Pradesh, Odisha (negligible)	Kharif Rabi
Finger millet	Karnataka (10%), Tamil Nadu (6.5%), Uttarakhand (10%), Maharashtra (9.6%), Odisha (4.8%) Andra Pradesh (3.6%), Gujrat, Jharkhand, West Bengal	Kharif Rabi Summer
Little millet	Madhya Pradesh, Karnataka, Andra Pradesh, Odisha, Tamil Nadu, Gujrat, Chhattisgarh, Maharashtra, Bihar	Kharif Summer
Proso millet	Madhya Pradesh, Karnataka, Andra Pradesh, Tamil Nadu, Gujrat, Chhattisgarh, Bihar, Telangana	Kharif Summer
Kodo millet	Madhya Pradesh, Tamil Nadu, Chhattisgarh, Gujrat, Karnataka	Kharif
Barnyard millet	Madhya Pradesh, Chhattisgarh, Maharashtra, Tamil Nadu, Uttara Pradesh, Uttarakhand	Kharif, Rabi Summer
Foxtail millet	Andhra Pradesh, Karnataka, Tamil Nadu, Telangana, Rajasthan, Maharashtra, Gujrat, Uttarakhand, NE states, Bihar	Kharif Summer
Browntop millet	Andhra Pradesh, Karnataka, Tamil Nadu	Kharif
Quinoa	Andhra Pradesh, Karnataka, Tamil Nadu, Uttarakhand	Rabi

Table 5: Growing ecology, growing seasons, varieties and crop establishment methods of millets in Odisha

Crop	Growing Ecology	Growing season	Varieties	Crop Establishment Methods

Ragi	Rainfed/ Irrigated	Kharif: June-Oct Rabi: Sept-Dec Summer: Jan-May	Divyasingha (85) VL 149 (90) Champabati (90) Kalua (110) Neelachal (100) RAU 8 (105) Arjun (125) Godavari Vegavathi	Dry direct seeding/ Transplanting
Jowar	Rainfed/ Irrigated	Kharif: June-Oct	CSH 1 (100) CSH 9 (105) ASH 2 (100) CSH 15 (110) CSH-2 (105)	Dry direct seeding
Bajra	Rainfed/ Irrigated	Kharif: June-Oct	HB-1, HB 2, HB 3	Dry direct seeding
Small millets	Rainfed	Kharif: June-Oct	Kolab (80) Sarba (75) TNAU (90) BLS (90)	Dry direct seeding
Little millets	Rainfed	Kharif: June-Oct	Chattisgarh Kutaki 1 Kalinga Suan 217	Dry direct seeding

Note: Number mentioned with in brackets reflects duration of the varieties

Water management strategies for enhancing productivity and profitability of millets

Millet species need relatively less water than the other crops, because they have short growing season. Most of the millets are grown during kharif season under rainfed ecologies. But some of them are also grown during post rainy season under residual soil moisture. Summer season millets are grown under assured irrigation facilities under different cropping systems in various part of India. From several studies it is observed that millet respond well to irrigation and judicious water management substantially increased the yield and income of the farmers. In this article crop wise water management options are described and some of the optimum management practices are highlighted for sustainable millet production in India.

Water management in Jowar

Sorghum grown for food, fodder and fuel purpose in India. The crop is grown in wet season (June-July to September-October) under both rainfed and irrigated ecologies and during rabi (September-October to February-March) under conserved soil moisture. But Summer jowar is grown exclusively on irrigated ecology. Reports from different sorghum growing regions of India reveals that water requirement varies with season that 325-500 mm in *kharif*, 400-500mm in *rabi* and 600-700 mm in summer season.

Water requirement of sorghum also influenced by plant population, genotype and methods of irrigation. Planting in flat bed followed by ridge making at 20-25 days after sowing (DAS) increases moisture availability in rainfed crop which ultimately records higher water use efficiency and water productivity. Mulching practices have shown improvement in moisture conservation in rainfed sorghum. Better crop yield can be achieved by dry sowing of sorghum seeds in 15-20 days before onset of monsoon rain. Under limited soil moisture availability, planting in paired row or wide row increases water use efficiency than the normal planting.

Under irrigated ecology, irrigation will be provided immediately after sowing and 15 DAS for the development of a strong root systems. Flower primordial initiation (FPI) at 20-30 DAS, flag leaf stage at 50-55 DAS, flowering at 60-70 DAS and grain filling stage at 80-90 DAS are critical growth stages for water stress. If there is sufficient water, application of irrigation water in all four stages has significant effect on crop yield. However, under limited irrigation FPI and flowering are most critical stage.Similarly, heading stage and first week after heading are crucial stages for irrigation. For irrigated *rabi* crop grown in medium to deep black soil, 3 irrigations at germination, panicle initiation stage and at grain filling stage are critical. Rabi sorghum at Telangana state responded well to green manuring with *dhaincha* and application of irrigation at panicle initiation, booting, anthesis and milk stage.

Water management in Bajra

Pearl millet popularly known as Bajra mostly grown in *kharif* season under rainfed ecology. The average actual evapotranspiration of pearl millet was found to be 1.7 to 5.31 mm per day. Besides, high water demand was observed in the high canopy development and heading stage of the crop (Rao *et al.*, 2012).The seasonal crop water requirement (ETc) estimates showed that, water requirement of summer Pearl millet is 499.2 mm and whereas *kharif*Pearl millet is323.6 mm (Meheta and Pandey 2016). To produce 100 kg of pearl millet grains the crop needs 14-15 mm of water per ha.If there is long dry spell during flowering and grain development stages, application of supplementary irrigation minimises yield loss of rainfed kharif bajra.

For transplanted summer millet, six irrigations at crucial stages of plant development from germination, to maturity are essential for better yield. Under water limitation, three irrigations at planting, tillering and flowering would provide maximum yield. Field studies showed high gain and stover yield was obtained in Uttar Pradesh under four irrigation time points during emergence, early tillering, booting stage, and grain filling(Ray et al., 2021). Summer pearl millet grown under clay soils of South Gujarat and irrigated at 0.8 IW: CPE ratio recorded significantly higher yield, but was found to be on par with 1.0 IW: CPE ratio of irrigation schedule (Thakoor *et al*., 2018). Application of irrigation at 40 mm depth to summer pearl millet in medium black soil gave higher grain and fodder yield highest net return and B: C ratio (2.33). The crop coefficients for summer pearl millets Kc initial, Kc mid, Kc end were found to be 0.33, 0.73 and 0.42 respectively (Rao *et al* 2012).Besides, the highest seed yield, straw yield, biological yield and water use efficiency was recorded with normal sown crop at 60 cm drip line spacing which was at par with paired row sown crop at 120 cm drip line spacing.

Methods of planting was observed to influence on crop yield and water use efficiency in pearl millet. Planting on ridges conserves soil moisture grain yield and water use efficiency as compared to conventional broad casting on flat beds. At Bichpuri, Uttar Pradesh, Peral millet sown in bed methods followed by irrigation at IW/CPE ratio of 0.9 registered highest grain and stover yield (Chauhan and Kaledhonkar 2018). Similarly sowing of bajra by seed drill recorded increase in grain and stover yield than broadcasting. Significantly, application of 6% kaolin (anti-transparent) enhanced the yield by 9.7% over control in summer irrigated pearl millet. Additionally, mulching with white plastic sheet (200 gauge)and irrigation scheduled at 1.1 IW:CPE ratio recorded significantly higher fodder and grain yield.

Summer pearl millet at Rahuri, Maharashtra irrigated with 100 mm CPE irrigation regime recorded highest grain yield, monetary benefits and water use efficiency. The soil moisture extraction was more from middle soil moisture layer of 15-30 cm and the consumptive use of water was 394.2 mm The consumptive use of water was more in 100 mm CPE irrigation regime (443.47 mm), followed by 125 mm (379.67 mm) (Pawar et al., 2018). The irrigation can be scheduled at 50% DASM all through the crop period (5-7 irrigations), for higher yield in rabi and summer seasons. However, during deficit supply, irrigation schedules at 50% DASM or at IW/CPE ratio 0.75 during moisture sensitive stages and 75% DASM or at IW/CPE 0.4 at other stages are ideal for obtaining higher yield.

Water management in finger millet

During wet season finger millet is mostly grown as rainfed and does not require any irrigation but if rain is delayed for an extended period during the tillering and flowering stages, application of supplementary irrigation helps in obtaining satisfactory yield. Pre-sowing seed treatment with 100 ppm Na2HPO4 or KH2PO4 or 0.25% CaCl2 was found to enhance the yield of finger millet. The peak value of crop coefficient of kharif finger millet recorded 1.02 on 66th day of sowing. Among the different species,brown finger millet tolerates water stress better than black finger millet (Khatoon and Singh 2016). Under moisture stress, application of brassinosteroid (0.3 ppm) or salicylic acid (100 ppm) was found to enhance the yield attributes in finger millet (Mohanabharathi*et al*., 2019).

During rabi and summer season it is grown under irrigated ecology. Water requirement of summer finger millet is 350-375 mm which can be accomplished by eight to nine numbers of irrigation depending on soil types (Dwivedi *et al*., 2016; Tripathi *et al*., 2020). Practice of soil mulch followed by irrigation scheduling at 60% soil moisture depletion level (SMDL)is beneficial for higher grain yield and water use efficiency. However,water-use efficiency was increased with less irrigationsand especially finger millet respond wells to water deficit conditions. Therefore, scheduling irrigation at an IW: CPE ratio of 0.9 along with sugarcane trash mulching at 10 cm thickness was ideal to achieve higher yield under irrigated ecology.

For transplanted ragi pre planting irrigation of 70-80 mm, lifesaving irrigation at 3 days after transplanting of ragi seedlings with small quantity of water is needed for proper crop establishment. For encouraging healthy and sound growth and tillering it is better to withheld irrigation for 10-15 days after establishment. Then irrigation at primordial initiation, flowering and grain filling stages ensures optimum grain and straw yield of irrigated transplanted ragi. Drip irrigation is an alternate and effective way of watering in drought-prone areas to generate good yields from finger millet-based farming systems. Finger millet is an emerging crop can be well fitted under changing climate scenario and ground water.

Water management in Proso millet

Proso millet is a short duration, drought-tolerant C_4 species suitable for dryland ecologies. Limited water-demanding and yield stability makes proso millet as climate resilient crop under different agroecosystems. Proso millet mostly grown as rainfed crop during *kharif* season kin most of the growing regions. But under prolonged dry spell at tillering and flowering stage, application of one irrigation minimises crop yield loss. Summer crop requires two to four irrigations based on soil nature and weather parameters. Application of first and second irrigation at 25-30 DAS and 40-45 DAS, respectively are sufficient for optimum grain yield. Heavy irrigation is harmful for proso millet due to its shallow root system. Proso millet has a water-limited yield response slope of 32.57 kg/ha per mm of water use.

Water management in foxtail millet

Foxtail millets are generally cultivated in dry lands and requireat least 257 g of water to produce 1 g of dry biomass which is relatively lesser than for maize and wheat at 470 and 510 g, respectively. However, rabi crop requires irrigation. Experimental results revealed that pre-sowing irrigation and irrigation at 20–25 and 40–45 DASshowed significantly higher yield. Planting of foxtail millet in ridge and furrow method conserves soil moisture, maintains topsoil temperature and results higher water use efficiencywhich ultimately reflects in good crop stand and subsequent grain and stover yield (Zhang *et al.*, 2019).

Water management in other minormillets

Little millet is a quick growing and short duration can withstand both drought and waterlogging. It requires an average rainfall of 300 -500mm.During rainy season mostly grown as rainfed crop. Tillering (30-35 DAS) and heading (55-60 DAS) are most sensitive for moisture stress, light irrigation under prolonged dry spell during critical growth stages is recommended for better crop yield. Summer little millet requires 2-5 irrigation depending on soil and climatic condition for optimum yield. Kodo millet is grown in warm and dry climate. It can be cultivated in areas receiving 40 to 50 cm of annual rainfall. During dry periods lifesavingirrigation at 25-30 and 40-45 DAS is beneficial for getting better grain yield. Drain out the excessive rainwater during heavy and continuous rains. Barnyard millet generally grown during *kharif* season under rainfed ecology. During long dry spells, lifesaving irrigation at tillering stage (25-30 DAS) and second irrigation at panicle initiation stage (45-50 DAS) minimises reduction in grin yield.

Water management in Quinoa:

Quinoa is a short duration and low water requirement (250 to 325 mm) pseudo millet crop grown mostly in rabi season in an area of 440 hectares with an average yield of 1053 tonnes (Srinivasa Rao, 2015) and gaining popularities in several states across the country. Proper management of residual soil moisture and irrigation water significantly influences the yield and economics of quinoa. From lysimetric study it was observed that the crop coefficient of Quinoa crop varies from 0.5 in the initial growth stage, 1.00 in the mid-season stage and 0.70 at harvest (Gracia *et al.*, 2003). Plants should not be irrigated until the two or three leaf stage. Excessive irrigation in the seedling stage causes several soil burn diseases which ultimately affect the crop stand establishment. Three and four irrigations during its growing cycle at critical growth stages from vegetative and grain formation period ensures optimum yield. Irrigation in furrows is superior than basin methods. Drip irrigation scheduled at 1.0 Epan throughout cropping period showed higher yield and water use efficiency. Under deficit water conditions, drip irrigation with 0.5 Epanand 1.0 Epan at vegetative and flowering stage showed the least reduction in yield (Kadam *et al.*, 2018)

Experiment conducted at ICAR-IIWM research farm revealed that Sowing of quinoa on broad bed and furrow methos had yield advantage of 13.1% over the sowing on flat beds. The yield advantage was due to better crop stand, crop growth and yield attributes. Irrigation schedule at 20, 35, 50 and 65 DAS resulted higher grain (1.63 t/ha) and stover yield.Quinoa grown with 4 irrigations resulted in higher crop productivity of 20.38 kg/ha/day, water use efficiency (5.82 kg/ha.mm) with net return of Rs60600/- and B: C ratio of 2.37. (Satapathy et al., 2023)

Conclusions

Millets are valuable food crops in tropical and subtropical regions due to short duration, low input requirements viz water, fertilizer and pesticides and capacity to grow under several stress conditions. Millets have innate mechanisms deal with environmental stresses like drought, heat, salinity, lodging and waterlogging. But productivity and profitability of millet-based production system can be enhanced by adoption of appropriate integrated crop management practices. Selection of suitable crop and cropping system based on ecology and local preference, quality seed, seed treatment for seed hardening and disease control, maintenance of optimum plant population through proper crop establishment, weed control at early growth stage. Further need based pest and disease management coupled with judicious water management will ensure the higher prediction and profitability of millet production system. Though millets are low water requirement crops but proper irrigation methods and irrigation scheduling based on soil moisture studies by using advance technologies like soil moisture sensors will be helpful for higher water productivity, low water footprint and increased yield and farm income. Ragi is the principal millet crop extensively grown in tribal dominant hilly districts of Odisha. Next to ragi little millet is also grown in some regions of Odisha as traditional crop but reduced their importance due to emergence of competitive crops. But Odisha Millet Mission has created awareness and scope for revival of millets in field as well as in food, feed and industrial use for which production and productivity of millets is increasing and it is also expanding to non-traditional millet growing regions. Millets particularly finger millet and little millet can be exploited as viable climate resilient crop of several districts in Odisha.

References

Dwivedi K, Tripathi MP, Chandrawanshi D and Bisen Y (2016). Studies on the effect of soil and water balance in finger millet (*Eleusine coracana*) under mid land condition of Chhattisgarh plains. *Agriculture and Technology*11(special -II): 672-676.

Gracia M, Raes D and Jacobsen SE (2003). Evapotranspiration analysis and irrigation requirement of Quinoa *(Chenopodium quinoa)* in the Bolivian highlands. *Agricultural Water Management* 60: 119-134.

Kadam VP, Suneetha Devi KB, Hussain SA and Uma M (2018). Economics of Quinoa (*Chenopodium quinoa*) as Influenced by Variable Irrigation Water Supply through Drip and Surface Methods, International journal of Current Microbiological Applied Science 7(7): 3428-3438.

Mohanabharathi M, Sritharan N, Senthil A and Ravikesavan R (2019). Physiological studies for yield enhancement in finger millet under drought condition Journal of Pharmacognosy and Phytochemistry 2019; 8(3): 3308-3312

Mehata R and Pandey V (2016). Crop water requirement (ET_c) of different crops of Middle Gujrat, Journal of Agrometerology 18 (1): 83-87.

Patil CS and Puttanna B (2009). Influence of actual evapotranspiration, growing degree days and bright Sunshine hours on yield of finger millets, *Mausam*60(3):343-348.

Ray S, Umesha C and Meshram MR (2021). Response of Irrigation and hydrogel on growth and yield of Pearl millet (Pennisetum glaucum L.) under Eastern Uttar Pradesh condition, Biological Forum 13 (2): 404-407.

Satapathy BS, Panda DK, Rautaray SK and Pradhan S (2023). A climate resilient crop, *Indian Farming* 73 (09):22-24.

Srinivasa Rao K (2015). *Sarikotha Panta Quinoa, Sakhi News Paper*, Page 10 on 11.08.2015

Thakoor KP, UsadadiaUP,Savoni NG, Arvadia LK, and Patel BP (2018). Effect of irrigation schedule and nitrogen management on productivity and profitability of summer Pearl millet grown under clay soils of south Gujrat, *International Journal of Agriculture Innovations and Research* 6 (4): 2319-1473.

Zhang X, Kamaran M, Li Fangjian, Xue X, Jia Z and Han Q (2019). Optimizing fertilization under ridge-furrow rainfall harvesting system to improve foxtail millet yield and water use in a semiarid region, China, Agricultural water management *https://doi.org/10.1016/j.agwat. 105852.*

Chapter 09

Efficient Nutrient Management Practices for Rice-Millet Cropping System

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Abstract

Rice- millet cropping system is an emerging cropping system now-a -days. The millet followed by the rice in rabi season needs lees water than other crops. The nutritional quality of millet is more superior than other crops. Both rice as well as millet in cropping system could be an option for global food security and nutrition. This study reviews different nutrients management aspects in rice-millet cropping system which are multi-faceted viz; Inorganic, organic, biofertilizers, integrated nutrient management (INM) and machine learning technology. INM enhances the growth, yield and yield attributing characteristics in rice based cropping system. Use of machine learning algorithm could predict the requirement of nutrient to the crop plant. Application of beneficial microbe to the crop increased the soil biological activities. Organic manuring increases the soil physico-chemical and biological properties. Millet cultivation is often associated with low-fertility soils and inadequate management practices, making the role of fertilization crucial for crop productivity. However, it's important to acknowledge some limitations in nutrient management studies related to finger millet. These include the need for more research to address soil health improvement for sustainable production, a lack of comprehensive studies on INM, the identification of efficient rice-finger millet cropping

systems, and the development of soil test crop response (STCR) based nutrient management strategies tailored to different agroclimatic zones.

Key words: Finger millet; grain quality; integrated nutrient management; crop yield; soil health

Introduction

Across the globe rice and millet are both important staple crops (Sen et al., 2020; Swain et al., 2021; Hassan et al., 2021), playing crucial roles in global food security and nutrition (Ceasar and Maharajan, 2022). Here's an overview of the importance of these grains: Rice is a primary staple food for more than half of the world's population (Fukagawa and Ziska 2019). It serves as a fundamental source of calories and nutrition for billions of people, especially in Asia, where it is a dietary staple. Rice is an important source of fibre, energy, minerals, proteins, vitamins, antioxidants and other biomolecules which may act in synergy and exerted an advantageous effect on health (Sen et al., 2020). Rice has cultural and traditional significance in many societies, often featuring prominently in religious ceremonies, festivals, and daily meals. Rice can be prepared and consumed in numerous ways, such as steamed, boiled, fried, or ground into flour (Kim, 2007). It serves as a base for a wide range of dishes, from sushi to biryani. While primarily a source of carbohydrates, rice also contains essential nutrients, including vitamins (B vitamins) and minerals (like iron and magnesium).

Nearly five decades ago, millets were a staple crop in India and many other nations. However, a 2014 report from the National Council of Applied Economic Research (NCAER) found that consumption of millets has drastically declined in favor of wheat, rice, and processed meals. This shift has been driven by the increased cultivation of wheat and rice, leading to a substantial reduction in millet farming areas. Since 1956, the cultivation area for various millet types has decreased by 58% for small millets, 64% for sorghum, 49% for finger millet, and 23% for pearl millet (Patil, 2016). Despite this decline, there is a growing awareness of the need for healthier, more accessible, and cost-effective diets due to the rising problems of malnutrition, encompassing both under-nutrition (deficiencies in vitamins, minerals, and protein) and over-nutrition (obesity, metabolic syndrome, and lifestyle diseases). Furthermore, the recent G20 discussions highlighted concerns about the unprecedented crisis involving Food, Fuel, and Fertilizer (the 3F crisis). Millets are now being recognized as an important crop that can address various critical challenges in the future, including food security, energy production, malnutrition, health, and climate change resilient crop (Srivastava et al., 2023). They are highly adaptable to different temperature and moisture conditions and have low input requirements, making them resilient to the impacts of climate change. Millets can withstand droughts and thrive with minimal rainfall, making them an ideal crop for cultivation. Additionally, they are naturally gluten-free and packed with nutrients, including protein, essential fatty acids, dietary fiber, and vitamin B (Saleem et al., 2023). Millets also contribute to the prevention of numerous non-communicable lifestyle diseases like diabetes, hypertension, and cardiovascular diseases (Saleem et al., 2023). They are considered a potential solution to combat rising malnutrition and enhance food and nutrition security. On a global scale, India stands as the world's leading producer of millets and the fifth-largest exporter of millets. As demand for millets continues to rise, exports are expanding rapidly, creating numerous business opportunities for entrepreneurs. The millet market was valued at over USD 9 billion in 2018 and is expected to grow at a rate of over 4.5% from 2018 to 2025, with a projected value exceeding USD 12 billion (Sood et al., 2023). The diet is rich in refined carbohydrates (sugar), and saturated fats of animal origin, but low in fiber; however, high consumption of the first two ingredients can lead to a pro-oxidative state after each meal due to their active oxidation and simultaneous reactive oxygen species (ROS) formation (Szabo et al., 2021).

In India rice based cropping system is most popular but the main reasons for leaving the lands fallow during the winter season are lack of irrigation, late harvesting of long–duration high yielding rice varieties, moistures stress at sowing during the rabi crops due to early withdrawal of monsoon, waterlogging and excessive moistures in November/December, and nuisance like stray cattle and blue bulls (Ali and Kumar 2009; Kumar et al., 2019). Rice fallow (~11.7 million ha) is a mono–crop rice–based production system in India and mostly (82%) is concentrated in the eastern states, .i.e. Chhattisgarh, Jharkhand, Upper Assam, Bihar, eastern Uttar Pradesh, Odisha and West Bengal (Pande et al., 2012, Kumar et al., 2018; Kumar et al., 2019). Rice-millet cropping system is an alternative and most soil sustainable cropping system.

While millet farming is gaining momentum, there is still ample room for ecosystem-level interventions to improve its sustainability, especially in the context of climate change. Recognizing the importance of millets in the face of climate change, the Food and Agriculture Organization and the United Nations General Assembly declared 2023 as the International Year of Millets (FAO, 2022). In areas where finger millet is grown, it is often the most viable crop for subsistence farmers due to its low fertilizer requirements. However, under low-nutrient conditions, finger millet yields are declined to its potential yield (Maitra et al., 2020). There are improved finger millet varieties that respond positively to added nutrients, and optimizing nutrient management is essential for sustainable production. This can be achieved by enhancing soil nutrient availability with crop demand both spatially and temporally. Best nutrient management practices offer several advantages, including increased yields, improved water use efficiency, better grain quality, higher economic returns, and overall sustainability. Site-specific nutrient management (SSNM) and soil testing for crop response (STCR) are valuable approaches to nutrient management in millet. In this article, we have compiled scientific information on various nutrient management options, sources, levels, and application methods to enhance the sustainability of millet production. This information aims to address the nutrient management challenges associated with millet cultivation across different agro-climatic conditions.

Rice-Millet Cropping System

Rice-millet cropping systems, where rice and millet are grown together or in a rotational sequence, offer unique characteristics and a range of benefits for agricultural sustainability and food security. Here are some of the key characteristics and benefits of rice-millet cropping systems: Rice-millet cropping systems involve the cultivation of two different cereal crops. Rice (*Oryza sativa*) is a water-intensive crop grown in flooded or submerged fields (Nishiuchi et al., 2012; Panda and Barik 2021), while millet (various species, e.g., pearl millet or finger millet) is drought-resistant and adapted to arid and semi-arid conditions (Chaturvedi et al., 2022). This diversity allows farmers to adapt to varying environmental conditions. In regions with water scarcity or irregular rainfall patterns, the inclusion of millet in the system can help balance water use. Millet requires less water than rice and can tolerate dry spells better, reducing the overall water footprint of the system (Ullah et al., 2017). The combination of rice and millet enhances the resilience of the cropping system to climate variability (Wilson and Van Buren 2022). Millet's ability to grow in drier conditions can mitigate the risk of crop failure during droughts or water shortages, ensuring food production in challenging environments. Crop rotation with millet can improve soil health by reducing the risk of soil degradation associated with continuous rice cultivation (Bado et al., 2022). Millet's deep roots can help break soil compaction and enhance nutrient cycling (Koudahe et al., 2022). Growing millet alongside rice can disrupt pest and disease cycles, reducing the need for chemical pesticides. This can contribute to a more sustainable and environmentally friendly cropping system. Rice and millet together provide a diverse range of staple foods. Rice is a primary source of carbohydrates (Sen 2020), while millet is rich in protein, fiber, vitamins, and minerals (Hassan et al., 2021). This diversification improves the nutritional quality of diets. Rice and millet cropping systems can enhance food security by providing a buffer against crop failures. If one crop fails due to adverse weather conditions, the other may still thrive, ensuring a food source for the community (Iizumi and Ramankutty, 2015). Farmers can benefit economically from rice-millet cropping systems. These systems promote efficient resource use. Millet's lower water requirements reduce the strain on water resources in areas prone to water scarcity. Moreover, it reduces the need for synthetic fertilizers and pesticides. Rice and millet are often integral to local cuisines and cultural traditions. Growing both crops can preserve cultural practices and contribute to culinary diversity. Rice-millet cropping systems align with principles of sustainable agriculture by diversifying crops, reducing environmental impacts, and improving resilience to climate change. When rice and millet are rotated, the benefits of crop rotation come into play. Rice-millet cropping systems offer a multifaceted approach to sustainable agriculture, providing environmental benefits, improved resilience to climate variability, diversified food production, and economic opportunities for farmers. These systems play a crucial role in addressing the complex challenges of food security and agricultural sustainability, especially in regions with varying agro-climatic conditions.

Nutrient management

Nutrient Management is an approach to crop nutrition that involves the judicious use of various nutrient sources to optimize nutrient availability to crops while maintaining soil fertility and sustainability. it aims to provide these crops with the right balance of essential nutrients for healthy growth and maximum yields. Some key aspects of nutrient management are presented in the figure 1.

Figure 1. Components of nutrient management

Soil nutrient management is defined by the USDA as managing the application of commercial fertilizers, manure, amendments, and organic by-products to agricultural landscapes as a source of plant nutrients. A common framework for approaching nutrient management is known as the "Four Rs": Right amount - the proper rate of application, Right source - applying the proper type, Right placement - using the appropriate method for application, Right timing - applying at the correct time in the lifecycle of the system (Figure 2). By considering the Four Rs, growers can maximize the nutrients taken up by a crop and minimize the amount of additions wasted or lost to the environment. Careful consideration of soil nutrient management is a critical component of sustainable agriculture because it provides growers with economic benefits while reducing the negative impacts that excess nutrient amendments may have on the environment.

Fig. 2: 4 R concept of nutrient management

Chemical Fertilizers

In order to maximize rice-millet cropping system yields and ensure the viability of its production, fertilizer application must be conducted precisely. It's important to note that many of the soils grown for growing millet are deficient in major nutrient. Previous research has demonstrated that finger millet positively responds to varying levels of nitrogen application, and a summary of these research findings is provided in Table 1. In order to maximize finger millet yields and ensure the viability of its production, nitrogen fertilizer application must be conducted precisely. It's important to note that many of the soils grown for growing finger millet are deficient in nitrogen. Previous research has demonstrated that finger millet positively responds to varying levels of nitrogen application, and a summary of these research findings is provided in Table 1. The timing of nitrogen application plays a critical role in optimizing finger millet production. According to research findings, incorporating nitrogen fertilizer during the seeding stage led to a 30% increase in yield compared to broadcasting it as a basal dose. To maximize yield and nitrogen use efficiency, it is essential to synchronize nitrogen supply with the crop's nitrogen demand. For instance, on sandy loam soils, applying nitrogen at 50 kg/ha resulted in lower grain yield when applied only at planting, whereas splitting the application between at basal and 25–30 days after planting increased yield. In another study, researchers recommended applying nitrogen in three splits: at time of transplanting, 30 and 60 days after transplanting, which resulted in higher dry matter production and better yield compared to other split applications. For directly seeded crops, the recommendation differed based on rainfall patterns. In areas with adequate rainfall, it was suggested to apply 50% of the recommended nitrogen at sowing and the remaining 50% in two equal splits at 25-30 and 40-45 days after sowing. In regions with uncertain rainfall, the recommendation was to apply 50% at sowing and the remaining 50% around 35 days after sowing. Hemalatha and Chellamuthu (2013) observed that continuous application of inorganic N fertilizer alone decreased the soil organic carbon content in a long-term field experiment in finger millet. Regarding phosphorus, finger millet is often grown in areas with low soil phosphorus levels. Research indicated that applying 125% of the recommended dose of phosphorus along with recommended nitrogen, potassium, and organic matter in soils with very low to medium fertility increased grain and straw yields. Optimal results were achieved with 100% or 75% of the recommended phosphorus dose, with higher phosphorus application rates showing diminishing returns, especially in high phosphorus fertility soils. The combination of nitrogen, phosphorus, and potassium (NPK) is essential for crop productivity. Field experiments have shown that the highest grain and straw yields for finger millet were obtained when applying 150% of the recommended dose of NPK, along with micronutrients like zinc and iron as foliar sprays. Overall, nutrient management, including timing and dosage of nitrogen, phosphorus, and potassium, plays a pivotal role in maximizing finger millet yields and ensuring sustainable agricultural practices.

Table 1. Impact of chemical fertilizer on yield of millets

Nutrient management	Soil type	Location	Results	Reference
N Application	Typical *Ultisols*, with sandy clay loam texture	West Bengal	As compared to 30, 40, and control applications of N@ 60 kg N ha^{-1} significantly increased grain yield.	Roy et al. (1996) Roy et al. (2002)
N Application	Silty clay loam	Uttarakhand	Addition of 60 kg Nha^{-1} significantly increased grain yield (2291 kg ha^{-1}) than 40 kg Nha^{-1} (2063 kg ha^{-1}), 20 kg Nha^{-1} (1661 kg ha^{-1}) and control (1385 kg ha^{-1}).	Yadav et al. (2010)
NPK Application	Clay loam texture	Zonal Agricultural Research station, Kolhapur	Application of RDF (60:30:00 kg NPK ha^{-1}) is an optimum dose and advisable for obtaining the maximum grain (2520 kg ha^{-1}) and straw yield (3272 kg ha^{-1}) as against control.	Patil et al. (2015)
NPK Application	Brown forest soil, sandy loam in texture	Odisha	As compared to the control (637 kg ha^{-1}), 100% RDF @ 40-20-20 kg N, P_2O_5, and K_2O ha^{-1} had the maximum grain yield (1412 kg ha^{-1}).	Harika et al. (2019)
NPK Application	Sandy loam soil	Paralakhemundi, Odisha	With 90 kg N ha^{-1}, growth and yield attributes increased compared to 0, 30 and 60 kg N ha^{-1}). Productivity was improved by raising the phosphorus level from 20 to 40 kg ha^{-1}. The highest grain and straw yield (1054 and 4369 kg ha^{-1}, respectively) was obtained with a combination of 90 kg N and 40 kg P ha^{-1}.	Vamshi Krishna et al. (2019)
NPK		Uganda	Yield enhancement of 24 and 43%. The physiological efficiencies, agronomic efficiencies, and apparent recoveries of N and P were low; often <25%	Ebanyat et al., 2021

Organic Matter Incorporation

Organic manures play a pivotal role in agriculture by providing a diverse range of nutrients and gradually releasing them into the soil. This not only enhances soil fertility but also boosts the effectiveness of chemical inputs. Various types of organic manures have been found to positively impact the productivity of finger millet. Adequate application of farmyard manure (FYM) at a rate of 7.5 to 10 tons per hectare has been shown to promote robust root growth (Prabhakar et al., 2017). Researches have consistently demonstrated increased growth and productivity when organic manures are applied either alone or in combination with other nutrient sources. For instance, Rangaswamy (1973) reported that FYM led to a 9.5% increase in grain yield for early maturing finger millet cultivars and a 3.5% increase for short-duration cultivars. In recent times, organic agriculture has gained popularity, with a growing area under organic cultivation and increased production of agricultural crops. This acceptance of organic agriculture is driven not only by the demand for pollution-free food but also by its natural advantages in supporting sustainability in farming. Finger millet, like other staple foods, has also attracted the attention of scientists, leading to trials and experiments focused on its organic production. Gawade et al. (2013) observed that different organic manures, such as poultry manure, farmyard manure, and vermicompost, applied at varying rates, significantly increased finger millet yields compared to unfertilized control plots. For example, the application of poultry manure at 1.32 tons per hectare, farmyard manure at 3.0 tons per hectare, and vermicompost at 1.5 tons per hectare, which is equivalent to 20 kg of nitrogen per hectare, resulted in finger millet yields of 2211 kg/ha, 1740 kg/ha, and 1942 kg/ha, respectively. In another experiment conducted at the Agricultural and Horticultural Research Station in Bavikere, University of Agricultural and Horticultural Sciences, Basavaraj Naik (2017) concluded that the combination of FYM at 10 tons per hectare and biodigester liquid manure at 75 kg of nitrogen per hectare (applied in two splits) led to superior growth, improved yield attributes, and higher overall yield for finger millet. In summary, organic manures contribute significantly to the enhancement of finger millet productivity, and their adoption aligns with the principles of sustainable and environmentally-friendly agriculture.

Biofertilizers in nutrient management

Bio-fertilizers consist of living microorganisms, including beneficial bacteria and fungi, that, under favorable conditions, multiply rapidly and play essential roles in supplying, mobilizing, and solubilizing plant nutrients. Integrating these bio-fertilizers with organic manures and chemical fertilizers enhances crop productivity by fostering a healthy and balanced ecosystem. For finger millet, treating seeds with *Azospirillum brasilense* (a nitrogen-fixing bacterium) and *Aspergillus awamori* (a phosphorus-solubilizing fungus) at a rate of 25 grams per kilogram of seed has proven beneficial (Prabhakar et al., 2017). Research findings indicate that the application of bio-fertilizers can significantly increase finger millet productivity. For instance, Maitra et al. (1997) reported that the application of *Azospirillum* resulted in higher yields (890 kg ha^{-1}) compared to the control (711 kg/ ha). Similarly, Ramakrishnan and Bhuvaneswari (2014) found that single inoculation with Arbuscular Mycorrhizal (AM) fungi (*Glomus mosseae*) and combined inoculation of AM fungi with *Azospirillum brasilense* or phosphate-solubilizing bacteria (PSB) moderately increased growth. However, the highest growth parameters were observed with triple inoculation involving AM fungi, *Azospirillum brasilense*, and PSB. Bio-fertilizers generally perform well when used in conjunction with organic manures and inorganic fertilizers. Harika et al. (2019) reported that applying farmyard manure (FYM) at 8 tons per hectare along with *Azospirillum* (5 kg/ ha) resulted in higher yields (701 kg /ha) compared to the unfertilized control (637 kg/ ha) in brown forest soil in South Odisha. Furthermore, Kejia et al. (2019) noted that bio-fertilizers complement chemical phosphorus fertilization effectively. They found that applying 100% of the recommended dose of phosphorus (40 kg/ ha) along with phosphate-solubilizing bacteria (PSB) at 750 ml/ha and vesicular-arbuscular mycorrhiza (VAM) at 12.5 kg/ ha led to increased dry matter production, improved yield attributes (such as the number of tillers per square meter, number of ear heads per square meter, number of fingers per ear head, and ear head length), higher grain yield (4328 kg/ ha), and stover yield. Additionally, this treatment resulted in improved grain quality parameters, including protein and carbohydrate content, for finger millet, while plots without any chemical fertilizer recorded significantly lower yields (3692 kg /ha). In summary, the use of bio-fertilizers, particularly in conjunction with organic manures and chemical fertilizers, can significantly enhance finger millet productivity and overall crop quality, contributing to sustainable agricultural practices

Integrated Nutrient Management (INM)

Integrated Nutrient Management (INM) is a strategy aimed at enriching soil health and promoting sustainability by supplying plant nutrients to crops from various sources in a suitable and compatible manner. INM combines the use of organic manures, biofertilizers, and chemical fertilizers to fulfil the nutritional requirements of crops. Organic manures, in particular, not only improve the physical and chemical properties of the soil but also create a favorable environment for soil microorganisms and enhance the efficiency of chemical fertilizers. Here are some research findings demonstrating the positive impact of INM on finger millet productivity, as presented in Table 2. Arulmozhiselvan et al. (2013) conducted a long-term fertilizer experiment starting in 1972, involving a maize-finger millet cropping sequence. They assessed the effects of continuous fertilization and manuring on productivity, soil health, and nutrient removal by the crop in 2011 at Tamil Nadu Agricultural University. The application of 100% NPK in combination with farmyard manure (FYM) at a rate of 10 tons per hectare resulted in significantly higher grain yield (2571 kg /ha) and straw yield of finger millet, increased NPK uptake by the crop, and enrichment of soil organic carbon. A long-term experiment conducted from 1992 to 2011 at the University of Agricultural Sciences (UAS), Bangalore, Karnataka, focused on finger millet cultivation. The study revealed that the highest soil quality index (SQI) of 7.29 was achieved when FYM was applied at a rate of 10 tons per hectare in combination with 100% NPK. Conversely, the lowest SQI value of 3.70 was observed in the control group. The application of 10 tons per hectare of FYM, along with NPK at rates of 50:50:25 kg/ha, consistently maintained a mean yield of 3884 kg/ha for finger millet. Key indicators contributing to the SQI in the crop rotation system included organic carbon, potentially available nitrogen, extractable phosphorus, potassium, and sulfur, as well as exchangeable calcium and magnesium, dehydrogenase activity, and microbial biomass carbon and nitrogen (Sathish et al., 2016). Furthermore, the application of 10 tons per hectare of FYM in combination with 100% NPK (50:50:25 kg /ha) sustained a mean finger millet yield of 3884 kg /ha. This highlights that integrated nutrient management not only ensures consistent crop productivity but also enhances soil quality, thereby promoting sustainable agricultural practices.

Table 2. Impact of integrated nutrient management on yield of millets

Nutrient management	Soil type	Location	Results	Reference
INM	Clay loam soil	Coimbatore Tamil Nadu	Application of recommended N (50% FYM + 50% urea) and 50% P and K along with seed inoculation of biofertilizers (Azospirillum and Aspergillus each @ 25 g kg^{-1} seed produced 56% grain yield over farmer practices	Ramamoorthy and Lourduraj (2002
INM	Red sandy loam soil	Hebbal, UAS, Bangalore (Karnataka)	Integrated use of recommended NPK and FYM significantly increased grain yield (3086 kgha^{-1}) as compared to recommended chemical NPK alone (2946 kg ha^{-1}).	Kumara et al. (2007)
INM		Ratnagiri Maharashtra	Application of FYM @ 5t ha^{-1} + RDF (60-30-00 kgNPK ha^{-1}) recorded significantly higher grain yield2227 kg ha^{-1} and it was at par with the treatment with application of FYM @ 5t ha^{-1} + 75% RDF + biofertilizers(Azospirillum and PSB) seed inoculation @25 g each inkg^{-1} seed (2075 kg ha^{-1}).	Ahiwale et al. (2011)
INM	*Inceptisols* sandy clay loam soil	Tamil Nadu	Application of 100% NPK along with FYM @ 10 t ha^{-1}significantly higher grain (2571 kg ha^{-1}) yield than control (1874 kg ha^{-1}).	Arulmozhiselvan etal. (2013)
INM	Sandy loam soil	Ranchi (Jharkhand	Grain (3337 kg ha^{-1}) and straw yield (6983 kg ha^{-1}) were higher with application FYM (10 t ha^{-1}) + Biofertilizers (Azospirillum brasilense + Bacillus spp. + Psuedomonasfluorosence @ 20 g kg^{-1} seed each) + $ZnSO_4$ (12.5 kg ha^{-1})+ Borax (kg ha^{-1}) + 100% RDF (50:30:25) against 100%RDF (grain and straw yield of 2391 and 4879 kg ha^{-1}respectively).	Roy et al. (2018)

Soil test crop response (STCR) approach

Efficiently managing crop fertilization programs to meet the nutrient requirements of crops is vital for sustainable agriculture. Among the various scientific methods for making fertilizer recommendations that take into account crop nutrient needs, soil nutrient contributions, organic manure application, and yield goals, the Soil Test Crop Response (STCR) approach stands out (Regar and Singh, 2014). This approach, pioneered by Troug (1960) and later adapted for Indian conditions by Ramomoorthy et al., (1967), provides a scientific foundation for balanced fertilization by ensuring a harmonious relationship between applied nutrients and the nutrients naturally present in the soil (Choudhary et al., 2019). The STCR approach aims to precisely adjust fertilizer doses based on varying soil test values, response conditions, and farmers' targeted crop production levels. While studies on nutrient management specific to finger millet using the STCR approach are limited, Sandhya Rani et al. (2017) reported encouraging results. They observed improved growth characteristics, yield-contributing factors, grain and straw yields, and soil nutrient availability when they used a treatment involving 200% recommended doses of nitrogen (RDN), 100% recommended doses of phosphorus (RDP), 100% recommended doses of potassium (RDK), and 25% recommended doses each of zinc (RDZn), sulfur (RDS), and boron (RDB), integrated with 5 tons per hectare of farmyard manure (FYM). This treatment yielded results on par with another treatment based on the STCR equation, aiming for a targeted yield of 4 tons per hectare. These experiments were conducted in soils with low nitrogen levels (below 140 kg ha^{-1}), high phosphorus levels, and medium potassium levels in Vizianagaram, Andhra Pradesh. The findings indicated that in soils with low nitrogen content, increasing the nitrogen dose up to 200% along with micronutrients could achieve yields similar to those obtained using the STCR approach, thus reaching the targeted yield for finger millet with integrated nutrient supply. In another study by Saraswathi et al. (2018) conducted on *Alfisols* in Karnataka, precision nutrient management in finger millet was assessed. They reported significantly higher grain yields (3238 kg ha^{-1}) when using the STCR-based application of nitrogen, phosphorus, and potassium, along with 10 tons per hectare of compost, to achieve a targeted yield of 4 tons per hectare, compared to a control treatment (2385.7 kg ha^{-1}). These results clearly demonstrate the superiority of the STCR approach when aiming for specific yield targets compared to other fertilizer recommendations. In summary, the Soil Test Crop Response (STCR) approach is a scientifically sound method for optimizing fertilizer recommendations and achieving targeted crop yields, as evidenced by studies in the context of finger millet cultivation and other crops. It ensures a balanced and precise nutrient supply for sustainable agriculture.

Cropping system and nutrient management

Millets are versatile and can be effectively integrated into various cropping systems, with nutrient management playing a crucial role in achieving optimal results. Here are some key findings from research on finger millet's performance in different cropping systems and the impact of nutrient management recorded by Pallavi et al. (2016) in Rajendranagar, Hyderabad, within an agro-forestry system based on *Melia azedarach*. They found that integrating 75% of the recommended dose of nitrogen (RDN) with 25% nitrogen from poultry manure, in addition to 100% recommended doses of chemical fertilizers (RDF), led to higher finger millet yields. Combining cereals like finger millet with legumes is considered an ideal approach for sustainable production. Long-term experiments are essential to assess changes in soil quality, the organic carbon pool, and agronomic sustainability in finger millet-based cropping systems. Srinivasarao (2012) reported that the application of farmyard manure (FYM), either alone or in combination with chemical fertilizers, contributed to higher carbon inputs, leading to the buildup of a larger soil organic carbon (SOC) pool. This finding was based on a 13-year-old soil fertility management experiment involving rainfed groundnut-finger millet rotation in semi-arid *Alfisols*. Goudar et al. (2016) observed significantly higher grain yields, net returns, and benefit-cost ratios when finger millet was part of a crop rotation, particularly in combination with groundnut. Crop rotations can enhance overall productivity and economic returns compared to monoculture finger millet farming. Intercropping finger millet with legumes can be beneficial in terms of efficient land resource utilization, increased total crop yield, and higher monetary returns. While some intercropping systems may lead to reduced finger millet yields due to decreased plant density compared to sole cropping, the combined yield of finger millet and legumes can be significantly higher. Various intercrop combinations, such as finger millet + red gram, finger millet + groundnut, and finger millet + soybean, have been found to result in higher land equivalent ratios and monetary advantages over sole finger millet cropping, particularly in regions like the red and lateritic belts of West Bengal. Effective nutrient management is crucial in intercropping systems. Supplying a balanced combination of nitrogen, phosphorus, and potassium (N-P-K) can significantly enhance productivity. Jagadeesha et al. (2010) reported that the application of organic manures like sewage sludge or poultry manure compost, equivalent to recommended nitrogen levels, resulted in significantly higher grain and straw yields for both finger millet and red gram in an intercropping system. This approach showed promise in substituting chemical fertilizers effectively. In summary, nutrient management practices within different cropping systems can have a substantial impact on finger millet productivity and overall sustainability. These practices can enhance yields, improve soil health, and reduce the reliance on synthetic fertilizers, promoting more sustainable and environmentally friendly agricultural systems.

Artificial Intelligence (AI) Techniques

Precision farming and digital agriculture were rapidly evolving fields, and several innovative nutrient management techniques were being explored or implemented in rice-millet cropping systems. However, please note that the specific techniques and technologies may have advanced further since then. Here are some of the latest and most innovative nutrient management techniques in precision farming and digital agriculture for rice-millet cropping systems: Nutrient Deficiency Detection: High-resolution satellite imagery and aerial drones equipped with various sensors can detect nutrient deficiencies in crops by analyzing the spectral signatures of plant leaves. This information helps farmers make targeted nutrient applications. Variable Rate Technology (VRT) enables the application of fertilizers, including macronutrients and micronutrients, at variable rates within a single field based on real-time data. Soil and plant sensors, GPS technology, and software algorithms help optimize nutrient distribution to match specific crop needs. Soil sensors and plant-based sensors provide real-time data on soil conditions and plant health. They measure nutrient levels, moisture content, and other relevant parameters, allowing farmers to adjust nutrient applications as needed. Digital platforms and nutrient management software offer data analysis and decision support. These tools integrate soil test results, weather forecasts, and crop growth models to provide farmers with nutrient management recommendations. IoT (Internet of Things)devices, including soil moisture sensors and weather stations, can be deployed across fields to continuously collect data. This data can inform precise nutrient management decisions and optimize irrigation practices. Machine learning is a branch of artificial intelligence in which the computer, referred to as a machine, learns to perform various tasks automatically Venkataraju et al. (2023).Machine learning algorithms and AI models can analyze historical data to predict nutrient requirements based on crop type, soil conditions, and weather patterns. These predictions help in proactive nutrient management. Mobile apps and software platforms provide farmers with tools for planning nutrient applications, tracking fertilizer usage, and monitoring crop progress using smart phones and tablets. ML Algorithms can predict yields using fertilizer rates, genetic data, and environmental and land management variables. Advances in machine learning, a subfield of artificial intelligence, are benefiting agriculture (Ennaji et al., 2023). Smart irrigation systems can be integrated with nutrient management by considering the interactions between water and nutrients. They optimize water use efficiency and nutrient uptake by crops. Blockchain technology is being explored to provide end-to-end traceability of agricultural inputs, including fertilizers. This ensures the quality and authenticity of nutrient sources. Online platforms and collaborative networks facilitate the sharing of nutrient management data and best practices among farmers, agronomists, and researchers. Innovative equipment, such as variable-rate fertilizer spreaders and injectors, allows precise nutrient delivery directly to the root zone of crops, reducing nutrient wastage. These innovative nutrient management techniques in precision farming and digital agriculture aim to optimize nutrient use, increase crop yields, reduce environmental impacts, and enhance the sustainability of rice-millet cropping systems. Farmers and agricultural stakeholders can benefit from adopting these technologies and practices to make more informed and efficient nutrient management decisions. It's advisable to consult local agricultural extension services or research institutions for the latest developments and recommendations specific to your region and cropping system.

This section describes various machine learning algorithms used in the area of nutrient management and fertilizer recommendations. This review focuses primarily on the current state-of-the-art ML techniques for nutrient management and fertilizer recommendation. It addresses the many factors that influence yield and how machine learning could help predict fertilizer recommendations. An extensive search was conducted to select relevant studies that use machine learning for nutritional management of cropping systems. In the first step, keywords such as "nutrient management", "machine learning in agriculture", "fertilizer forecasting" were used in various combinations including "machine learning in nutrient management", "fertilizer recommendation tools with machine learning" for a broad search through Science Direct, Pubmed, and Scopus. At a first level, publications were classified into two general categories: Nitrogen Management and Nitrogen Phosphorous Potassium (NPK) Management. Only articles published in peer reviewed journals were selected. Although climate prediction is critical to agricultural productivity, it is not covered in this review because machine learning applications to climate prediction are part of a separate area of study. Finally, all articles covered here were selected for the period from 2010 to July 2022 and found to be all within the scope of this work.

Conclusion

Millet cultivation is often associated with low-fertility soils and inadequate management practices, making the role of fertilization crucial for crop productivity. The quantity, timing, and method of nutrient application are key factors in achieving optimal finger millet yields. A well-balanced fertilization approach is essential for maximizing finger millet production. To further boost finger millet yields and improve soil health, the use of organic manures, biofertilizers, and integrated nutrient management (INM) practices is highly beneficial. Additionally, adopting legume-based cropping systems as part of nutrient management strategies plays a crucial role in enhancing finger millet production. However, it's important to acknowledge some limitations in nutrient management studies related to finger millet. These include the need for more research to address soil health improvement for sustainable production, a lack of comprehensive studies on INM, the identification of efficient finger millet-based cropping systems, and the development of soil test crop response (STCR) based nutrient management strategies tailored to different agroclimatic zones.

Reference

Ahiwale, P. H., Chavan, L. S., Jagtap, D. N., Mahadkar, U. V., and Gawade, M. B. (2013). Effect of establishment methods and nutrient management on yield attributes and yield of finger millet (Eleusine coracana G.). Crop Research. 45, 6-12.

Ali M and Kumar S. 2009. Major technological advances in pulses-Indian scenario. Milestones in Food Legumes Research, 20 p. (Eds. M Ali and S Kumar). Indian Institute of Pulses Research, Kanpur, India. MoA. Report of Expert Group on Pulses. Department of Agriculture and Cooperation, Ministry of Agriculture, Govt. of India, New Delhi. 9–10.

Arulmozhiselvan, K., Elayarajan, M., and Sathya, S. (2013). Effect of long-term fertilization and manuring on soil fertility, yield and uptake by finger millet on Inceptisol. Madras Agricultural Journal. 100, 1.

Bado BV., Bationo A., Whitbread A., Tabo R and Manzo MLS. (2022). Improving the productivity of millet based cropping systems in the West African Sahel: Experiences from a long-term experiment in Niger. Agriculture, Ecosystems and Environment. 335, 107992.

Basavaraj Naik, T., Kumar Naik, A. H., and Suresh Naik, K. P. (2017). Nutrient management practices for organic cultivation of finger millet (Eleusine coracana L.) under southern transitional zone of Karnataka, India. International Journal of Current Microbiological Applied Sciences. 6, 3371-3376.

Ceasar SA and Maharajan T. (2022). The role of millets in attaining United Nation's sustainable developmental goals. Plants People Planet. 4, 345–349.

Chaturvedi P, Govindaraj M, Govindan V and Weckwerth W. (2022). Editorial: Sorghum and Pearl Millet as Climate Resilient Crops for Food and Nutrition Security. Front. Plant Sci. 13, 851970.

Choudhary, S., Baghel, S. S., Upadhyay, A. K., and Singh, A. (2019). STCR-based manure and fertilizers application effect on performance of rice and chemical properties of Vertisol. Int. J. Curr. Microbiol. App. Sci. 8, 2080-2086.

Ebanyat P, de Ridder N, Bekunda M, Delve RJ and Giller KE (2021). Efficacy of Nutrient Management Options for Finger Millet Production on Degraded Smallholder Farms in Eastern Uganda. Front. Sustain. Food Syst. 5,674926.

Ennaji O.,Vergütz L., Allali AE. (2023). Machine learning in nutrient management: A review. Artificial Intelligence in Agriculture. 9, 1–11.

Fukagawa NK and Ziska LH. (2019). Rice: Importance for Global Nutrition. J Nutr Sci Vitaminol (Tokyo). 65, 2-3.

Gawade, M. B., Mahadkar, U. V., and Jagtap, D. N. (2013). Effects of organic manures, sources and levels of fertilizers on yield attributes and yield of finger millet (Eleusine coracana G.). International Journal of Agricultural Sciences. 9, 795-798.

Harika, J. V., Maitra, S., Shankar, T., Bera, M., and Manasa, P. (2019). Effect of integrated nutrient management on productivity, nutrient uptake and economics of finger millet (Eleusine coracana L. Gaertn). International Journal of Agriculture, Environment and Biotechnology. 12, 273-279.

Hassan ZM, Sebola NA and Mabelebele M. (2021). The nutritional use of millet grain for food and feed: a review. Agriculture and Food Security. 10, 16.

Hemalatha, S., and Chellamuthu, S. (2013). Impacts of long term fertilization on soil nutritional quality under finger millet: maize cropping sequence. Journal of Environmental Research and Development. 7, 1571-1576.

Iizumi T and Ramankutty N. (2015). How do weather and climate influence cropping area and intensity? Global Food Security. 4, 46-50.

Jagadeesha, N., Reddy, V. C., Krishnamurthy, N., and Sheshadri, T. (2010). Effect of organic manures on productivity of finger millet and redgram inter cropping system under protective irrigation. International Journal of Agricultural Sciences. 6, 453-455.

Kejiya, P., Vajantha, B., Naidu, M. V. S., and Nagavani, A. V. (2019). Effect of Phosphatic Fertilizer and Biofertilizers on Yield and Quality of Finger Millet (Eleusine coracana L.). Int. J. Curr. Microbiol. App. Sci. 8, 846-852.

Kim SH. (2007). Cultural perspectives and current consumption changes of cooked rice in Korean diet. Nutrition Research and Practice. 1, 8-13.

Koudahe K., Allen SC and Djaman K. (2022). Critical review of the impact of cover crops on soil properties. International Soil and Water Conservation Research. 10, 343-354.

Kumar R, Mishra J S, Hans H. (2018). Enhancing productivity of rice–fallows of eastern India through inclusion of pulses and oilseeds. Indian Farming. 68, 7–10.

Kumar R., Mishra JS., Upadhyay PK and Hans H. (2019). Rice fallows in the eastern India: Problems and prospects. Indian Journal of Agricultural Sciences. 89, 567–77.

Kumara, O., Basavaraj Naik, T., and Palaiah, P. (2010). Effect of weed management practices and fertility levels on growth and yield parameters in finger millet. Karnataka Journal of Agricultural Sciences. 20.

Maitra, S. (1997). Effect of different nutrients and other agronomic management practices on growth and yield of finger millet in sub-tropical humid region of West Bengal. Environment and Ecology. 15, 263-268.

Maitra, S., Reddy, M. D., and Nanda, S. P. (2020). Nutrient management in finger millet (Eleusine coracana L. Gaertn) in India. International Journal of Agriculture, Environment and Biotechnology. 13, 13-21.

Nishiuchi S., Yamauchi T., Takahashi H., Kotula L. and Nakazono M. (2012). Mechanisms for coping with submergence and waterlogging in rice. Rice. 5, 2.

Pallavi, C., Joseph, B., Aariff Khan, M. A., and Hemalatha, S. (2016). Effect of integrated nutrient management on nutrient uptake, soil available nutrients and productivity of rainfed finger millet. International Journal of Science, Environment and Technology. 5, 2798-2813.

Panda D and Barik J. (2021). Flooding Tolerance in Rice: Focus on Mechanisms and Approaches. Rice Science. 28, 43-57.

Pande S, Sharma M and Ghosh R. (2012). Role of pulses in sustaining agricultural productivity in the rainfed rice-fallow lands of India in changing climatic scenario. Climate change and food Security in India: Proceeding of National Symposium on Food Security in Context of Changing Climate. 53–70.

Patil, J. V. (Ed.). (2016). Millets and sorghum: biology and genetic improvement. John Wiley and Sons.

Patil, S. V., Bhosale, A. S., and Khambal, P. D. (2015). Effect of various levels of fertilizers on growth and yield of finger millet. IOSR Journal of Agriculture and Veterinary Science. 8, 49-52.

Prabhakar, P. C. G., Boraiah, B., Sujata Bhat, N. C., Kiran, T. V., and Manjunath, H. A. (2017). Improved Production Technologies for Finger Millet. Project Coordinating Unit ICAR-AICRP on Small Millets GKVK, Bengaluru-560. 6, 10-12.

Pravinkumar, G., Ramachandrappa, B. K., Thimmegowda, M. N., and Sahoo, S. (2017). Influence of Rotation, Use of Organic and Inorganic Sources of Nutrients on Growth, Yield and Quality of Eleusine coracana (L.) Gaertn. Environment and Ecology. 35, 2306-2311.

Ramakrishnan, K., and Bhuvaneswari, G. (2014). Effect of inoculation of am fungi and beneficial microorganisms on growth and nutrient uptake of Eleusine coracana (L.) Gaertn. (Finger millet). International Letters of Natural Sciences. 8.

Ramamoorthy, B., Narasimhan, R. L., and Dinesh, R. S. (1967). Fertilizer recommendations based on fertilizer application for specific yield of Sonara-64. Indian Farming. 17, 51.

Ramamoorthy, K., and Lourduraj, A. C. (2002). Intrgrated nutrient management in direct sown rainfed fingermillet (Eleusine coracana Gaertn.). Madras Agricultural Journal. 89, 1.

Rangaswamy, P. (1973). Effect of nitrogen and farm yard manure on finger millet Eleusine coracana (L.) Gaertn.

Regar, K. L., and Singh, Y. V. (2014). Fertilizer recommendation based on soil testing for the targeted yield of rice in eastern plain zone of Utter Pradesh. The Bioscan. 9, 531-534.

Roy, A. K., Ali, N., Lakra, R. K., Alam, P., Mahapatra, P., and Narayan, R. (2018). Effect of integrated nutrient management practices on nutrient uptake, yield of finger millet (Eleusine coracana L. Gaertn.) and post-harvest nutrient availability under rainfed condition of Jharkhand. International Journal of Current Microbiology and Applied Sciences. 7, 339-347.

Roy, D. K. (1996). Response of Finger-Millet Varieties to Levels of Nitrogen Under Rainfed Red and Laterite Zone of West Bengal. Environment and Ecology. 14, 367-370.

Roy, D. K., Chakraborty, T., Sounda, G., and Maitra, S. (2002). Growth and yield attributes of finger millet as influenced by plant population and different levels of nitrogen and phosphorus. Indian agriculturist. 46, 65-71.

Saleem, S., Mushtaq, N. U., Shah, W. H., Rasool, A., Hakeem, K. R., Seth, C. S., ... and Rehman, R. U. (2023). Millets as smart future food with essential phytonutrients for promoting health. Journal of Food Composition and Analysis. 105669.

Sandhya Rani, Y., Triveni, U., Patro, T. S. S. K., and Anuradha N, N. (2017). Effect of nutrient management on yield and quality of finger millet (Eleusine coracana (L.) Gaertn). International Journal of Chemical Studies. 5, 1211-1216.

Saraswathi, S. V., and Dinesh Kumar, M. (2018). Effect of NPK application through different approaches on yield and secondary nutrient uptake by finger millet under rainfed conditions. Int. J. Pure App Biosci. 6, 735-741.

Sathish, A., Ramachandrappa, B. K., Shankar, M. A., Srikanth Babu, P. N., Srinivasarao, C. H., and Sharma, K. L. (2016). Long term effects of organic manure and manufactured fertilizer additions on soil quality and sustainable productivity of finger millet under a finger millet–groundnut cropping system in southern India. Soil Use and Management. 32, 311-321.

Sen S, Chakraborty R, Kalita P. (2020). Rice - not just a staple food: A comprehensive review on its phytochemicals and therapeutic potential. Trends in Food Science and Technology. 97, 265-285.

Sood, V. K., Sharma, V., Dixit, S. P., Verma, R., and Katna, G. (2023). Present Status and Revival of Millets Cultivation in Himachal Pradesh. Himachal Journal of Agricultural Research. 49, 18-37.

Srinivasarao, C., Venkateswarlu, B., Lal, R., Singh, A. K., Kundu, S., Vittal, K. P. R., ... and Gajanan, G. N. (2012). Long-term effects of crop residues and fertility management on carbon sequestration and agronomic productivity of groundnut–finger millet rotation on an Alfisol in southern India. International Journal of Agricultural Sustainability. 10, 230-244.

Srivastava, P., Sangeetha, C., Baskar, P., Mondal, K., Bharti, S. D., Singh, B. V., and Agnihotri, N. (2023). Unleashing the Potential of Millets Promoting Nutritious Grains as Vital Cereal Staples during the International Year of Millets: A Review. Int. J. Plant Soil Sci. 35, 1860-1871.

Swain P, Panda N and Pattanayak S.K. (2021). Effect of long term integrated nutrient management practices on yield and nutrient uptake by finger millet (Eleusine coracana L.) in an acidic Inceptisols. Annals of Plant and Soil Research. 23, 473-476.

Szabo Z., Koczka V., Marosvolgyi T., Szabo E., Frank E., Polyak E., Fekete K., Erdelyi A., Verzar Z and Figler M. (2021). Possible Biochemical Processes Underlying the Positive Health Effects of Plant-Based Diets—A Narrative Review. Nutrients. 13, 2593.

Troug, E. (1960). Fifty years of soil testing, transactions of 7th International Congress of Soil Science. Vol. III, Commission IV. 746, 53.

Ullah A., Ahmad A., Khaliq T and Akhtar J. (2017). Recognizing production options for pearl millet in Pakistan under changing climate scenarios. Journal of Integrative Agriculture. 16, 762–773.

Vamshi Krishna, K., Deepthi, C. H., Reddy, M. D., Raju, P. S., and Pal, A. (2020). Effect of nitrogen and phosphorus levels on growth and yield of finger millet [Eleusine coracana (L.)] during summer. Indian Journal of Agricultural Research. 54, 227-231.

Venkataraju, A., Arumugam, D., Stepan, C., Kiran, R., Peters, T. (2023). A review of machine learning techniques for identifying weeds in corn. Smart Agricult. Technol. 3, 100102.

Wilson ML and VanBuren R. (2022). Leveraging millets for developing climate resilient agriculture. Current Opinion in Biotechnology. 75, 102683.

Yadav, R., Naresh, M., and Yadav, V. K. (2010). Response of finger millet (Eleucine coracana (L.) Gaertn) genotypes to nitrogen under rainfed situations of western Himalayan hills. International Journal of Agricultural Sciences. 6, 325-326.

Chapter 10

Microbial Manipulations for Sustaining Millet Production Under Climate Change Scenario

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Abstract

An improvement in the production of millet is a demand for the human population owing to the nutritional quality of this food. However, exposure to climatic change and different abiotic stresses reduces crop yield. The growth, development, and productivity of millet are influenced by the microbial communities in the rhizosphere. This chapter focuses on the positive effects of

soil microbes on millet productivity under extreme environmental conditions. A comprehensive approach for analyzing the impact of plant growth-promoting microorganisms (bacteria, fungi, and actinomycetes) and mycorrhizae was adopted in this study. Moreover, microbial-induced physiological, morphological, and molecular modulations in millet development are described here. Increases in mineral acquisition, changes in root architecture, improved metabolic production, and elicitation of plant hormones are the major contributions of microbes. This chapter aids in improving the knowledge regarding the role of rhizospheric microbes in improving millet production.

Keywords: climatic change, plant growth-promoting microorganisms, stresses, millet, omics.

Introduction

Men's increased urge for a luxurious lifestyle has pushed our mother earth globally towards the verge of extreme climate change, which has in turn dropped its overall agricultural production. The global food system housing production for various stable crops and grains has diminished. In turn, this is a major threat to food shortages by creating a food security crisis in the future. Hence, the global agricultural market withstands a formidable threat to livelihoods and food security by making the survival of crops vulnerable. Thus, the need to increase the agricultural yields of crops and millet has become a significant matter of concern. In summary, it can be stated that upbringing new staple alternatives endowed with unique attributes such as stress resistance, tolerance to natural factors that might become disastrous, and microbial manipulations will carve a transformative way for the sustainable future of our siblings.

Millets are nutrient-rich, small-grained grasses that serve as major staples in semi-arid parts of Africa and Asia. They are desirable candidates for underdeveloped agricultural areas because of their all-season growth and low water requirements. There are six mainly of 6 types ranging from finger millet to pearl millet (Lata et al., 2013). Millet is often regarded as a climate-resilient, drought-tolerant cereal crop that upholds the innate potency to thrive under drastic climate change to enhance the diversity of dietary staples compared to classical cereal crops (Amadou et al., 2013). Despite these traits, millet is tortured by erratic rainfall, varied temperatures, altered soil factors, and a higher risk of pests and diseases (Lobell et al., 2011). These abiotic stressors can be reduced by advocating sustainable agricultural methods, such as the manipulation of soil microbial consortia.

The adaptive capacity of millet grains is enhanced by the soil microbes that inhibit the rhizosphere. The soil microbiome housing mycorrhizal fungi and Plant growth promoting rhizobacteria plays the crucial part by imparting positively on their overall growth *via* resistance to pathogens, increased nutrient uptake, efficient water usage, and tolerance to abiotic stressors (Lladó and Baldrian, 2017) Millet yield can be bolstered by application of microbial inoculants (biofertilizers), biocontrol agents and incorporation of genetic engineering practices for uplifting microbe- millet interaction zone (Marschner et al., 2004; Nadeem et al., 2014; Altieri and Nicholis, 2020). Hence, it can be justified that in the adverse climate change phase, by inculcating sustainable agricultural practices in millet production, the food security of future generations can be preserved.

Impact of climatic change on millet production

Shifts in climate patterns, which are mainly caused by anthropogenic activities, have gravely affected global agriculture. The greenhouse gases emitted by these activities are the primary sources of rising temperatures (Ortiz-Bobea et al., 2021). This increase in global temperature causes heat stress in the plants. A mere increase of 1 °C in global temperature can enhance the water requirement of a crop by at least 10% (Shahzad et al., 2021). Such conditions can escalate drought stress in drought-prone areas and poor irrigation practices can cause increased episodes of salinity. The sensitivity of agriculture to unprecedented conditions affects global food security (Abbass et al., 2022). A descendant of African grass, millet, is an important stable crop cultivated globally on more than 30 million hectares. Small-seeded plants belonging to the Poaceae family are highly nutritious. It is an excellent source of vitamins B and E and minerals. The phenolic content of millet is associated with its high antioxidant activity (Meena et al., 2021; Chandra et al., 2021).

Owing to the diversity of millet species, they are widely used in various societies. Altogether, African and Asian nations are the largest millet producers. Countries such as Nigeria, Niger, Sudan, China, and India have a long history of millet production. Global millet production has been relatively stable over the years, as the crop is well suited to most regions compared to other cereals (Meena et al., 2021; Satyavathi et al., 2021). However, a changing climate could affect this otherwise hardy crop. Although millet is a kharif crop, its optimum growth temperature falls around 33-34 °C. With each degree of temperature increase beyond this range, the yield of millet crops is affected. High temperatures can delay germination of millet plants (Heureux et al., 2022). When observed around the grain-filling stages, extreme temperatures caused a reduction in the tiller number, grain weight, and overall grain development. High temperatures also increase the prevalence of biotic stressors. If not managed properly, it can enhance the disease progression. In the long run, changes in global temperatures could potentially lead to changes in the millet growing season, which would hamper optimum yield (Saleem et al., 2021; Muthuvel and Amai 2022). When coupled with reduced rainfall, heat stress can lead to drought-like conditions.

Millet production is highly affected by drought stress because of the relatively high water demand. Frequent dry spells, reduced rainfall, and high temperatures are primary causes of reduced millet production. Plants tend to close their stomata as a defence mechanism against drought stress. This further causes an increase in oxidative stress owing to the generation of higher reactive oxygen species. This dominant effect leads to lipid peroxidation and damages vital functions in millets. Oxidative stress eventually reduces pigment production and photosynthetic activity (Saleem et al., 2021; Shrestha et al., 2023). Overall, plant height was significantly reduced, and the roots and leaves curled. In addition, the biomass, fresh and dry weights of the plants, and grain number also decreased (Figure 1). Although millet can tolerate mild drought conditions, it can reduce production to as low as 150 kg/ha compared to the typical yield of ~900-1500 kg/hectare (Shrestha et al., 2023).

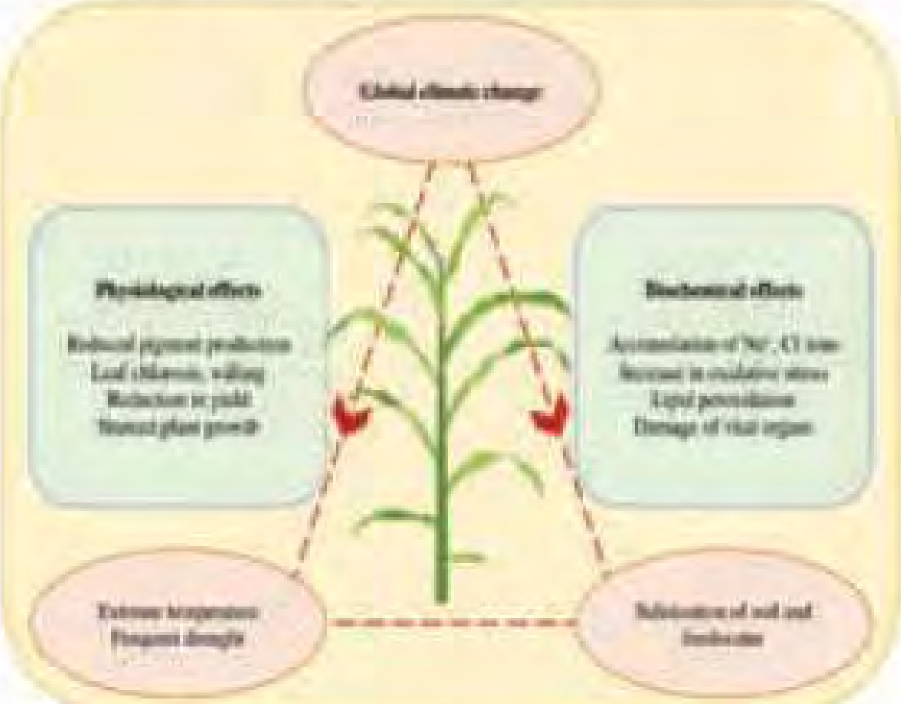

Fig. 1: Effect of climate change on physiological and biochemical attributes of millet plant.

Drought stress is often associated with salinity. According to previous reports, 20-33% of global arable land is affected by salinity. This number is expected to double by 2050, and Na+ and Cl- ions are expected to cause ion-specific toxicity in millet plants (Singh 2022). Salinity stress restricts water absorption in plants, and as a result, the uptake and transportation of nutrients is severely hampered. Reduced nutrition causes a decrease in physiological attributes such as fresh plant weight, dry weight, and pigment production. Salinity stress also causes chlorosis in various parts of the plant, particularly in the leaves. The relative water content of plants decreases as a result of which plant wilt and yield are reduced (Kumar and Sharma 2020; Saleem et al., 2021).

Unsuitable climatic and edaphic conditions pose the risk of migration to existing communities in vulnerable areas. Many areas use indigenous practices for millet cultivation, and rapid changes in the global climate can disrupt these practices. Because millet is a source of nutrition for millions of people, any reduction in millet production risks food security. Therefore, it is imperative to address the effects of climate change on agriculture in order to ensure sustainability. Changing weather patterns, droughts, and extreme temperatures directly influence productivity and food price. Various developing countries have agrarian economies; thus, reliance on agriculture is vital for nations and their citizens. Training and knowledge of climate-resilient farming techniques are crucial (Lenka et al., 2020; Mohod et al., 2023). This will allow farmers to adapt to unprecedented scenarios. Climate-smart policies and corporate collaborations with local farmers can ensure the sustainability of food systems. Additionally, continuous and long-term assessments are required to adapt to this situation.

Different methods in improving stress resilience of millet

In recent decades, many attempts have been made to apply and improve various methods to obtain more climate-flexible and stress-resistant plants in a sustainable manner to enhance agricultural productivity and ensure food security. Currently, the constantly changing climatic conditions impose several abiotic and biotic stress factors on agronomy. For example, abiotic stresses, including salinity, water scarcity, extreme temperature, and ultraviolet radiation, and biotic stresses, such as diseases causing plant pathogens and insects. (González et al., 2022). These stressors adversely affect global agricultural productivity. The stresses responsible for worldwide food crops are projected to decline by 50% (abiotic stress) and 30% (biotic stress), ultimately threatening food security for the anticipated 10 billion population by 2050 (Kelbessa, 2023). Millet is a necessary food crop in the global agricultural system. Therefore, it is crucial to pay attention to potential approaches, such as the utilization of plant growth-promoting microorganisms, plant growth regulators, and molecular techniques, to improve the tolerance and/or resilience of millet crops against various abiotic and biotic stresses in the context of climate smart and sustainable agriculture.

Plant growth promoting microorganisms (PGPMs)

The most sustainable and economically realistic method to cope with the negative effects of stress on crops is the use of plant growth-promoting microorganisms (PGPMs). PGPMs support plants under several stress conditions owing to their plant growth-promoting attributes. Mahadik and Kumudini (2020) found that plant growth-promoting rhizobacteria (PGPR) *Florescent Pseudomonads* enhance the growth of salinity-sensitive finger millet under salinity. The strain *Florescent Pseudomonads* was able to increase spikelet number, plant height, germination, phenolics, total chlorophyll, flavonoids, antioxidant enzyme proteins, and proline content, while lowering the H_2O_2 amount and lipid peroxidation. Drought tolerant 1-aminocyclopropane-1-carboxylic acid (ACC) deaminase-producing strain Pseudomonas spp. enhances antioxidant activity and improves finger millet growth under drought stress (Chandra et al., 2018). The ACC deaminase gene-containing Sphingomonas faeni mutant enhances biomass, shoot height, root length, and antioxidant activity in foxtail and finger millet under cold stress (Srinivasan et al., 2017). The bioinoculant halophilic Enterobacter sp. PR14 demonstrated a salt-stress-mitigating ability in millet. Plant growth-promoting attributes include the production of ACC deaminase and IAA, phosphate solubilization, and antioxidant enzyme activity. In addition, millet growth is promoted by increased germination, dry weight, shoot height, and root length (Sagar et al., 2020). The halotolerant endophytic strain *Bacillus amyloliquefaciens* EPP90 showed multi-stress tolerance and growth promotion in pearl millet (Kushwaha et al., 2020).

Indigenous rhizosphere *Pseudomonas* sp. MSSRFD41 exhibits biotic stress resistance against blast disease and promotes finger millet growth promotion (Sekar et al., 2018). The endophyte *Aspergillus terreus* promotes plant growth in pearl millet under salt stress by increasing the total chlorophyll content, soluble sugars, RWC, soluble sugar, and flavonoids (Khushdil et al., 2019). Inoculation with drought-tolerant PGPR improves foxtail millet growth under water-scarce conditions (Niu et al., 2018). Kour et al. (2020) found that phosphate-solubilizing strains *Acinetobacter calcoaceticus* and *Penicillium* sp. were capable of alleviating the negative effects of drought stress in foxtail millet by enhancing proline, glycine betaine, and soluble sugar content. Inoculation with the root-colonizing endophytic *Piriformospora indica* fungi improved grain quantity, pinnacle length, plant height, and phosphorus, chlorophyll, protein, and nitrogen *Panicum miliaceum* under water scarcity conditions (Ahmadvand et al., 2018). Several studies have shown that bioinoculation with plant growth-promoting bacteria (PGPB) such as *Florescent pseudomonads, Acinetobacter calcoaceticus*, and *Enterobacter* sp. PR14 mitigates the adverse effects of abiotic stress in millet (Saleem et al., 2021).

Plant growth regulators (PGRs)

Application of spermidine (Spd) and biogenic amine putrescine (Put) to foxtail millet under salinity stress resulted in increased amounts of biomass, total chlorophyll, relative water content, carotenoids, and upregulation of antioxidant enzyme activity, while reducing electrolyte leakage and H_2O_2 levels (Rathinapriya et al., 2020). The combination of salicylic acid (SA) and sodium nitroprusside (SNP) alleviated the adverse effects of nickel (Ni) by enhancing shoot height, root length, total chlorophyll, minerals, and dry biomass in finger millet under nickel-induced stress (Kotapati et al., 2017). Sulfur dioxide (SO_2) treatment increased tolerance of foxtail millet to cadmium-induced stress. SO_2 was able to enhance antioxidative enzyme activity, phytochelatins, and glutathione while lowering the uptake and translocation of Cd (Han et al., 2018). According to Rasool et al. (2020), the application of 1 μM selenium (Se) improves the growth of *Setaria italica* and *Panicum miliaceum* under salinity (50–200 mM NaCl). Selenium treatment mitigated the negative effects of salt stress by increasing the amount of antioxidant enzymes, biomass, and osmoprotectants, and decreasing the quantity of H_2O_2. Combined treatment with proline and hydrogen sulfide (H_2S) mitigated the negative effects of cadmium (Cd^{2+}) in foxtail millet (Tian et al., 2016). Basilio-Apolinar et al. (2021) reported that the use of silicon (Si) notably improved the stress tolerance of *Panicum miliaceum* L. under salt and drought stress conditions by supporting millet at physiological and biochemical levels.

Molecular approaches

Plant responses to different environmental stressors are expressed and recognized at the molecular level. Shinde et al. (2018) performed a comparative *de novo* transcriptomic analysis (RNA-Seq approach) and provided informative clues such as ion transporters, DEGs encoding transcription factors, and regulators of metabolic pathways to understand the salt stress tolerance mechanism of salinity-tolerant and salinity-susceptible pearl millet crops. These findings are beneficial for improving salt stress in millet through crossbreeding and transgenic techniques. Vaezi et al. (2020) demonstrated that the tolerance genotype selection index (TGSI) is a suitable strategy for screening drought-adapted ecotypes in plant breeding. The five ecotypes with the highest grain and forage yields among the 96 ecotypes were identified.

These ecotypes are promising ecotypes that can be considered a new variety of millet via the appropriate selection of drought-affected areas. According to Jangra et al. (2019), marker-assisted selection is an appropriate technique for obtaining drought stress and downy mildew resistance characteristics in pearl millet by inserting desired QTLs/traits. Li et al. (2014) used the target character gene bank breeding method to create a new cultivar of foxtail millet, Jigu32, with stable, high yield, and superior qualities.

Sharma et al. (2021) developed biotic and abiotic stress-resistant varieties of millet using two blast-resistant varieties by the backcross method. Hema et al. (2014) produced transgenic finger millet with improved salt and drought stress resistance traits using agrobacterium tumefaciens-mediated genetic transformation. Loni et al. (2023) conducted an integrative meta-analysis survey to identify the most significant genome sections and potential genes involved in the genetic control of yield preservation and drought tolerance in foxtail millet. These results will also be helpful in the production of high-yielding drought-resistant varieties. Several studies have been conducted to provide detailed information on different techniques to achieve better abiotic and biotic stress tolerance in millet crops under changing climatic conditions (Singh et al., 2022; Vetriventhan et al., 2020; Yameogo et al., 2022; Satyavathi et al., 2019; Lata, 2015; Mbinda and Mukami, 2021; Gupta et al., 2017; Shivhare and Lata, 2017, 2016; Numan et al., 2021; Bollam et al., 2018; Wilber et al., 2021; Serba and Yadav, 2016; Mbinda and Masaki, 2021; Choudhary et al., 2023; Han et al., 2022)

Role of microbes in plant stress tolerance
Plant Growth Promoting Bacteria

Bacteria, the most common soil microorganisms, colonize plant roots and improve plant growth under stressful conditions, with various bacterial families involved. For instance, the growth of tomato seedlings, groundnuts, and salinity-induced osmotic stress in pepper have all been found to benefit from the use of ACC deaminase-containing bacteria, such as *Achromobacter piechaudii* ARV8, *Pseudomonas fluorescens*, and *Bacillus* sp. (Jurić et al., 2020). Additionally, *P. fluorescens* has been demonstrated to increase tolerance by reducing osmolyte synthesis and generating salt-stress proteins such as osmotins and dehydrins (Khan et al., 2021). It has been established that PGPR, including *Paenibacillus polymyxa*, *Achromobacter piechaudi*, *Azospirillum brasiliense*, *Pseudomonas* sp., *Burkholderia*, *Arthrobacter*, *Micrococcus luteus*, and *Bacillus*, improved the drought tolerance of *Arabidopsis thaliana* (Trivedi et al., 2020), pepper, tomato (Ali & Khan, 2021; Kaur & Suseela, 2020)frequency, and duration in many parts of the world, with potential negative impacts on plant growth and productivity.

The plants have evolved complex physiological and biochemical mechanisms to respond and adjust to water-deficient environments. The physiological and biochemical mechanisms associated with water-stress tolerance and water-use efficiency have been extensively studied. Besides these adaptive and mitigating strategies, the plant growth-promoting rhizobacteria (PGPR wheat (Jurić et al., 2020), and maize (Khan et al., 2021) plants.

Some of these bacterially induced tolerances have been linked to an increase in mRNA transcription of the drought response gene ERD15, production of 1-aminocycloropropane-1-carboxylic acid (ACC) deaminase, higher proline synthesis, and an improvement in relative and absolute water content (Chukwuneme et al., 2021)with studies reporting reduced microbial activities due to anthropogenic activities. In this study, we analyzed and compared the composition, diversity, and metabolic profiles of microbial communities in maize rhizosphere soils of a former grassland and an intensively cultivated land. Metagenomic DNA was extracted from maize rhizosphere and bulk samples and sequencing was performed using the shotgun metagenomic approach. Comparative analyses of the metagenomes revealed differences in the distribution of microbial communities across the soils. Alpha diversity indices (Simpson, Shannon, and Evenness . According to (Kerbab et al., 2021), PGPRs can be inoculated along with other microorganisms to reduce the effects of salt stress. For instance, *Pseudomonas mendocina* enhances the growth, nutrient absorption, and other physiological activities of salt-stressed *Lactuca sativa* when used alone or in conjunction with an AM fungus such as *Glomus intraradices* or *Glomus mosseae*.

Extreme temperatures can be mitigated by the PGPR, as has long been demonstrated. When canola was exposed to 5 °C between spring and winter, Keswani et al. (2020) discovered that the bacterial strain *Pseudomonas putida* GR 12-2 encouraged growth and root elongation. Other studies have revealed that *Bradyrhizobium japonicum*, *Serratia proteamaculans*, and *Serratia liquefaciens* benefit the growth and physiology of soybean cultivated under suboptimal root-zone temperatures (Keswani et al., 2020).

The alleviation of heavy metals has also been linked to PGPR. Some studies have reported that bacterial strains including *Pseudomonas brassicacearum*, *Pseudomonas marginalis*, *Pseudomonas oryzihabitans*, *Pseudomonas putida*, *Pseudomonas tolaasii* ACC23, *Alcaligenes xylosoxidans*, *Alkaligenes* sp. ZN4, *Variovorax paradoxus*, *Bacillus pumilus*, and *Rhodococcus* sp. improve the growth of the metal-accumulating plant *Brassica juncea* (Asad et al., 2019). The bacterial strain *Kluyvera ascorbata* SUD165 protects canola seedlings against nickel toxicity (Chakraborti et al., 2022). Furthermore, the inoculation of lettuce seeds with *Azospirillum* prior to exposure to NaCl enhances germination and vegetative development (Samaddar et al., 2019). Decreased amounts of endogenous ethylene have been linked to bacterial tolerance to salt stress, according to certain studies (Kerbab et al., 2021). Bacteria that promote plant growth may help plants adapt to environmental challenges, regardless of their specific defenses. Owing to the stabilization and replanting of abiotically stressed abandoned lands, food production will correspondingly increase.

Mycorrhiza

Arbuscular mycorrhizal fungi have been found to induce a variety of stress tolerances while living harmlessly inside the host plant. Abiotic stress tolerance may be generated by the use of numerous endophytic AM that coexist with approximately 80% of plants in mutually advantageous interactions (Poveda et al., 2020). AM has been demonstrated to enhances salt tolerance through several different mechanisms, including altering the K+/Na+ ratio in plant cells, transferring ion salts into the vacuole, producing growth hormones, improving soil and rhizospheric conditions, and improving photosynthetic or water use efficiency (Sofy et al., 2021). Additionally, AM serves as an osmoregulator by improving the effects of salt stress by increasing sugar and electrolyte concentrations (Singh et al., 2019). In another study, AM increased the antioxidant capacity by turning on the glutathione-ascorbate cycle in plants to produce tolerance to salt stress. Additionally, it has been shown that AM symbiosis increase the salt tolerance of plants such as maize, clover, tomato, cucumber, and lettuce (Singh et al., 2019). AM-induced tolerance is a typical aspect of abiotic stress tolerance in drought-stressed plants (Ullah et al., 2019).

Abiotic stress tolerance in drought-stressed plants typically involves AM-induced tolerance (Ullah et al., 2019). AM has also been claimed to increase a plant's resistance to temperature change. In particular, it has been demonstrated that AM *Glomus mosseae* helps tomato plants (*Lycopersicon esculentum* cv Zhongzha105) recover from the damage caused by chilling stress by reducing membrane lipid peroxidation while increasing the amount of photosynthetic pigments, accumulating osmotic adjustment compounds, and antioxidant enzyme activity (Sytar et al., 2019). AM confers stress tolerance in heat-stressed plants by increasing phytohormone levels, postponing premature plant senescence and boosting secondary metabolites (proline and anthocyanins) (Kapoor & Hasanuzzaman, 2020). AM reduces membrane lipid peroxidation and plasma membrane permeability under chilling stress, increases osmolyte accumulation, activates antioxidant enzymes, and improves photosynthetic performance (Riaz et al., 2021).

AM also has a significant effect on heavy-metal tolerance in metal-toxic soils.

For instance, AM inoculation has been suggested to improve the growth of tomato seedlings, canola, maize, and rice grown in soils contaminated with heavy metals by reducing the uptake of toxic metals, enhancing the uptake of essential nutrients from the soil, and increasing the production of glycoproteins, glomalin, and cell wall chitin, which form complexes with heavy metals (Sytar et al., 2019). Additionally, AM enhances the performance of heavy metal-stressed plants by enhancing antioxidant enzyme activity and accumulation of soluble amino acids. AM ecotypes, such as *Glomus mossae*, *Glomus claroideum*, *Viola calaminaria*, and *Aspergillus niger*, have been isolated from soils contaminated with high concentrations of heavy metals and have been employed to reduce heavy metal stress (Betekhtina et al., 2021).

Plant Growth Promoting Fungi

Rhizosphere fungi have also been associated with stress tolerance and the adaptation of plants to different habitats, particularly those subjected to abiotic pressures (Brundrett, 2002). The rhizosphere is a habitat for plant-associated fungi known as rhizosphere fungi. These fungi utilize nutrients to establish plant-soil-rhizospheric fungal interactions that are crucial for the sustainability of ecosystems and the environment (Pattnaik & Busi, 2019). "Plant growth-promoting fungi" (PGPF) are fungi that live in the rhizosphere and are beneficial to plants (Murali et al., 2021). There are a vast range of fungi with these characteristics, and the relationships between plants and fungi that foster plant growth are advantageous for plants. They are primarily found in the genera *Trichoderma, Penicillium, Aspergillus, Fusarium, Mortierella, Phoma*, and *Piriformospora* (Javed et al., 2020; Jin et al., 2022; Lombardi et al., 2020; Zhu et al., 2022), according to the information that has been provided. These beneficial fungi reinforce plant growth and protection via both direct and indirect mechanisms. The production of organic acids and siderophores (nitrogen, phosphorus, potassium, zinc, and iron), the production of phytohormones (auxins, cytokinins, gibberellins, and abscisic acid), the production of hydrolytic enzymes (xylanases, laccases, pectinases, and cellulases), and decreased ethylene levels due to the production of the enzyme 1-aminocyclopropane-1-carboxylate deaminase (ACCD) are some of these mechanisms (Devi et al., 2020; Silva et al., 2021). Enhanced germination, seedling vigor, biomass production, root hair development, photosynthetic efficiency, blooming, biochemical composition, yield, and disease control are examples of these mechanisms in plants (Hossain et al., 2017).

Plant Growth Promoting Actinobacteria

According to numerous studies, a diverse group of microorganisms, known as Actinobacteria, are essential for promoting plant growth while alleviating abiotic stress through various processes (Sathya et al., 2017)through symbiotic nitrogen fixation, meet a major part of their own N demand and partially benefit the following crops of the system by enriching soil. In realization of this sustainability advantage and to promote pulse production, United Nations had declared 2016 as the "International Year of pulses". Grain legumes are frequently subjected to both abiotic and biotic stresses resulting in severe yield losses. Global yields of legumes have been stagnant for the past five decades in spite of adopting various conventional and molecular breeding approaches. Furthermore, the increasing costs and negative effects of pesticides and fertilizers for crop production necessitate the use of biological options of crop production and protection. The use of plant growth-promoting (PGP. One of these strategies is nitrogen fixation, in which Actinobacteria assist in converting atmospheric nitrogen into forms that plants can utilize (Qin et al., 2015)information about the endophytic actinobacteria with ACC deaminase activity associated with native plants is still very scarce. In this study, a total of 257 endophytic actinobacterial isolates were obtained using actinobacteria-selective media from surface sterilized roots, stems, leaves and seeds of the oil-seed plant Jatropha curcas L. collected from dry-hot valley soil. Morphological and the 16S rRNA sequence analysis showed that most of the isolates belong to the Streptomyces genus and other non-. Streptomyces strains distributed onto 13 genera, with several new species. 19 strains were found to have ACC deaminase activity and they belong to the genera Streptomyces, Nonomuraea, Micrococcus and Kibdelosporangium. The functional ability of the ACC deaminase producing isolates to produce indole-3-acetic acid (IAA. Phosphorus, a crucial nutrient for plant growth, is readily available to plants via the capacity of Actinobacteria to solubilize it (Passari et al., 2016).

The production of siderophores is another crucial task performed by these bacteria perform (El-Tarabily et al., 2020). Siderophores are iron-chelating substances that assist plants in absorbing iron even in soils with low element levels. Auxins (IAA) (Qin et al., 2015)information about the endophytic actinobacteria with ACC deaminase activity associated with native plants is still very scarce. In this study, a total of 257 endophytic actinobacterial isolates were obtained using actinobacteria-selective media from surface sterilized roots, stems, leaves and seeds of the oil-seed plant Jatropha curcas L. collected from dry-hot valley soil. Morphological and the 16S rRNA sequence analysis showed that most of the isolates belong to the Streptomyces genus and other non-. Streptomyces strains distributed onto 13 genera, with several new species. 19 strains were found to have ACC deaminase activity and they belong to the genera Streptomyces, Nonomuraea, Micrococcus and Kibdelosporangium. The functional ability of the ACC deaminase producing isolates to produce indole-3-acetic acid (IAA, gibberellins (Etminani & Harighi, 2018)samples were collected from the leaves and stems of healthy wild Pistachio trees (Pistacia atlan-tica L., and cytokinins (El-Tarabily et al., 2020) are only a few phytohormones produced by Actinobacteria. These phytohormones control abiotic stress and regulate plant growth and development. Actinobacteria also contribute to the health of plants through the production of volatile organic compounds (VOCs) (Passari et al., 2020) and 1-aminocyclopropane 1-carboxylate (ACC) deaminase activity (Qin et al., 2015)information about the endophytic actinobacteria with ACC deaminase activity associated with native plants is still very scarce. In this study, a total of 257 endophytic actinobacterial isolates were obtained using actinobacteria-selective media from surface sterilized roots, stems, leaves and seeds of the oil-seed plant Jatropha curcas L. collected from dry-hot valley soil. Morphological and the 16S rRNA sequence analysis showed that most of the isolates belong to the Streptomyces genus and other non-. Streptomyces strains distributed onto 13 genera, with several new species. 19 strains were found to have ACC deaminase activity and they belong to the genera Streptomyces, Nonomuraea, Micrococcus and Kibdelosporangium. The functional ability of the ACC deaminase producing isolates to produce indole-3-acetic acid (IAA, Actinobacteria also contribute to the health of plants. These VOCs can help plants grow and function as pathogen-defeating signaling molecules. Polyamine formation further improves the ability of Actinobacteria to stimulate plant development (El-Tarabily et al., 2020).

Moreover, the multifaceted contributions of Actinobacteria to plant growth and health, including their involvement in nutrient acquisition, phytohormone production, VOC synthesis, and biocontrol activities, make them indispensable for sustainable agriculture (Yadav et al., 2020). By harnessing these biological processes, farmers can stimulate plant growth, improve productivity, and maintain soil fertility, thereby promoting environmentally friendly and sustainable agricultural practices (Raklami et al., 2019).

OMICS approaches for Millet improvement

Modern science defines omics approaches as the amalgamation of bioinformatics, analytical methods, and computational analysis with high-end technologies for diving deep into the mystery of proteins, genes, metabolites, mRNA, and epigenetics to unravel the intricacies of millet phenotypes (Banshidhar et al., 2023). The arena of crop improvement has been removed using multi-omics approaches, such as metabolomics, transcriptomics, proteomics, and genomics. Scientists have employed these techniques to unmask the mysteries of millet biology in order to mold better crops with enhanced nutritional value and resilience. By applying genomics to the millet genome of pearl millet *via* sequencing, genes specific for stress tolerance and nutritional quality were identified and used to breed better varieties (Varshney et al., 2017). In foxtail millet, the application of transcriptomics has resulted in the screening of specific genes to optimize the drought stress response by genetic engineering practice (Lata et al., 2010). The nutraceutical potency of finger millet is enhanced by the incorporation of nutrigenomics along with genome sequencing for the identification of key genes to upgrade the nutrient efficiency of the crop (Kumar et al., 2016). Transcriptomic studies have removed tolerance to stress-defining factors, such as salinity, water deficit, heat, and light quality, by identifying the expression patterns of genes responsible for the former. The response to heat and drought stress has been optimized for the pearl millet Tifleaf3 genotype (Sun et al., 2020). Salinity stress tolerance is enhanced in foxtail, broomcorn, and pearl millets (Yue et al., 2016; Shinde et al., 2018; Pan et al., 2020). Proteomic studies on finger millet have revealed the role of jasmonic acid in framing responses to stressful environments (Sen et l., 2016). Metabolomic studies of fox tail millet have reframed the pathway of flavonoids, lysophospholipids, phenylpropanoids, and lignin as key aspects aiding seed germination and salt stress (Pan et al., 2020). Epigenomic studies of pearl millet have shown that hemimethylation is an effective defense against stress caused by spraying salicylic acid (Ngom et al., 2018). In brief, it can be stated that the application of mutliomics in millet has improved specific traits and continues its progress to carve out a better form of this staple.

Microbial nano-materials mediated biostimulant for sustainable growth of millet plant

Microbial-based nanomaterials are eco-friendly, and this green technology aids in improving the tolerance of millets to different abiotic stresses (Tolisano and Buono., 2023). Bacteria, fungi, and algae are the different microbial populations used for nanoparticle synthesis. *Lactobacillus rhamnosus* GG, *Rhodopseudomonas capsulate*, Yeast, *Cryptococcus laurentii*, *Rhodotorula glutinis*, *Chlorella vulgaris*, and *Ulva lactuca* are promising microbial species used for nanoparticle biosynthesis (Bora et al., 2022). Microbially synthesized nanomaterials act as biotic elicitors and regulate oxidative stress in plants (Giri and Kumari., 2023). Millet-based nano-particle biosynthesis has also been reported. Biologically synthesized silver nano-particle using Pearl Millet (*Pennisetum glaucum*) are a prominent example, and this specific nanomaterial is useful for removing algae from wastewater (Musere et al., 2021).

Conclusion

Microbes play a crucial role in millet production by improving the morphophysiological responses of crops. Different soil microbes, such as bacteria, mycorrhizae, and actinomycetes, differentially influence millet growth. Nanoscience, omics analysis, and biotechnology are the current trends in agriculture to establish high crop production. This chapter concludes that the synergetic effects of novel technologies with beneficial microbes should increase millet yield. Therefore, the progression and application of recent advances in crop production using suitable microbes are essential to fulfil the demand for millet production.

References

Abbass, K., Qasim, M. Z., Song, H., Murshed, M., Mahmood, H., Younis, I. (2022). A review of the global climate change impacts, adaptation, and sustainable mitigation measures. Environmental Science and Pollution Research. 29, 42539-42559.

Ahmadvand, G., and Hajinia, S. (2018). Effect of endophytic fungus on yield and some physiological traits of millet under water stress. Crop and Pasture Science, 69, 594-560.

Altieri, M. A., and Nicholls, C. I. (2020). Agroecology and the reconstruction of a post-COVID-19 agriculture. The Journal of Peasant Studies. 47, 881-898.

Amadou, I., Gounga, M. E., and Le, G. W. (2013). Millets: Nutritional composition, some health benefits and processing-A review. Emirates Journal of Food and Agriculture. 501-508.

Banshidhar, Pandey, S., Singh, A., Jaiswal, P., Singh, M. K., Meena, K. R., and Singh, S. K. (2023). The potentialities of omics resources for millet improvement. Functional and Integrative Genomics. 23, 210.

Basilio-Apolinar, A., Vara, L. E. G. D. L., Ramírez-Pimentel, J. G., Aguirre-Mancilla, C. L., Iturriaga, G., Covarrubias-Prieto, J., & Raya-Pérez, J. C. (2021). Silicon induces changes in the antioxidant system of millet cultivated in drought and salinity. Chilean journal of agricultural research. 81, 655-663.

Bollam, S., Pujarula, V., Srivastava, R.K., Gupta, R. (2018). Genomic Approaches to Enhance Stress Tolerance for Productivity Improvements in Pearl Millet. In: Gosal, S., Wani, S. (eds) Biotechnologies of Crop Improvement. 3.

Bora, K. A., Hashmi, S., Zulfiqar, F., Abideen, Z., Ali, H., Siddiqui, Z. S., and Siddique, K. H. (2022). Recent progress in bio-mediated synthesis and applications of engineered nanomaterials for sustainable agriculture. Frontiers in Plant Science. 13, 999505.

Chandra, A. K., Chandora, R., Sood, S., Malhotra, N. (2021). Global production, demand, and supply. In: Singh, M., Sood, S. (eds) Millets and pseudo cereals. Woodhead Publishing. 7-18.

Chandra, D., Srivastava, R., Glick, B. R., and Sharma, A. K. (2018). Drought-tolerant spp. improve the growth performance of finger millet ((L.) Gaertn.) under non-stressed and drought-stressed conditions. Pedosphere. 28, 227-240.

Choudhary P, Shukla P, Muthamilarasan. (2023). M. Genetic enhancement of climate-resilient traits in small millets: A review. Heliyon. 9,e14502.

Giri, V. P., and Kumari, M. (2023). Microbial Approaches in Fabrication of Nanoscale Materials Effectively Enhance the Antimicrobial and Crop Protection Potential-A Review. Plant Nano Biology. 100027.

González Guzmán M, Cellini F, Fotopoulos V, Balestrini R, Arbona V. (2022). New approaches to improve crop tolerance to biotic and abiotic stresses. Physiology Plant. 174,e13547.

Gupta SM, Arora S, Mirza N, Pande A, Lata C, Puranik S, Kumar J and Kumar A. (2017). Finger Millet: A "Certain" Crop for an "Uncertain" Future and a Solution to Food Insecurity and Hidden Hunger under Stressful Environments. Front. Plant Sci. 8:643.

Han, F.; Sun, M.; He, W.; Guo, S.; Feng, J.;Wang, H.; Yang, Q.; Pan, H.; Lou, Y.; Zhuge, Y. (2022). Transcriptome Analysis Reveals Molecular Mechanisms under Salt Stress in Leaves of Foxtail Millet (Setaria italica L.). Plants. 11, 1864.

Han, Y., Wu, M., Hao, L., and Yi, H. (2018). Sulfur dioxide derivatives alleviate cadmium toxicity by enhancing antioxidant defence and reducing Cd uptake and translocation in foxtail millet seedlings. Ecotoxicology and Environmental Safety, 157, 207-215.

Hema, R., Vemanna, R. S., Sreeramulu, S., Reddy, C. P., Senthil-Kumar, M., & Udayakumar, M. (2014). Stable Expression of mtlD Gene Imparts Multiple Stress Tolerance in Finger Millet. PLoS ONE 9: e99110.

Heureux, A. M. C., Alvar-Beltrán, J., Manzanas, R., Ali, M., Wahaj, R., Dowlatchahi, M., Gutiérrez, J. M. (2022). Climate trends and extremes in the Indus River Basin, Pakistan: implications for agricultural production. Atmosphere. 13, 378.

Jangra, S., Rani, A., Yadav, R. C., Yadav, N. R., & Yadav, D. (2019). Introgression of terminal drought stress tolerance in advance lines of popular pearl millet hybrid through molecular breeding. Plant Physiol. Rep. 24, 359–369.

Kelbessa, B. G., Dubey, M., Catara, V., Ghadamgahi, F., Ortiz, R., & Vetukuri, R. R. (2023). Potential of plant growth-promoting rhizobacteria to improve crop productivity and adaptation to a changing climate. CABI Reviews.

Khushdil, F., Jan, F. G., Jan, G., Hamayun, M., and Iqbal, A. (2019). Salt stress alleviation in through secondary metabolites modulation by . Plant Physiology and Biochemistry. 144, 127-134.

Kotapati, K. V., Palaka, B. K., and Ampasala, D. R. (2017). Alleviation of nickel toxicity in finger millet (L.) germinating seedlings by exogenous application of salicylic acid and nitric oxide. Crop Journal. 5, 240-250.

Kour, D., Rana, K. L., Yadav, A. N., Sheikh, I., and Kumar, V. (2020). Amelioration of drought stress in Foxtail millet (L.) by P-solubilizing drought-tolerant microbes with multifarious plant growth promoting attributes. Environmental Sustainability. 3, 23-34.

Kumar, A., Metwal, M., Kaur, S., Gupta, A. K., Puranik, S., Singh, S., and Yadav, R. (2016). Nutraceutical value of finger millet [Eleusine coracana (L.) Gaertn.], and their improvement using omics approaches. Frontiers in plant science. 7, 934.

Kumar, P., Sharma, P. K. (2020). Soil salinity and food security in India. Frontiers in Sustainable Food Systems. 4, 533781.

Kushwaha, P., Kashyap, P. L., Kuppusamy, P., Srivastava, A. K., and Tiwari, R. K. (2020). Functional characterization of endophytic bacilli from pearl millet and their possible role in multiple stress tolerance. Plant Biosystems–An International Journal Dealing with all Aspects of Plant Biology. 154, 503-514.

Lata, C., Gupta, S., and Prasad, M. (2013). Foxtail millet: a model crop for genetic and genomic studies in bioenergy grasses. Critical reviews in biotechnology. 33(3), 328-343.

Lata, C., Sahu, P. P., and Prasad, M. (2010). Comparative transcriptome analysis of differentially expressed genes in foxtail millet (Setaria italica L.) during dehydration stress. Biochemical and Biophysical Research Communications. 393(4), 720-727.

Lata, Charu. (2015). Advances in Omics for Enhancing Abiotic Stress Tolerance in Millets. Proceedings of Indian National Science Academy. 81. 397-417.

Lenka, B., Kulkarni, G. U., Moharana, A., Singh, A. P., Pradhan, G. S., Muduli, L. (2020). Millets: Promising Crops for Climate-Smart Agriculture. International Journal of Current Microbiology and Applied Sciences. 9, 656-668.

Li, S.Y., An, S.J., Liu, Z.L., Cheng, R.H. and Wang, Z.J. (2014). Innovation of the New Superior Quality Foxtail Millet [Setaria italica (L.) P.Beauv] Variety-Jigu32 with Characteristics of Stress Resistance, Stable and High Yield and Its Physiological Mechanism. Agricultural Sciences. 5, 304-316.

Lladó, S., and Baldrian, P. (2017). Community-level physiological profiling analyses show potential to identify the copiotrophic bacteria present in soil environments. PLoS One. 12, e0171638.

Lobell, D. B., Schlenker, W., and Costa-Roberts, J. (2011). Climate trends and global crop production since 1980. Science. 333, 616-620.

Loni, F., Ismaili, A., Nakhoda, B., Darzi Ramandi, H., & Shobbar, Z. S. (2023). The genomic regions and candidate genes associated with drought tolerance and yield-related traits in foxtail millet: an integrative meta-analysis approach. Plant Growth Regulators. 101, 169–185.

Mahadik, S., and Kumudini, B. S. (2020). Enhancement of salinity stress tolerance and plant growth in finger millet using fluorescent pseudomonads. Rhizosphere. 15, 100226.

Marschner, P., Crowley, D., and Yang, C. H. (2004). Development of specific rhizosphere bacterial communities in relation to plant species, nutrition and soil type. Plant and soil. 261, 199-208.

Mbinda W and Masaki H. (2021). Breeding Strategies and Challenges in the Improvement of Blast Disease Resistance in Finger Millet. A Current Review. Front. Plant Science. 11, 602882.

Mbinda W and Mukami A. (2021). A Review of Recent Advances and Future Directions in the Management of Salinity Stress in Finger Millet. Front. Plant Science. 12, 734798.

Meena, R. P., Joshi, D., Bisht, J. K., Kant, L. (2021). Global Scenario of Millets Cultivation. In: Kumar, A., Tripathi, M.K., Joshi, D., Kumar, V. (eds) Millets and Millet Technology. Springer, Singapore. 33-50.

Mohod, N. B., Ashoka, P., Borah, A., Goswami, P., Koshariya, A. K., Sahoo, S., Prabhavathi, N. (2023). The International Year of Millet 2023: A Global Initiative for Sustainable Food Security and Nutrition. International Journal of Plant and Soil Science. 35, 1204-1211.

Musere, P. S., Rahman, A., Uahengo, V., Naimhwaka, J., Daniel, L., Bhaskurani, S. V., and Jonnalagadda, S. B. (2021). Biosynthesis of silver nanoparticles using pearl millet (Pennisetum glaucum) husk to remove algae in the water and catalytic oxidation of benzyl alcohol. Journal of Cleaner Production. 312, 127581.

Muthuvel, D., Amai, M. (2022). Multivariate analysis of concurrent droughts and their effects on Kharif crops—A copula-based approach. International Journal of Climatology. 42, 2773-2794.

Nadeem, S. M., Ahmad, M., Zahir, Z. A., Javaid, A., and Ashraf, M. (2014). The role of mycorrhizae and plant growth promoting rhizobacteria (PGPR) in improving crop productivity under stressful environments. Biotechnology advances. 32, 429-448.

Ngom, B., Mamati, E., Goudiaby, M. F., Kimatu, J., Sarr, I., Diouf, D., and Kane, N. A. (2018). Methylation analysis revealed salicylic acid affects pearl millet defense through external cytosine DNA demethylation. Journal of Plant Interactions. 13, 288–293

Niu X, Song L, Xiao Y and Ge W. (2018). Drought-Tolerant Plant Growth-Promoting Rhizobacteria Associated with Foxtail Millet in a Semi-arid Agroecosystem and Their Potential in Alleviating Drought Stress. Front. Microbiol. 8, 2580.

Numan, M.; Serba, D.D. Ligaba-Osena, A. (2021). Alternative Strategies for Multi-Stress Tolerance and Yield Improvement in Millets. Genes. 12, 739.

Ortiz-Bobea, A., Ault, T. R., Carrillo, C. M., Chambers, R. G., Lobell, D. B. (2021). Anthropogenic climate change has slowed global agricultural productivity growth. Nature Climate Change, 11, 306-312.

Pan, J., Li, Z., Dai, S., Ding, H., Wang, Q., Li, X., and Liu, W. (2020). Integrative analyses of transcriptomics and metabolomics upon seed germination of foxtail millet in response to salinity. Scientific reports. 10, 13660.

Rasool, A., Shah, W. H., Tahir, I., Alharby, H. F., Hakeem, K. R. and Rehman R. (2020). Exogenous application of selenium (Se) mitigates NaCl stress in proso and foxtail millets by improving their growth, physiology and biochemical parameters. Acta Physiology Plant. 42, 116.

Rathinapriya, P., Pandian, S., Rakkammal, K., Balasangeetha, M., and Alexpandi, R. (2020). The protective effects of polyamines on salinity stress tolerance in foxtail millet (L.), an important C4 model crop. Physiology and Molecular Biology of Plants. 26, 1815-1829.

Sagar, A., Sayyed, R. Z., Ramteke, P. W., Sharma, S., and Marraiki, N. (2020). ACC deaminase and antioxidant enzymes producing halophilic sp. PR14 promotes the growth of rice and millets under salinity stress. Physiology and Molecular Biology of Plants. 26, 1847-1854.

Saleem, S., Mushtaq, N. U., Shah, W. H., Rasool, A., Hakeem, K. R., Rehman, R. U. (2021). Morpho-physiological, biochemical and molecular adaptation of millets to abiotic stresses: a review. Phyton. 90, 1363.

Saleem, Seerat and Mushtaq, Naveed and Shah, Wasifa and Rasool, Aadil and Hakeem, Khalid and Rehman, Reiaz. (2021). Morpho-Physiological, Biochemical and Molecular Adaptation of Millets to Abiotic Stresses: A Review. Phyton. 90, 1363-1385.

Satyavathi, C. T., Ambawat, S., Khandelwal, V., Srivastava, R. K. (2021). Pearl millet: a climate-resilient nutricereal for mitigating hidden hunger and provide nutritional security. Frontiers in Plant Science. 12, 659938.

Satyavathi, C. T., Solanki, R. K., Kakani, R. K., Bharadwaj, C., Singhal, T., Padaria, J., ... & Iqubal, M. A. (2019) Genomics Assisted Breeding for Abiotic Stress Tolerance in Millets. In: Rajpal, V., Sehgal, D., Kumar, A., Raina, S. (eds) Genomics Assisted Breeding of Crops for Abiotic Stress Tolerance, Vol. II. Sustainable Development and Biodiversity, Springer, Cham. vol 21.

Sekar, J., Raju, K., Duraisamy, P., and Ramalingam, V. P. (2018). Potential of finger millet indigenous rhizobacterium Pseudomonas sp. MSSRFD41 in blast disease management-growth promotion and compatibility with the resident rhizomicrobiome. Front. Microbiol. 9, 1029.

Sen, S., Kundu, S., and Dutta, S. K. (2016). Proteomic analysis of JAZ interacting proteins under methyl jasmonate treatment in finger millet. Plant Physiology and Biochemistry. 108, 79-89.

Serba DD and Yadav RS. (2016). Genomic Tools in Pearl Millet Breeding for Drought Tolerance: Status and Prospects. Front. Plant Sci. 7, 1724.

Shahzad, A., Ullah, S., Dar, A. A., Sardar, M. F., Mehmood, T., Tufail, M. A., Haris, M. (2021). Nexus on climate change: Agriculture and possible solution to cope future climate change stresses. Environmental Science and Pollution Research. 28, 14211-14232.

Sharma, S., Sharma, R., Pujar, M., Yadav, D., Yadav, Y., Rathore, A., ... & Gupta, S. K. (2021). Use of wild Pennisetum species for improving biotic and abiotic stress tolerance in pearl millet. Crop Science. 61, 289–304.

Shinde, H., Tanaka, K., Dudhate, A., Tsugama, D., Mine, Y., Kamiya, T., and Takano, T. (2018). Comparative de novo transcriptomic profiling of the salinity stress responsiveness in contrasting pearl millet lines. Environmental and Experimental Botany. 155, 619-627.

Shinde, Harshraj and Tanaka, Keisuke and Dudhate, Ambika and Tsugama, Daisuke and Mine, Yoko and Kamiya, Takehiro and Gupta, Sk and Liu, Shenkui and Takano, Tetsuo. (2018). Comparative de novo transcriptomic profiling of the salinity stress responsiveness in contrasting pearl millet lines. Environmental and Experimental Botany. 155.

Shivhare R and Lata C. (2017). Exploration of Genetic and Genomic Resources for Abiotic and Biotic Stress Tolerance in Pearl Millet. Front. Plant Science. 7, 2069.

Shivhare, R., Lata, C. (2016). Selection of suitable reference genes for assessing gene expression in pearl millet under different abiotic stresses and their combinations. Sci Rep. 6, 23036.

Shrestha, N., Hu, H., Shrestha, K., Doust, A. N. (2023). Pearl millet response to drought: A review. Frontiers in Plant Science. 14, 1059574.

Singh, A. (2022). Soil salinity: A global threat to sustainable development. Soil Use and Management, 38, 39-67.

Singh, S., Mahalle, M.D., Mukhtar, M., Jiwani, G., Sevanthi, A.M., Solanke, A.U. (2022). Advances in Omics for Enhancing Abiotic Stress Tolerance in Finger Millets. In: Pudake, R.N., Solanke, A.U., Sevanthi, A.M., Rajendrakumar, P. (eds) Omics of Climate Resilient Small Millets. Springer, Singapore

Srinivasan, R., Mageswari, A., Subramanian, P., Maurya, V. K., and Sugnathi, C. (2017). Exogenous expression of ACC deaminase gene in psychrotolerant bacteria alleviates chilling stress and promotes plant growth in millets under chilling conditions. Indian Journal of Experimental Botany. 55, 463-468.

Sun, M., Huang, D., Zhang, A., Khan, I., Yan, H., Wang, X., and Huang, L. (2020). Transcriptome analysis of heat stress and drought stress in pearl millet based on Pacbio full-length transcriptome sequencing. BMC Plant Biology. 20, 1-15.

Tian, B., Qiao, Z., Zhang, L., Li, H., and Pei, Y. (2016). Hydrogen sulfide and proline cooperate to alleviate cadmium stress in foxtail millet seedlings. Plant Physiology and Biochemistry. 109, 293-299.

Tolisano, C., and Del Buono, D. (2023). Biobased: Biostimulants and biogenic nanoparticles enter the scene. Science of The Total Environment. 163912.

Vaezi, H., Mohammadi-Nejad, G., Majidi-Heravan, E., Nakhoda, B., & Darvish-Kajouri, F. (2020). Effective Selection Indices for Improving Tolerance to Water Stress in Millet Germplasm. Int. J. Plant Prod. 14, 93–105.

Varshney, R. K., Shi, C., Thudi, M., Mariac, C., Wallace, J., Qi, P., and Xu, X. (2017). Pearl millet genome sequence provides a resource to improve agronomic traits in arid environments. Nature biotechnology. 35, 969-976.

Vetriventhan, M., Azevedo, V. C., Upadhyaya, H. D., Nirmalakumari, A., Kane-Potaka, J., Anitha, S., ... & Tonapi, V. A. (2020). Genetic and genomic resources, and breeding for accelerating improvement of small millets: current status and future interventions. Nucleus 63, 217–239.

Wilber Wambi, Gloria Otienno, Wycliffe Tumwesigye and John Mulumba. (2021). Genetic and genomic resources for finger millet improvement: opportunities for advancing climate-smart agriculture, Journal of Crop Improvement. 35, 204-233.

YAMEOGO, Philippe and ZIGANI, Saturnin and JIAO, Xiaoqiang and ZHANG, Hongyan and ZHANG, Junling. (2022). improving fertilization methods and cropping systems for sustainable production of pearl millet (Pennisetum glaucum) in West Africa: a review. Frontiers of Agricultural Science and Engineering. 9, 588.

Yue, H., Wang, L., Liu, H., Yue, W., Du, X., Song, W., andNie, X. (2016). De novo assembly and characterization of the transcriptome of broomcorn millet (Panicum miliaceum L.) for gene discovery and marker development. Frontiers in Plant Science. 7, 1083.

Chapter 11

Harnessing millet microbiome using Artificial Intelligence – Current trends and the way forward

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Abstract

Climate change is a major threat for agricultural productivity. Majority of the cultivable lands are changing into arid and semi-arid regions. Millets are C4 plants that can be cultivated using minimal resources and are resilient to climate changes. Recent studies highlighted the role of microbiome in shaping the architecture of crop plants against multiple stresses. Millet associated microbiomes are key players in enduring millet crops to harsh environmental conditions like salinity, drought, heavy metal etc. The recent advancement in the next-generation technologies dissect the microbial assemblage and its associated function from the millet rhizosphere, phyllosphere and seed. However, due to limited database information, functional annotation of these datasets become a challenge. This can be addressed by the recent AI/ ML techniques which enable genome prediction based on the functional

ontologies of the metagenome dataset. Further, the microbiome data can be used to predict the plant phenotype. Since the application of AI in millet microbiome is in its infancy, here in this chapter we have presented the scope of applying the power of AI in understanding millet-microbiome associations. Concerted research works done in different millets have been depicted to draw deeper insights on the interaction of millet genomics, microbiome data and environment. Among the machine learning approaches, deep learning algorithms especially convolutional neural network models can dive deep in to the microbiome datasets and reveal the unrevealed information for sustainable farming.

Keywords: Millet microbiome, Artificial intelligence, Deep Learning, Patterns, SynCom

Introduction

Plants are in constant relationship with microbes, playing unsung role in their growth and health. The microbial component of plants termed as holobiont' comprises plant microbiota (all microbes) and the microbiome (all microbial genomes) in the rhizosphere, phyllosphere and endosphere. Plants share their habitat with microbes that includes bacteria, fungi, archaea, and viruses (Compant et al., 2021). The functional capacities of plant-microbe interactions and the factors shaping the community assembly may lead to a better understanding on how both the partners are actually benefitted. The outcome of Plant-microbe interaction is either, mutualistic, commensal, proto-cooperation or pathogenic. Plants evolve with microbes so that due to this co-evolution, the microbiome is species specific and also varies according to the genotypes (Ramalho et al.,2017). This give forth the concept of core microbiome, which is gaining more attention in the recent days.

The recent challenges of climate pose both abiotic and biotic stress that affect the crop productivity adversely. In general crop breeding and improvement programmes has developed several climate resilient cultivars against abiotic and biotic stresses, however such efforts are time consuming and labour intensive (Coleman-Derr & Tringe, 2014). For these reasons, development of alternative strategies to ensure crop fitness are needed (Lesk et al., 2016). Due to huge application of chemicals in the present intensive farming, the soil health is deteriorating, which ultimately impacts the plant health as well. It has been shown that plant-growth promoting microbes play a tremendous role in combating climate change-based threats in plants (Rubin et al., 2017)). The crops grown in arid ecosystem act as resource islands for effective PGPM (Marasco et al., 2012) Substantial efforts to understand the community structure and functional diversity of soil, plant and insect- associated microbiome showed that plant-associated microbiome could contribute for agro-ecosystem health. Therefore, in the recent days plant-associated microbiome has emerged as an untapped resource for sustainable agriculture.

Millets known as 'future food', are a polyphyletic group of cereal crops known for rich nutrient properties, providing for the livelihood in dry regions. They are predominantly C4 plants, grown in the marginal lands under rainfed conditions. Millets are usually climate resilient and most of the crop-period is exposed to drought. Studies have shown that millets evade droughts and other stresses due to their unique association with microbiome making them as a suitable option for combating malnutrition and climate change (Tian et al., 2022). Unravelling this unique microbiome interaction of millet crops may reveal more insights on their unique community structure and functional capacities, that enable millet crops to withstand adverse environment. Despite the growing interest and next generation sequencing technologies, research has struggled to understand the full potential of plant microbiome to improve crop fitness. The big data generated through NGS has to be analysed using high-throughput data analytic tools for meaningful interpretation and visualization, which is lacking. Here we highlight the current progress and emerging strategies for understanding microbiome, manging microbiomes for enhanced crop productivity and knowledge gaps in the microbe-mediated crop production.

Plant- microbial assemblages and Core microbiome of millets

In general, microbial assemblage in plant is determined by assembly rules, where plant-associated factors prefer a particular set of microbes while inhibiting the others (Hassani et al., 2018). It was evident that plant associated microbial communities differ widely in the soils and particular plant eventually chooses specific core microbiome (Hamonts et al., 2018). Microbial diversity reduces sequentially from bulk soil to rhizosphere, sole cropping and intercropping. For instance, a shift in microbiome community was observed in the millet root zone, influenced by long-term woody shrub intercropping with millets in Senegal. The operational taxonomic units (OTUs) belonging to *Chitinophaga* were significantly observed in the intercropped samples, and "*Candidatus* Koribacter" in samples where millet was grown alone. *Chitinophaga* OTUs formed a distinct subgroup from all OTUs detected in the genus. OTUs of eight fungal genera such as *Aspergillus, Coniella, Epicoccum, Fusarium, Gibberella, Lasiodiplodia, Penicillium*, were observed in the intercropped sites whereas *Epicoccum, Fusarium, Gibberella,* and *Haematonectria*were enriched at millet-alone. Therefore, intercropping system recruits potentially beneficial microbe in the root zone of millets and aid enhanced productivity (Debenport et al., 2015).

Millet microbiome types

Plant microbiomes comprises beneficial and harmful rhizospheric microorganisms, endophytic and pathogenic (Enespa& Chandra, 2022). Based on their occurrence and interactions with the plant, it can be further categorized into: 1) Rhizospheric microbiome; 2) Phyllospheric microbiome; and 3) Endophytic microbiome or endobiome.

Millet rhizomicrobiome

Soil underscores remarkable diversity of microbiome. Rhizoplane refers to soil particles that are closely adhered to the root surface The rhizosphere is the region which is under immediate vicinity of plant roots, characterized by microbial mass and their metabolites (Bi et al., 2021). Rhizosphere is distinguished into two parts: a) edaphosphere (one side bordered by soil region) and b) histosphere (the other side surrounded by plant tissues (Hu et al., 2020). Rhizopheric soil have high moisture holding capacity and nutrient availability due to numerous mutual interactions between the microorganisms and plant roots in the soil (Mahmud et al., 2021). Rhizospheric microbiomes, influence crop growth and fitness. Some of the mechanisms are phytohormone secretion (indole-3 acetic acid, gibberellin, ABA and cytokinin), production of siderophore and ammonia, solubilization of phosphate, zinc, and potassium, and indirectly by decomposition of detritus, nutrient cycling, pathogen inhibition, secretion of stress hormone (ACC deaminase), soil-plant feedback, stimulation of the plant immune response and other ecosystem services (Kudoyarova et al., 2019).

The root exudates shape the rhizospheric microbiome (Sasse et al., 2018). Comparison of the bacterial microbiota composition in the root-adhering soil fraction of nine pearl millet lines revealed a dominance of the phyla Proteobacteria, Firmicutes, and Actinobacteria (Ndour et al., 2017). Further, recent research has evidenced the display of contrasting patterns of abundance and co-occurrence in pearl millet mycobiome in the domesticated and wild species (Mofini et al., 2022). In broomcorn millet fields, studies on network topologies and the contributions of the microbial assemblages under diverse environment showed diverse bacterial and fungal networks. Proteobacteria, Actinobacteria, Chloroflexi, Acidobacteria, and Ascomycota and their stochastic processes were relatively different across three regions in China. Further, it indicated the rhizospheric processes mediating microbial community assembly and their distribution pattern across the three environmentally distinct regions (Tian et al., 2022). These studies illustrate the vast diversity in millet-associated soil microbiome and the influence of millets on rhizospheric soil microbial community. Millet rhizobiome are known to improve soil health and plant nutrition, thereby reducing the dependence of chemical fertilizers and offers an affordable alternative for regenerative agriculture (Agnihotri & Mathimaran, 2023).

Phyllosphere associated microbiome in millets

Plants co-habit with the core-microbiota that impact plant growth, yield and productivity. These include the phyllospheric microbes that survive on plant's leaf surfaces and the endophytic microorganisms that survive within the internal plant tissues (Mohanram & Kumar, 2019). The phyllosphere performs a dynamic function by colonizing severe, stressful, and changing settings(Bringel & Couée, 2015). In comparison to the rhizosphere or endophytic zone, the phyllosphere has a low nutritional content. However, it is a significant point of entry for phytopathogens into plant tissues, where they cause disease (Gottel et al., 2011). The phyllosphere microbial assemblage is influenced by the stomata, hairs, and veins (Nongkhlaw & Joshi, 2014). The phyllosphere microbes endures large fluctuations in temperature, radiation, moisture, and light throughout the day and night. Changes in environmental factors influence, plant metabolism and thereby affecting phyllospheremicrobiome (Carvalho & Castillo, 2018). One of the earlier studies by (Kumar& Balasubramanian, 1981) on the analysis of phyllosphere microflora in pearl millet reported that the cultivar (PHB-14) which is resistant to downy mildew registered higher population of fungi, gram-positive and gram-negative bacteria, as compared to susceptible cultivar (NHB-3).

Methylobacterium, a ubiquitous C1-compund utilizing bacterial symbiont in the phylloplane, enhanced the growth and yield in barnyard millet (Poorniammal et al.,2020). Likewise, several diazotrophs has been reported in the phyllosphere of foxtail millet (*Setariaitalica* L. Beauv) (Raffi et al.,2016).

Endosphere associated microbiome in millets

Endophytes represents soil microbiome that colonizes the internal tissues of the plants without affecting the host due to rhizosphere competency, or the inherent potential to bind to the root surface, by secreting exopolysaccharides. They are mostly represented by bacteria and fungi, are reported from all parts of the plant including root, stem, leaves, firuits, and seeds. Though they are thought to have penetrated from the rhizosphere, they exhibit unique characteristics from rhizospheric microbes. This implies that not all rhizospheric microbes can penetrate into the root and above ground parts (Vishwakarma et al., 2020). Entry of rhizopheric microbiome changes the physiological/metabolic processes in the plants and enable them to adapt to the host (Jacoby et al., 2017).

The interaction of plants with endophytic symbionts plays a crucial role in the development and growth of millets. Endophytic microbes link the interaction between plants, rhizospheric microbes and soil thus vectoring nutrients to the plants (Verma et al., 2021). Upon entering the plant, the endophytes become either intracellular or extracellular (Farrar et al.,2014). Endobiometweeks the host against biotic and abiotic stress through diverse metabolic pathways than those colonizing the rhizosphere (Wang et al., 2017).
In pearl millet root, stem and leaf, Kushawa and his colleagues reported 102 endophytic *Bacillus* strains that could mediate multiple stress tolerance. (Kushwaha et al.,2020). According to Ribeiro et al., (Ribeiro et al., 2018) endophytic *Bacillus* strains enhanced pearl millet growth and nutrient uptake under limited nutrient conditions of low soil phosphorus, because of their ability to solubilize phosphates, besides producing siderophores and indole-acetic acid (IAA).

Endophytic diazotrophic bacteria, *Pseudomonas aeruginosa* associated with pearl millet contributed for nutrient cycling (Gupta & Pandey, 2019). Similarly, the natural resistance of finger millet to various fungal pathogens including *Fusarium* sp. has been attributed to the endophytic microbes which produce antifungal compounds viz. viridicatol, tenuazonic acid, alternariol, and alternariol monomethyl ether (Mousa et al., 2015). Antagonistic activities of bacterial endophytes obtained from millets against *Rhizoctonia solani*in foxtail millet has also been reported (Reddy & Shivaprakash, 2018). Further, (Misganaw et al., 2019)also reported geo-specific variations in the distribution of various taxonomic groups of endophytes along with differences in their plant growth promotion potential.

Seed endophytes

Seed microbiome are viewed as an important factor as it connects microbial memory to the next generation of plants. It was known that seed borne endophytes are crucial for early seedling establishment. Seeds acquire microbiota through two ways: i) Vertical transmission in which the microbes enter into the seeds either through the xylem pathway or floral pathway (through the stigma of the mother plant); ii) Horizontal transmission by the contact in the soil (Barret et al., 2016). Seed endobiome stimulates the expression of developmental genes related to root architecture and priming against biotic and abiotic stresses (Imtiyaz & Earanna, 2021). More recently, seed endobiome, such as *Kosakoniacowanii,Bacillus subtilis, Bacillus tequilensis, Pantoeastewartii, Paenibacillusdendritiformis, Pseudomonas aeruginosa* and *Bacillus velezensis* were reported from pearl millet seeds. These seed endophytes were found to be potential plant growth promoters while exhibited antagonistic property against fungal phytopathogens, mainly *Fusarium* sp. (Kumar et al., 2021).

Table 1: Millet microbiome representing different plant parts

Millet host	Dominant community	Functional capacity	Reference
	Rhizosphere		
Pearl millet (*Pennisetum glaucum*)	Dominant phyla (> 20% abundance) belonged to Proteobacteria, Firmicutes, and Actinobacteria. Least dominant (abundance < 20%) represents Bacteroidetes, Acidobacteria, Chloroflexi, Planctomycetes and Gemmatimonadetes	Carbon, nitrogen, and sulphur cycling, suppression of plant-pathogens	(Ndour et al., 2017)
Pearl millet (*Pennisetum glaucum*)	Core fungal taxa belonged to the phyla: Ascomycota, Basidiomycota, Chytridiomycota and Glomeromycota. Ascomycota, is the most dominant, represented from 63.8 to 97% of the core OTUs with 22 families, (Pleosporaceae : 31 OTUs and Nectriaceae :31 OTUs) with relative abundance of 4.9% and 4.46%, respectively	Decomposers and nutrient recyclers	Mofini et al. (2022)
Finger millet (*Eleusine coracana*)	Abundance of culturable *Bacillus cereus* and *Paenibacillus* spp., *Pseudomonas*, *Serratia*, *Stenotrophomonas*, and *Streptomyces*; Fungal representatives were from the genera *Ampelomyces*, *Coniothyrium*, and *Trichoderma*	Plant growth promotion, nutrient uptake, and hormone stimulation	(Dheeman et al., 2017) (Choudhary, Rawat, Kumar, & Kumar, 2020)
Finger millet -Root (*Eleusine coracana*)	Taxonomic analysis based on relative abundance revealed the abundance of Chloroflexi (8.51%), followed by actinobacteria (7.45%) cyanobacteria and proteobacteria (6.38 % each), bacteroides and verrumicrobia (5.32%), gemmatimonadates (4.26%), firmicutes and planctomyces (3.19). Other classes such as Fusobacteria, Fibrobacters, Synergistetes, Lentispharae,	Microbial volatiles such as nonanol, 1-pentanol, benzathiazole and glucopyranoside benzo sulphonate were unraveled as signature volatiles	Sugitha Thankappan et al.,2021

	Thermotogae and Cladothrix represented a relatively minor portion of the total diversity		
Finger millet -Shoot (*Elcusine coracana*)	The predominant genus are *Spingopyxis*with 329 clade reads *Pseudomonas* (117), *Micorcoleus* (88 clade reads) followed by *Leptolynbya, Sinorhizobium, Rhizobium, Stenotrophomonas, Pseudoalteromonas, Blautia, Megaspira, Gemella etc.* Interestingly at species level, *Bradyrhizobiumelkanii, Lactobacillus delbruecki, Propionibacterium acenes, Bifidobacterium longum* etc.	Osmoprotectants synthesis such as proline, phenol, ethanol, ascorbic acid and geranyl isovalerate, the precursor of abscisic acid (ABA)	Sugitha Thankappan et al.,2021
Foxtail millet (*Setariaitalica*), Pearl millet (*Pennisetum glaucum*), Prosomillet (*Panicum miliaceum*), Japanese millet (*Echinochloa esculenta*)	The predominant indicator taxa under drought are Actinobacteria, while indicator taxa of watered condition belonged to Firmicutes and Chloroflexi	Decomposition, carbon and nutrient cycling	(Simmons et al., 2020)
Phyllosphere			
Barnyard millet	*Methylobacterium*	Growth and yield	(Poorniammal, Senthilkumar, Prabhu, & Anandhi, 2020)
Foxtail millet *Setariaitalica* L. Beauv	Diazotrophs	Nitrogen Fixation	Raffi et al.
Endophytes			

Pearl millet (*Pennisetum glaucum*) Root, stem and leaves	*B. amyloliquefaciens, B. aryabhattai, B. halotolerans, B. haynesii, B. pacific, B. paramycoides, B. proteolyticus, B. pumilus, B. subtilis, B. siamensis, B. tequilensis, B. wiedmanniiand B. zhangzhouensis*	Multiple stress tolerance	(Kushwaha et al., 2020)
Pearl millet (*Pennisetum glaucum*)	*Bacillus* strains	P solubilization, Siderophore production and IAA	(Ribeiro et al., 2018)
Pearl millet (*Pennisetum glaucum*)	*Bacillus amyloliquefaciens*	Antioxidant defense system	(Murali et al., 2021)
Finger millet (*Eleusine coracana*)	*Bacillus sp* and other endophytes	Antifungal compounds such as viridicatol, tenuazonic acid, alternariol, and alternariol monomethyl ether	Mousa et al., 2015
Finger millet (*Eleusine coracana*)	*Pantoea, Pseudomonas, Enterobacter, Sphingobacterium, Microbacterium* and *Curtobacterium*	IAA production, N fixation, Nutrient mobilization (P)	Misganaw et al., 2019
	Seed microbiome		
Pearl millet (*Pennisetum glaucum*)	*Kosakoniacowanii,Bacillus subtilis, Bacillus tequilensis, Pantoeastewartii, Paenibacillusdendritiformis, Pseudomonas aeruginosa* and *Bacillus velezensis*	Growth promotion, antagonistic property against fungal phytopathogens, mainly *Fusarium sp*	Kumar et al., 2021
Finger millet (*Eleusine coracana*)	*Paenibacillusquercus EC1 Bacillus cereus EC2*	Plant growth promotion	(Hemapriya et al., 2023)

The phyllospheric and endophytic components of the millet-associated microbiome along with the soil microbiome are often involved in nutrient cycling, nutrient uptake, plant protection from pathogens and plant growth promotion and hence, have immense potential to be utilized in developing microbial formulations for boosting crop growth, yield and productivity. However, the composition of these microbiomes is highly dependent on the plant species, environment, and the season. To better understand the impact of these plant-associated microbiomes, unraveling the mechanisms involved in the plant microorganism inter-relations is warranted.

Factors Influencing millet-microbiome

Extrinsic factors, both biotic and abiotic factors exert profound effect on plant-microbe interaction, microbial community structure and composition.

Abiotic and biotic Factors

Millet crops exhibit efficient morphological, physiological, molecular and biochemical traits that contribute to their ability to withstand complex abiotic stresses namely, salinity, drought, heat, nutrient deficiency, heavy metals and lodging (Ajeesh Krishna et al., 2023).The soil factors such as soil pH, texture and structure, macro and micronutrient, soil organic matter, porosity, salinity, and moisture decides the rhizosphere microbiome (Breidenbach et al. 2016). In addition, different millet species and their genotypes recruit distinct microbial communities in the rhizosphere, rhizoplane and endosphere even soil conditions are same (Toju et al., 2018). Based on all these factors, it can be concluded that plant phenome is the overall outcome of interactions between plant genotype-microbiota-environment (GxMxE) (Compant et al., 2019). Phyllosphere microbiota is influenced by climate, light, water, ultraviolet (UV) radiation, and geographic location (Kalaiselvi & Panneerselvam, 2021).

Signalling cues in the crosstalk between microbe -host interaction

Geographical location, host genotype, age, root phenomics, root and plant secretomes, and the inherent immune system are the key factors governing microbial community. Of which many reports have confirmed plant genotype as a major intriguing factor in deciding its own microbial pattern (Philippot et al., 2013). Plant genotypes emits root metabolome that act as chemical cues and ascertain the nutrient availability for microbes (Bulgarelli et al., 2015). For instance, coumarins and lectin compounds influence the host microbiota preferably root microbiome besides acting as a semio-chemical (Stringlis et al., 2019). Plant volatiles also act as cues in tailoring the core microbiome (Sridharan et al., 2020). Apart from beneficial/symbiotic microbial abundance in rhizosphere and phyllosphere, pathogenic microbes also cause a shift in the antagonistic microbial population and plant immune responses (Durán et al., 2018).

The general elicitors of plant-pathogens that resemble pathogen-associated molecular patterns (PAMPs) are recognized as molecules involved in triggering innate immunity. Microbe-associated molecular patterns (MAMPs) bind to pattern recognition receptors (PRRs) and triggers innate immune responses (Erbs &Newman, 2012). These MAMPs are perceived by plants as danger cues and trigger a net-work of signaling cascades that activates defense responses at the downstream. PRRs are specific receptors in the plant cell plasma membrane for the recognition of PAMPs and the activated PRRs system further triggers various genes including *BAK1* (Brassinosteroid insensitive1 Associated Kinase1), *BIK1* (Botrytis-Induced Kinase1), *BIR1* (Branching Inhibiting Receptor1) (Postel et al., 2010). Consequently, the downstream events succeeding are: i) ROS production by the activation of NAD kinase, ii) Activation of WRKY transcription factors and nitric oxide production (enzyme in phenolics biosynthesis) ; iii) chalcone synthase (CHS) which is involved in isoflavonoid phytoalexins synthesis and transcription modulated by NO ; iv) Activation of SID2 gene (isochorismatesynthase), responsible for salicylic acid signaling system; v) Activation of NADPH oxidase, responsible for jasmonic acid signaling system; vi) Activation of ACC synthase and oxidase responsible for ethylene signaling system; vii) Activation of Mitogen Activated Protein Kinase (MAPK), responsible for various signaling systems involved in plant defense(Li et al., 2003).

Significance of millet microbiome in stress mitigation for sustainable Agriculture

Microbial communities can promote resilience to adverse abiotic stress conditions, such as heat, drought, or high salinity as well as for biotic stress (insect/pathogens) (Xiong et al., 2020). However, microbiome can also be affected by the plant through molecular interactions (Li et al., 2018). In the recent trend of regenerative agriculture, microbiota can be used as the best alternative to chemical inputs. Plant growth-promoting microbes (PGPM) are particularly effective in mitigating stresses on plants by degrading ACC, the ethylene precursor (ACC deaminase activity), producing biofilms, exopolysaccharides, siderophores, HCN, metabolites and microbial volatiles. Exploring novel microbes to alleviate the stresses in plants has opened up new and growing avenues in sustainable agriculture.

Table 2: Functional capacities of millet microbiome towards resilience to diverse stresses

Stress type	Millet species	Microbe	Mechanism	Reference
Drought	Finger millet	*Pseudomonasspp*	ACC deaminase	Chandra et al., 2020
Salinity	Finger millet	Florescent *Pseudomonads*	ROS scavenging, decreased lipid peroxidation	Mahadik & Kumudini, 2020
Salinity	Sorghum and Finger millet	Enterobacter sp.	ACC deaminase	Sagar et al., 2020
Cold stress	Finger and foxtail millet	*Sphingomonasfaeni*	ACC deaminase	Srinivasan et al., 2017
Drought	*Panicumsp*	*Piriformospora indica*	Regulates plant hormones	Ahmadvand & Hajinia, 2018
Drought	Foxtail millet	*Acinetobacter sp and Penicillium sp*	P solubilization	Kour et al., 2020
Salinity	Pearl millet	*Aspergillus terreus*	Increased chlorophyll content, RWC, and accumulation of soluble sugar, phenol and flavonoids	Sethi et al., 2016
Salinity	Pearl millet	*Aspergillus terreus*	Accumulation of osmoprotectants	Khushdil et al., 2019
Salt stress	Pearl millet	*Bacillus amyloliquefaciens* EPP90	Antioxidant activity and growth promotion	Kushwaha et al., 2020
Copper stress	Proso millet	*Piriformospora indica*	Antioxidant enzymes, reduced lipid peroxidation and H_2O_2 activities	Saman & Sepehri, 2022

Decoding millet- microbiome association

Microbiota collaborates with plants depending on the genetic determinants and metabolic communications. Exploring the millet microbiome association involves profiling the composition structure of millet-associated microbial community and defining the core microbial taxa. This presents the community assembly and reveals distinct features (Agler et al., 2016). Microbial structure analysis is followed by functional studies to indicate plant-microbe network under varied environments (Toju et al., 2018). The current high thorough-put and low-cost sequencing technologies gathers microbiome data which can be harnessed to improve cropping systems. However, microbiome data analysis is challenged by the size and data complexities as well as incomplete databases. Artificial intelligence has emerged as a powerful tool for managing large sequencing datasets and analyse the significant interaction

***Next generation or omics tools and techniques* toexplore millet -microbe interactions**

Metagenomics is one of the most recent technologies to explore the whole genomes retrieved from an environment. Several sophisticated next-generation sequencing techniques, like pyrosequencing and Illumina sequencing, were established, which are useful in metagenomics and meta-transcriptomic studies. The species abundance, population size, species consistency and distribution pattern are influenced by ecological factors.The 454-platform generates longer read lengths whereas, Illumina produces shorter reads based on the chemistry used, either HiSeq or MiSeq(Reuter et al., 2015). The recent advance in this field is the fourth-generation sequencing technology termed as nanopore sequencing which is more reliable and very rapid in generating longer read lengths.

Metabolomic profiling and fingerprints yields novel biomarkers, which can be integrated into microbiome research for a more holistic understanding of the plant microbiome(Lucaciu et al., 2019).Metatranscriptomicsis a useful technique for deducing community function and activity, as well as identifying novel pathways in uncultured microorganisms(Song et al., 2019).For transcript mapping, meta-transcriptomics can be used along with metagenomics to give assembled genomes as templates. Some of the pipelines developed for this purpose are Top Hat and HISAT, Cufflinks and HTSeq.

Metaproteomics, is a potent technique for deciphering active metabolic processes in a more direct manner than metagenomics or metatranscriptomicswhich represent the, dynamics, structure and metabolic activities of a microbial community(Hettich et al., 2013). The response of a PGPB *Bacillus amyloliquefaciens* FZB42 to the root exudates and the variation in the soil protein abundance was explored using metaproteomics(Levy et al., 2018).Spectral comparisons can be made either by exploring current protein/

peptide databases or by comparing to theoretical in silico created peptide spectra from metagenomes (Blakeley-Ruiz & Kleiner, 2022).
Nucleic acid amplification techniques, mass spectrometry methods, and receptor-ligand binding assays are the three approaches for multiplex detection from complicated matrices. Nanobiotechnology has been used in biosensors to improve sensitivity and performance of assays by improving the signal transduction. (Mokhtarzadeh et al., 2017).

Microbiome Data Analysis

Microbiome-wide association studies (MWAS) establish associations between microbiota, and the host genotype by comparing different samples statistically (Wang & Jia, 2016). The raw sequence reads obtained in MWAS from multiple samples are pre-processed by removing sequence errors (Caporaso et al., 2010). Operational taxonomic units (OTUs) were obtained by grouping same species into clusters based on the similarity of sequences of marker genes (Olson et al., 2019). These OTUs are representative sequence and are used to build tress based on the phylogenetic distance and homology. Microbial community characteristics like diversity, composition, stable core microbiome relatives and host specificity can be explored. Heritable microbiome taxa in distinct maize lines were identified by Walters and his co-workers (Walters et al., 2018).

To understand the impact of the microbiota on plants, functional gene discovery and annotation is mandated. The workflow involves three sub-steps unlike amplicon data. The steps are: assembling the reads to at least contig level (Sangwan et al., 2016); binning reads, contigs, or genes to bins, species- or strain-level taxonomic units (Alneberg et al., 2014)and mapping reads or contigs to reference genome, marker genes, annotated contigs or genes, proteins, or metabolic pathways (Quince et al., 2017). The species diversity and their significant function endows microbial community with resilience and redundancy (García-García et al., 2019).

Artificial Intelligence as a powerful tool to explore millet microbiome

A deep understanding on plant-microbiome interaction, leverages the microbiome information to imply in sustainable crop production. However, it has been difficult to understand the stochastic and deterministic drivers including the genetic background of the host and its respective phytomicrobiome composition and assembly (Kwak et al., 2018). There exist a temporal and geographic differences in the stress pattern of the crops(Mendes et al., 2011). Thus, for evaluating crop phenotypes for stress resistance, the information on microbiome and its assembly needs to be integrated. To understand and analyse the large genomic datasets, the recent advances in the field of artificial intelligence (AI) techniques and machine learning are widely used Deep learning models, one of the subsets of AI, have been developed to harness microbiome data as it is powerful to handle huge set of multivariate data(Panch et al., 2018). The plant phenotype can be predicted based on the microbiome data, which is a new paradigm in the area of plant-microbe interaction.

Representation learning and biomarker detection from microbiome data through deep learning models

The raw microbiome dataset comprises of the information on three aspects: taxonomic and functional composition, bilateral interactions between the community member and their association with the host genotype influenced by the environment. In genomic sequence data, the features are represented by k-mer counts (Liu et al., 2018), and position weight matrix (Alipanahi et al., 2015). Plant productivity can be predicted from soil metagenomic data using machine learning. The ML models learn the patterns and find significant information from the soil metagenome data. A typical training model has four steps: i) preparation of dataset for prediction ii) construction of a suitable model architecture iii) training and optimizing the model and iv) complete end-end prediction and testing the performance on new datasets. Subsequently, the MWAS programme has three key steps: a) input data preparation and parsing b) pattern and feature identification by DL models c) classification or regression based on correlation data(Li et al., 2019; Zou et al., 2019).

For metagenomics, the input dataset is derived from 16S amplicon or shotgun sequencing data which is numerically encoded into one hot matrix (Pan and Shen, 2018) and a feature table. These can be achieved by classical bioinformatics pipeline such as OUT table or amplicon sequence variant (ASV) table (Bolyen et al., 2019). The similar sequences are clustered and aligned to the marker genes (16S, 18S, and ITS) and the sequences displaying maximum similarity are considered as OTUs (operational taxonomic units). The high abundant OTUs with in a plant genotype represent the core taxa in its microbiome community.

Further, in shotgun sequencing data, the predicted functional genes act as biomarkers, representing its functional capacities (Segata et al., 2011). Herealso, the feature representation was based on the OTUs, ASVs, or alpha-diversity. In DL, the pattern learning and feature extraction is conducted by multilayer perception in deep neural network (DNN). The major advantage of DL is that it has the capacity of feature representation through multiple hidden layers compared to ML. Thus, prediction target in DL is much nearer and tighter (LeCun et al., 2015). Asgari and his co-workers demonstrated that k-mer counting (frequency of all sub-sequences of different k length) outperforms on the same datasets due to less computation complexity (LeCun et al., 2015).

Through embedding, k-mers encoded to vectors can also be used as an input layer (Woloszynek et al.,2019). Few deep learning models for phenotype prediction from microbiome data is discussed below in this chapter.

Applications of AI

Some of the high computationally efficient DL models are convolutional neural networks (CNN), recurrent neural networks (RNN), and graph convolutional neural networks(GCN) (Erasian et al., 2019).

Genomic Prediction against Pathogens

Qualitative disease resistance is governed by a single resistance gene (*R gene*), that recognizes avirulence factors in a gene-for-gene mechanism. Crop improvement for disease resistance targets molecular markers for qualitative traits controlled by single genes, for selecting desired gene in marker assisted selection. However, DNA markers tightly associated with the desired traits is highly challenging in marker assisted selection which can be addressed through genomic prediction (GP). The scope of GP enables to select individuals with desirable traits at an earlier stage. It can save time and resources and also used to select complex traits such as disease resistance and yield. Genomic prediction relies on robust statistical models based on the genotypic and phenotypic data. Genomic best linear unbiased prediction (GBLUP) is one of the frequently used DL architectures, which was based on the contribution of SNPs, in heritability (Heffner et al., 2010). Several DL architectures have been developed to predict complex traits in crops (Khaki & Wang, 2019). GP transformer-based DL architecture was developed to perform genomic prediction in barley against Fusarium head blight (Jubair et al., 2021). Likewise, a CNN based semantic segmentation model was developed to classify powdery mildew on leaf images. The model showed 96.08%-pixel accuracy level, which is higher than the K-means and rand forest models. at accurate pixel level (Lin et al., 2019).

Based on the above models, the DL approach was applied to identify mildew disease in pearl millet (*Pennisetum glaucum*), and an accuracy of 95.0%was achieved (Coulibaly et al., 2019). However, progression of disease can be acquired using hyperspectral imaging and remote sensing(Bergsträsser et al., 2015). Changes in the plants metabolite profile can be analyzed with mass spectrometry (MS) and nuclearmagnetic resonance (NMR) spectroscopy techniques (Hong et al., 2016), while plant transpiration andtemperature variations in the diseased plant can be measured through infrared thermography (Wani et al., 2022). The information generated can be used as an input data for different DL models and its validation. Inorder to enhance the phenotype accuracy, all the omics data including proteomics, microbiome, metabolomics, weather and soil data are to be integrated.

Dissecting Microbiome composition in millets

Microbiome data is of high dimensional consisting both known and unknown species. Supervised ML methods such as CNN and deep belief network (DBN) architectures havebeen used for taxonomic classification into phylum to genus level based on k-mer values of 16S rRNA reads (Fiannaca et al., 2018). As an improvement over CNN and DBN, an integrative framework has been tailored to decode the functions of microbial communities depending n its structure and phylogeny(Wassan et al., 2019). This method targets to decipher the biomarkers (OTU features), functional annotation of genome sequences and relate with their functions (Khodabandelou et al.,2020). A CNN model (CNN-MGP) recognizes ORF from raw metagenomic dataset and distinguish coding and non-coding regions(Al-Ajlan & El Allali, 2019). The functional annotation of metagenomic reads were made by using reference dataset from GenBank, KEGG pathways, FunGene, COG and MG-RAST (Deng et al., 2021).

Phenotype prediction

The major advance in ML is the exploration of the association of host with its microbiome for MWAS. Chang and his teammates used random forest methods to conduct binary classification and divided the samples into high or low productivity based on a threshold amount at taxonomic level (Chang et al.,2017). In foxtail millet, the productivity amplicon dataset of size 2,882 was used to extract 16,109 OTUs/features. Further, the dataset was subjected to a binary classification with 30 classes which is used to predict 30 productivity groups according to the grain weight per plant(Jin et al., 2017).

AI in designing synthetic communities

It was well established that phytomicrobiome can promote plant growth,repress pathogens and combat abiotic stresses. Therefore, engineering the microbiome through artificial inoculation of a plant growth promoting microbes (PGPM) community can boost millet growth and productivity. PGPMs mediates phytohormone production, ACC deaminase, mVOCs and soluble metabolites, nutrient mobilization and so on. SynComs (synthetic microbial communities) concept is more trending in the recent days. It refers to an artificially designed small-scale consortia of microbe representing the structure and function of microbial community in a natural environment. Thus, SynComs preservethe native interactions between microbes and plants, while reducing the complexity of themicrobial community. It is possible to either add or delete a member according to their functions. In a study with maize, excluding *Enterobacter cloacae* from the SynComs enabled to discover its function in managing maize blight (Niu et al.,2017). Novel approaches using ANN models were used to design microbial communities and predicting the plant response to phosphate limitation (Herrera Paredes et al., 2018). Thus, ANN guided designs can be employed to study microbe–plant bilateral interactions. The ANN models validated based on the response of plants at transcriptional level may be used to design SynComs. Although designing SynComs with AI have been rarely reported, this technique will be a promising one in the near future.

Conclusion

The current challenge in the plant microbiome data analysisis the insufficiency of sample number and incomplete databases. Hence, deciphering the interplay between the host and the microbiome is a difficult task. Data mining of large omics datasets reveals taxonomic compositions and their functional genes which is helpful to predict the crop phenotype. AI is more powerful in integrating high dimensional variables, data processing with flexible architectures, pattern exploration and feature extraction. This approach enables to analyse and interpret microbiome datasets which have high-dimensionality and incomplete databases. AI predicts plant traits such as climate resilience, tolerance to disease and pest, based on the microbial assembly and its interaction across the environment. Combining microbiome datasets with crop phenomics, genomics and climate data, it is possible to predict crop performance and disease outbreak. However, AI application in the extrapolation of millet microbiome is in its infancy. Recently, foxtail millet has been dissected and decoded for microbiome and predicting the grain yield based on the response to phosphorous. This approach has to be extended to other millet crops for microbiome engineering and phenome prediction. More accurate and precision models usher new era of microbiome assisted millet crop research for sustainable farming.

References

Agler, MT., Ruhe, J., Kroll, S., Morhenn, C., Kim, S.T., Weigel, D., Kemen, E M. (2016). Microbial hub taxa link host and abiotic factors to plant microbiome variation. *PLoS biology, 14*(1), e1002352.

Agnihotri, R., & Mathimaran, N. (2023). Diversity and Function of Microbes Associated with the Rhizosphere of Millets *Millet Rhizosphere* (pp. 11-34): Springer.

Ahmadvand, G., Hajinia, S. (2018). Effect of endophytic fungus Piriformospora indica on yield and some physiological traits of millet (Panicum miliaceum) under water stress. *Crop and Pasture Science, 69*(6), 594-605.

Ajeesh Krishna, T., Maharajan, T., Antony Ceasar, S., Ignacimuthu, S. (2023). Zinc supply influences the root-specific traits with the expression of root architecture modulating genes in millets. *Journal of Soil Science and Plant Nutrition*, 1-15.

Al-Ajlan, A., El Allali, A. (2019). CNN-MGP: convolutional neural networks for metagenomics gene prediction. *Interdisciplinary Sciences: Computational Life Sciences, 11*, 628-635.

Alipanahi, B., Delong, A., Weirauch, MT., & Frey, BJ. (2015). Predicting the sequence specificities of DNA-and RNA-binding proteins by deep learning. *Nature biotechnology, 33*(8), 831-838.

Alneberg, J., Bjarnason, B. S., De Bruijn, I., Schirmer, M., Quick, J., Ijaz, UZ., Quince, C. (2014). Binning metagenomic contigs by coverage and composition. *Nature methods, 11*(11), 1144-1146.

Barret, M., Guimbaud, JF., Darrasse, A., Jacques, MA. (2016). Plant microbiota affects seed transmission of phytopathogenic microorganisms. *Molecular plant pathology, 17*(6), 791.

Bergsträsser, S., Fanourakis, D., Schmittgen, S., Cendrero-Mateo, MP., Jansen, M., Scharr, H., Rascher, U. (2015). HyperART: non-invasive quantification of leaf traits using hyperspectral absorption-reflectance-transmittance imaging. *Plant methods, 11*, 1-17.

Bi, B., Wang, K., Zhang, H., Wang, Y., Fei, H., Pan, R., Han, F. (2021). Plants use rhizosphere metabolites to regulate soil microbial diversity. *Land Degradation & Development, 32*(18), 5267-5280.

Blakeley-Ruiz, JA., Kleiner, M. (2022). Considerations for constructing a protein sequence database for metaproteomics. *Computational and structural biotechnology journal, 20*, 937-952.

Bolyen, E., Rideout, JR., Dillon, MR., Bokulich, NA., Abnet, CC., Al-Ghalith, GA., Asnicar, F. (2019). Reproducible, interactive, scalable and extensible microbiome data science using QIIME 2. *Nature biotechnology, 37*(8), 852-857.

Breidenbach, B., Pump, J., & Dumont, MG. (2016). Microbial community structure in the rhizosphere of rice plants. *Frontiers in microbiology, 6*, 1537.

Bringel, F., & Couée, I. (2015). Pivotal roles of phyllosphere microorganisms at the interface between plant functioning and atmospheric trace gas dynamics. *Frontiers in microbiology, 6*, 486.

Bulgarelli, D., Garrido-Oter, R., Münch, PC., Weiman, A., Dröge, J., Pan, Y., Schulze-Lefert, P. (2015). Structure and function of the bacterial root microbiota in wild and domesticated barley. *Cell host & microbe, 17*(3), 392-403.

Caporaso, J. G., Kuczynski, J., Stombaugh, J., Bittinger, K., Bushman, FD., Costello, EK., Gordon, J. I. (2010). QIIME allows analysis of high-throughput community sequencing data. *Nature methods, 7*(5), 335-336.

Carvalho, SD., & Castillo, JA. (2018). Influence of light on plant–phyllosphere interaction. *Frontiers in plant science, 9*, 1482.

Chandra, D., Srivastava, R., Glick, B. R., Sharma, AK. (2020). Rhizobacteria producing ACC deaminase mitigate water-stress response in finger millet (*Eleusine coracana* (L.) Gaertn.). *3 Biotech, 10*, 1-15.

Chang, HX., Haudenshield, JS., Bowen, CR., Hartman, GL. (2017). Metagenome-wide association study and machine learning prediction of bulk soil microbiome and crop productivity. *Frontiers in microbiology, 8*, 519.

Choudhary, R., Rawat, G., Kumar, V., Kumar, V. (2020). Diversity and function of microbes associated with rhizosphere of finger millet (*Eleusine coracana*). *Rhizosphere Microbes: Soil and Plant Functions*, 431-451.

Coleman-Derr, D., Tringe, SG. (2014). Building the crops of tomorrow: advantages of symbiont-based approaches to improving abiotic stress tolerance. *Frontiers in microbiology, 5*, 283.

Compant, S., Cambon, MC., Vacher, C., Mitter, B., Samad, A., Sessitsch, A. (2021). The plant endosphere world–bacterial life within plants. *Environmental Microbiology, 23*(4), 1812-1829.

Compant, S., Samad, A., Faist, H., Sessitsch, A. (2019). A review on the plant microbiome: Ecology, functions, and emerging trends in microbial application. *Journal of advanced research, 19*, 29-37.

Coulibaly, S., Kamsu-Foguem, B., Kamissoko, D., Traore, D. (2019). Deep neural networks with transfer learning in millet crop images. *Computers in industry, 108*, 115-120.

Debenport, SJ., Assigbetse, K., Bayala, R., Chapuis-Lardy, L., Dick, RP., McSpadden Gardener, BB. (2015). Association of shifting populations in the root zone microbiome of millet with enhanced crop productivity in the Sahel region (Africa). *Applied and Environmental Microbiology, 81*(8), 2841-2851.

Deng, Z., Zhang, J., Li, J., Zhang, X. (2021). Application of deep learning in plant–microbiota association analysis. *Frontiers in Genetics, 12*, 697090.

Dheeman, S., Maheshwari, DK., Agarwal, M., Dubey, RC., Aeron, A., Kim, K., Bajpai, VK. (2017). Polyphasic and functional diversity of high altitude culturable *Bacillus* from rhizosphere of *Eleusine coracana* (L.) Gaertn. *Applied Soil Ecology, 110*, 127-136.

Durán, P., Thiergart, T., Garrido-Oter, R., Agler, M., Kemen, E., Schulze-Lefert, P., Hacquard, S. (2018). Microbial interkingdom interactions in roots promote Arabidopsis survival. *Cell, 175*(4), 973-983. e914.

Enespa, Chandra, P. (2022). Tool and techniques study to plant microbiome current understanding and future needs: an overview. *Communicative & Integrative Biology, 15*(1), 209-225.

Eraslan, G., Avsec, Ž., Gagneur, J., Theis, FJ. (2019). Deep learning: new computational modelling techniques for genomics. *Nature Reviews Genetics, 20*(7), 389-403.

Erbs, G., Newman, MA. (2012). The role of lipopolysaccharide and peptidoglycan, two glycosylated bacterial microbe-associated molecular patterns (MAMPs), in plant innate immunity. *Molecular plant pathology, 13*(1), 95-104.

Farrar, K., Bryant, D., Cope-Selby, N. (2014). Understanding and engineering beneficial plant–microbe interactions: plant growth promotion in energy crops. *Plant biotechnology journal, 12*(9), 1193-1206.

Fiannaca, A., La Paglia, L., La Rosa, M., Lo Bosco, G., Renda, G., Rizzo, R., Urso, A. (2018). Deep learning models for bacteria taxonomic classification of metagenomic data. *BMC bioinformatics, 19*, 61-76.

García-García, N., Tamames, J., Linz, A. M., Pedrós-Alió, C., Puente-Sánchez, F. (2019). Microdiversity ensures the maintenance of functional microbial communities under changing environmental conditions. *The ISME journal,* *13*(12), 2969-2983.

Gottel, N. R., Castro, H. F., Kerley, M., Yang, Z., Pelletier, DA., Podar, M., Vilgalys, R. (2011). Distinct microbial communities within the endosphere and rhizosphere of Populus deltoides roots across contrasting soil types. *Applied and Environmental Microbiology, 77*(17), 5934-5944.

Gupta, S., Pandey, S. (2019). ACC deaminase producing bacteria with multifarious plant growth promoting traits alleviates salinity stress in French bean (Phaseolus vulgaris) plants. *Frontiers in microbiology, 10*, 1506.

Hamonts, K., Trivedi, P., Garg, A., Janitz, C., Grinyer, J., Holford, P., Singh, BK. (2018). Field study reveals core plant microbiota and relative importance of their drivers. *Environmental Microbiology, 20*(1), 124-140.

Hassani, M., Durán, P., Hacquard, S. (2018). Microbial interactions within the plant holobiont. *Microbiome, 6*(1), 1-17.

Heffner, EL., Lorenz, AJ., Jannink, JL., & Sorrells, ME. (2010). Plant breeding with genomic selection: gain per unit time and cost. *Crop science, 50*(5), 1681-1690.

Hemapriya, M., Nataraja, K., Shaanker, R. (2023). Seed-inhabiting Endophytic Bacteria of Finger Millet [*Eleusine coracana* (L.) Gaertn] Enhance Early Seedling Growth and Development. *Mysore Journal of Agricultural Sciences, 57*(2).

Herrera Paredes, S., Gao, T., Law, TF., Finkel, OM., Mucyn, T., Teixeira, PJ.,Shank, EA. (2018). Design of synthetic bacterial communities for predictable plant phenotypes. *PLoS biology, 16*(2), e2003962.

Hettich, RL., Pan, C., Chourey, K., & Giannone, RJ. (2013). Metaproteomics: harnessing the power of high performance mass spectrometry to identify the suite of proteins that control metabolic activities in microbial communities. *Analytical chemistry, 85*(9), 4203-4214.

Hong, J., Yang, L., Zhang, D., Shi, J. (2016). Plant metabolomics: an indispensable system biology tool for plant science. *International journal of molecular sciences, 17*(6), 767.

Hu, J., Wei, Z., Kowalchuk, GA., Xu, Y., Shen, Q., Jousset, A. (2020). Rhizosphere microbiome functional diversity and pathogen invasion resistance build up during plant development. *Environmental Microbiology, 22*(12), 5005-5018.

Imtiyaz, T., Earanna, N. (2021). Characterization of Bacterial Endophyte Imparting Drought Tolerance in Rice (*Oryza sativa* L.). *Mysore Journal of Agricultural Sciences, 55*(4).

Jacoby, R., Peukert, M., Succurro, A., Koprivova, A., Kopriva, S. (2017). The role of soil microorganisms in plant mineral nutrition—current knowledge and future directions. *Frontiers in plant science, 8*, 1617.

Jin, T., Wang, Y., Huang, Y., Xu, J., Zhang, P., Wang, N., Jiang, H. (2017). Taxonomic structure and functional association of foxtail millet root microbiome. *Gigascience, 6*(10), 1-12.

Jubair, S., Tucker, J. R., Henderson, N., Hiebert, C. W., Badea, A., Domaratzki, M., Fernando, W. (2021). GPTransformer: A transformer-based deep learning method for predicting Fusarium related traits in barley. *Frontiers in plant* *science, 12*, 761402.

Kalaiselvi, S., Panneerselvam, A. (2021). Growth promotion utility of the plant microbiome. *Microbiome-host interactions*, 307-319.

Khaki, S., Wang, L. (2019). Crop yield prediction using deep neural networks. *Frontiers in plant science, 10*, 621.

Khodabandelou, G., Routhier, E., Mozziconacci, J. (2020). Genome annotation across species using deep convolutional neural networks. *PeerJ Computer Science, 6*, e278.

Khushdil, F., Jan, FG., Jan, G., Hamayun, M., Iqbal, A., Hussain, A., Bibi, N. (2019). Salt stress alleviation in *Pennisetum glaucum* through secondary metabolites modulation by Aspergillus terreus. *Plant Physiology and Biochemistry, 144*, 127-134.

Kour, D., Rana, K. L., Yadav, A. N., Sheikh, I., Kumar, V., Dhaliwal, HS., Saxena, AK. (2020). Amelioration of drought stress in Foxtail millet (*Setaria italica* L.) by P-solubilizing drought-tolerant microbes with multifarious plant growth promoting attributes. *Environmental Sustainability, 3*, 23-34.

Kudoyarova, G., Arkhipova, T., Korshunova, T., Bakaeva, M., Loginov, O., Dodd, IC. (2019). Phytohormone mediation of interactions between plants and non-symbiotic growth promoting bacteria under edaphic stresses. *Frontiers in plant science, 10*, 1368.

Kumar, C. P. C., Balasubramanian, K. (1981). Phyllosphere and rhizosphere microflora of pearl millet with reference to downy mildew incited by *Sclerospora graminicola* (Sacc.) Schroet. *Plant and Soil, 65-80*.

Kumar, K., Verma, A., Pal, G., Anubha, White, JF., Verma, SK. (2021). Seed endophytic bacteria of pearl millet (Pennisetum glaucum L.) promote seedling development and defend against a fungal phytopathogen. *Frontiers in microbiology, 12*, 774293.

Kushwaha, P., Kashyap, PL., Kuppusamy, P., Srivastava, AK., Tiwari, R. K. (2020). Functional characterization of endophytic *Bacilli* from pearl millet (*Pennisetum glaucum*) and their possible role in multiple stress tolerance. *Plant Biosystems-An International Journal Dealing with all Aspects of Plant Biology, 154*(4), 503-514.

Kwak, MJ., Kong, HG., Choi, K., Kwon, SK., Song, JY., Lee, J.,Lee, HJ. (2018). Rhizosphere microbiome structure alters to enable wilt resistance in tomato. *Nature biotechnology, 36*(11), 1100-1109.

LeCun, Y., Bengio, Y., Hinton, G. (2015). Deep learning. *Nature, 521*(7553), 436-444.

Lesk, C., Rowhani, P., Ramankutty, N. (2016). Influence of extreme weather disasters on global crop production. *Nature, 529*(7584), 84-87.

Levy, A., Conway, JM., Dangl, JL., Woyke, T. (2018). Elucidating bacterial gene functions in the plant microbiome. *Cell host & microbe, 24*(4), 475-485.

Li, C., Liu, G., Xu, C., Lee, GI., Bauer, P., Ling, HQ., Howe, GA. (2003). The tomato suppressor of prosystemin-mediated responses2 gene encodes a fatty acid desaturase required for the biosynthesis of jasmonic acid and the production of a systemic wound signal for defense gene expression. *The Plant Cell, 15*(7), 1646-1661.

Li, T., Kim, A., Rosenbluh, J., Horn, H., Greenfeld, L., An, D., Natoli, T. (2018). GeNets: a unified web platform for network-based genomic analyses. *Nature methods, 15*(7), 543-546.

Li, Y., Huang, C., Ding, L., Li, Z., Pan, Y., Gao, X. (2019). Deep learning in bioinformatics: Introduction, application, and perspective in the big data era. *Methods, 166*, 4-21.

Lin, K., Gong, L., Huang, Y., Liu, C., Pan, J. (2019). Deep learning-based segmentation and quantification of cucumber powdery mildew using convolutional neural network. *Frontiers in plant science, 10*, 155.

Liu, X., Yu, Y., Liu, J., Elliott, CF., Qian, C., Liu, J. (2018). A novel data structure to support ultra-fast taxonomic classification of metagenomic sequences with k-mer signatures. *Bioinformatics, 34*(1), 171-178.

Lucaciu, R., Pelikan, C., Gerner, SM., Zioutis, C., Köstlbacher, S., Marx, H., Rattei, T. (2019). A bioinformatics guide to plant microbiome analysis. *Frontiers in plant science, 10*, 1313.

Mahadik, S., Kumudini, B. S. (2020). Enhancement of salinity stress tolerance and plant growth in finger millet using fluorescent Pseudomonads. *Rhizosphere, 15*, 100226.

Mahmud, K., Missaoui, A., Lee, K., Ghimire, B., Presley, H. W., Makaju, S. (2021). Rhizosphere microbiome manipulation for sustainable crop production. *Current Plant Biology, 27*, 100210.

Marasco, R., Rolli, E., Ettoumi, B., Vigani, G., Mapelli, F., Borin, S.,Cherif, A. (2012). A drought resistance-promoting microbiome is selected by root system under desert farming. *PloS one, 7*(10), e48479.

Mendes, R., Kruijt, M., De Bruijn, I., Dekkers, E., Van Der Voort, M., Schneider, JH., Bakker, PA. (2011). Deciphering the rhizosphere microbiome for disease-suppressive bacteria. *Science, 332*(6033), 1097-1100.

Misganaw, G., Simachew, A., Gessesse, A. (2019). Endophytes of finger millet (*Eleusine coracana*) seeds. *Symbiosis, 78*, 203-213.

Mofini, M.-T., Diedhiou, AG., Simonin, M., Dondjou, DT., Pignoly, S., Ndiaye, C., Kane, A. (2022). Cultivated and wild pearl millet display contrasting patterns of abundance and co-occurrence in their root mycobiome. *Scientific Reports, 12*(1), 207.

Mohanram, S., Kumar, P. (2019). Rhizosphere microbiome: revisiting the synergy of plant-microbe interactions. *Annals of Microbiology, 69*, 307-320.

Mokhtarzadeh, A., Eivazzadeh-Keihan, R., Pashazadeh, P., Hejazi, M., Gharaatifar, N., Hasanzadeh, M., de la Guardia, M. (2017). Nanomaterial-based biosensors for detection of pathogenic virus. *TrAC Trends in Analytical Chemistry, 97*, 445-457.

Mousa, W. K., Schwan, A., Davidson, J., Strange, P., Liu, H., Zhou, T., Raizada, MN. (2015). An endophytic fungus isolated from finger millet (Eleusine coracana) produces anti-fungal natural products. *Frontiers in microbiology, 6*, 1157.

Murali, M., Singh, SB., Gowtham, H., Shilpa, N., Prasad, M., Aiyaz, M., Amruthesh, K. (2021). Induction of drought tolerance in Pennisetum glaucum by ACC deaminase producing PGPR-*Bacillus amyloliquefaciens* through Antioxidant defense system. *Microbiological Research, 253*, 126891.

Ndour, P. M., Gueye, M., Barakat, M., Ortet, P., Bertrand-Huleux, M., Pablo, AL., Kane, N. A. (2017). Pearl millet genetic traits shape rhizobacterial diversity and modulate rhizosphere aggregation. *Frontiers in plant science, 8*, 1288.

Niu, B., Paulson, JN., Zheng, X., Kolter, R. (2017). Simplified and representative bacterial community of maize roots. *Proceedings of the National Academy of Sciences, 114*(12), E2450-E2459.

Nongkhlaw, FMW., Joshi, S. (2014). Distribution pattern analysis of epiphytic bacteria on ethnomedicinal plant surfaces: A micrographical and molecular approach. *Journal of Microscopy and Ultrastructure, 2*(1), 34-40.

Olson, ND., Shah, N., Kancherla, J., Wagner, J., Paulson, JN., Corrada Bravo, H. (2019). metagenomeFeatures: An R package for working with 16S rRNA reference databases and marker-gene survey feature data. *Bioinformatics, 35*(19), 3870-3872.

Panch, T., Szolovits, P., Atun, R. (2018). Artificial intelligence, machine learning and health systems. *Journal of global health, 8*(2).

Philippot, L., Raaijmakers, J. M., Lemanceau, P., Van Der Putten, WH. (2013). Going back to the roots: the microbial ecology of the rhizosphere. *Nature reviews microbiology, 11*(11), 789-799.

Poorniammal, R., Prabhu, S., Senthilkumar, M., Anandhi, K. (2020). Effect of Phyllosphere Application of Methylobacterium on Growth and Yield of Barnyard Millet (Echinochloa frumentacea Var. COKV 2). *Int J Curr Microbiol Appl Sci, 9*(4), 1860-1866.

Poorniammal, R., Senthilkumar, M., Prabhu, S., Anandhi, K. (2020). Effect of Methylobacterium on seed germination, growth and yield of Barnyard Millet (*Echinochloa frumentacea* Var. COKV 2) under Rainfed Condition. *Journal of Pharmacognosy and Phytochemistry, 9*(2), 1675-1677.

Postel, S., Küfner, I., Beuter, C., Mazzotta, S., Schwedt, A., Borlotti, A., Nürnberger, T. (2010). The multifunctional leucine-rich repeat receptor kinase BAK1 is implicated in Arabidopsis development and immunity. *European journal of cell biology, 89*(2-3), 169-174.

Quince, C., Walker, AW., Simpson, JT., Loman, NJ., Segata, N. (2017). Shotgun metagenomics, from sampling to analysis. *Nature biotechnology, 35*(9), 833-844.

Raffi, MM.2016. Studies on diazotrophic bacteria in the phyllosphere of foxtail millet setaria italica L beauv. shodhganga.inflibnet.ac.in

Ramalho, MO., Bueno, OC., Moreau, CS. (2017). Species-specific signatures of the microbiome from Camponotus and Colobopsis ants across developmental stages. *PloS one, 12*(11), e0187461.

Reddy, MR., Shivaprakash, M. (2018). Antagonistic activity of bacterial endophytes isolated from millets against Rhizoctonia solani in foxtail millet. *Mysore Journal of Agricultural Sciences, 52*(2), 241-247.

Reuter, JA., Spacek, DV., & Snyder, MP. (2015). High-throughput sequencing technologies. *Molecular cell, 58*(4), 586-597.

Ribeiro, VP., Marriel, IE., Sousa, SM. , Lana, UG., Mattos, BB., Oliveira, CA.,Gomes,

E. A. (2018). Endophytic Bacillus strains enhance pearl millet growth and nutrient uptake under low-P. *brazilian journal of microbiology, 49*, 40-46.

Rubin, RL., van Groenigen, KJ., Hungate, BA. (2017). Plant growth promoting rhizobacteria are more effective under drought: a meta-analysis. *Plant and Soil, 416*, 309-323.

Sagar, A., Sayyed, R., Ramteke, P., Sharma, S., Marraiki, N., Elgorban, AM., Syed, A. (2020). ACC deaminase and antioxidant enzymes producing halophilic *Enterobacter* sp. PR14 promotes the growth of rice and millets under salinity stress. *Physiology and Molecular Biology of Plants, 26*, 1847-1854.

Saman, M., Sepehri, A. (2022). Serendipita indica (Piriformospora indica) inoculation improves photosynthetic performance and antioxidative potential of proso millet (Panicum miliaceum L.) under copper stress conditions. *Brazilian Journal of Botany, 45*(4), 1177-1182.

Sangwan, N., Xia, F., Gilbert, JA. (2016). Recovering complete and draft population genomes from metagenome datasets. *Microbiome, 4*(1), 1-11.

Sasse, J., Martinoia, E., Northen, T. (2018). Feed your friends: do plant exudates shape the root microbiome? *Trends in plant science, 23*(1), 25-41.

Segata, N., Izard, J., Waldron, L., Gevers, D., Miropolsky, L., Garrett, WS., Huttenhower, C. (2011). Metagenomic biomarker discovery and explanation. *Genome biology, 12*, 1-18.

Sethi, BK., Jana, A., Nanda, PK., DasMohapatra, PK., Sahoo, S. L., Patra, JK. (2016). Production of α-amylase by Aspergillus terreus NCFT 4269.10 using pearl millet and its structural characterization. *Frontiers in plant science, 7*, 639.

Simmons, T., Styer, AB., Pierroz, G., Gonçalves, AP., Pasricha, R., Hazra, AB., Coleman-Derr, D. (2020). Drought drives spatial variation in the millet root microbiome. *Frontiers in plant science, 11*, 518243.

Song, L., Sabunciyan, S., Yang, G., Florea, L. (2019). A multi-sample approach increases the accuracy of transcript assembly. *Nature communications, 10*(1), 5000.

Sridharan, A., Thankappan, S., Karthikeyan, G., Uthandi, S. (2020). Comprehensive profiling of the VOCs of Trichoderma longibrachiatum EF5 while interacting with Sclerotium rolfsii and Macrophomina phaseolina. *Microbiological Research, 236*, 126436.

Srinivasan, R., Mageswari, A., Subramanian, P., Maurya, V. K., Sugnathi, C., Amballa, C., Gothandam, K. (2017). Exogenous expression of ACC deaminase gene in psychrotolerant bacteria alleviates chilling stress and promotes plant growth in millets under chilling conditions.

Stringlis, I. A., De Jonge, R., Pieterse, CM. (2019). The age of coumarins in plant–microbe interactions. *Plant and Cell Physiology, 60*(7), 1405-1419.

Sugitha Thankappan, Binodh AK., Prabina JB. (2022). Decoding the micorbiome of fingermillet. In Proceedings of International Conference on harnessing the potential of fingermillet conducted by UAS Jan 19-22.

Tian, L., Feng, Y., Gao, Z., Li, H., Wang, B., Huang, Y., Feng, B. (2022). Co-occurrence pattern and community assembly of broomcorn millet rhizosphere microbiomes in a typical agricultural ecosystem. *Applied Soil Ecology, 176*, 104478.

Toju, H., Peay, K. G., Yamamichi, M., Narisawa, K., Hiruma, K., Naito, K., Onoda, Y. (2018). Core microbiomes for sustainable agroecosystems. *Nature plants, 4*(5), 247-257.

Verma, SK., Sahu, P. K., Kumar, K., Pal, G., Gond, S. K., Kharwar, RN., White, JF. (2021). Endophyte roles in nutrient acquisition, root system architecture development and oxidative stress tolerance. *Journal of Applied Microbiology, 131*(5), 2161-2177.

Vishwakarma, K., Kumar, N., Shandilya, C., Mohapatra, S., Bhayana, S., Varma, A. (2020). Revisiting plant–microbe interactions and microbial consortia application for enhancing sustainable agriculture: a review. *Frontiers in microbiology, 11*, 560406.

Walters, WA., Jin, Z., Youngblut, N., Wallace, JG., Sutter, J., Zhang, W., Shi, Q. (2018). Large-scale replicated field study of maize rhizosphere identifies heritable microbes. *Proceedings of the National Academy of Sciences, 115*(28), 7368-7373.

00Wang, J., Jia, H. (2016). Metagenome-wide association studies: fine-mining the microbiome. *Nature reviews microbiology, 14*(8), 508-522.

Wang, WX., Zhang, F., Chen, ZL., Liu, J., Guo, C., He, JD., Wu, QS. (2017). Responses of phytohormones and gas exchange to mycorrhizal colonization in trifoliate orange subjected to drought stress. *Archives of Agronomy and Soil Science, 63*(1), 14-23.

Wani, JA., Sharma, S., Muzamil, M., Ahmed, S., Sharma, S., Singh, S. (2022). Machine learning and deep learning based computational techniques in automatic agricultural diseases detection: Methodologies, applications, and challenges. *Archives of Computational methods in Engineering, 29*(1), 641-677.

Wassan, JT., Wang, H., Browne, F., Zheng, H. (2019). Phy-PMRFI: phylogeny-aware prediction of metagenomic functions using random forest feature importance. *IEEE transactions on nanobioscience, 18*(3), 273-282.

Woloszynek, S., Zhao, Z., Chen, J., Rosen, G. L. (2019). 16S rRNA sequence embeddings: Meaningful numeric feature representations of nucleotide sequences that are convenient for downstream analyses. *PLoS computational biology, 15*(2), e1006721.

Xiong, W., Song, Y., Yang, K., Gu, Y., Wei, Z., Kowalchuk, G. A., Geisen, S. (2020). Rhizosphere protists are key determinants of plant health. *Microbiome, 8*, 1-9.

Zou, J., Huss, M., Abid, A., Mohammadi, P., Torkamani, A., Telenti, A. (2019). A primer on deep learning in genomics. *Nature genetics, 51*(1), 12-18.

Management of Insect-Pests and Diseases of Millets

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About one billion people in the semi-arid tropics rely on millets, which are significant nutritional grains cultivated for food, feed, or forage, as their main source of protein and energy. According to Naylor et al. (2004) and Rooney (2004), the crop is free from gluten and rich in micronutrients, fibre, protein, and vitamin B complexes. Due to its high nutritional value, low susceptibility to biotic stressors, and broad tolerance to climate change, this crop is mostly planted in resource-poor farmers' marginal land, hills, tribal, and rain-fed areas in India (Maitra, 2020). Despite being referred to as resistant crops, millets are also subject to disease infestations and insect pest attacks, which can reduce crop productivity (Chandrashekar and Satyanarayana, 2006; Ramesh et al. 2021). About 150 insect pests have been identified in millets, and important pests include insects like shoot flies, stem borers, and ear head midges. In India, yield losses of 10 to 20% in millets have been attributed to insect pests. Along with numerous sucking pests, shoot flies, stem borers, and other pests associated with millets cause significant losses. A few pests have recently been seen attacking millets, and a few previously minor pests have grown significantly in some areas. Before planning the management operations for the majority of recently discovered pests, information on the causes of their outbreak, bionomics, yield losses, etc., is required (Repellin et al., 2001; Reddy and Zehr, 2004). Chemicals have primarily been utilized as a quick remedy for high-yielding varieties and hybrids. However, it has been found that combining cultural practices with resistant varieties cultivation is effective.

Low grain yields in farmers' fields are a result of general insect occurrence and damage that varies over time and place. Some insect pests are related to millet crops, while others, like white grubs, are confined to a certain area. In some seasons, sporadic infestations by armyworms, grasshoppers, chinch bugs, leaf beetles, head caterpillars, and head bugs cause significant yield losses.

Keywords: Millets, Insect pests, Diseases, Management

Insect pests of Millets

Shoot flies

Shoot flies typically attack seedlings in the first to fourth week following germination. The mature adult is a small (3 mm long), dark grey housefly with dark spots on each segment of its abdomen. Figure 1 shows how the maggot destroys the growth point after entering the seedling through the whorl and displays symptoms of a "dead heart" (Edde, 2022).

Fig. 1: Shoot fly damage in millets

Spotted stem borer

The larvae feed on the upper surface, while the lower surface of the whorl leaves remains intact as a transparent window. A mixture of punctures and scrapes from epidermal feeding became more noticeable as the feeding severity increased. Because of early attacks, 'dead heart' symptoms can occasionally appear in younger plants (Singh et al., 1983). The larvae then began to tunnel extensively into the stem as they continued going down into it. Tunneling of the peduncle leads to either breaking or full or partial chaffy panicles. The larvae go into diapause during the dry season and survive in harvested stalks and stems as well as in the field's leftover stubble.

Ragi stem borer/ Pink borer

Between the leaf sheath and stem, the female moth lays about 150 hemispherical, creamy-white eggs in two or three rows. The pink larva bores into the stem and harms the core shoot, leaving a dead heart (Fig 2) (Jagadish et al., 2008).

Fig. 2: Stem borer damage in millets

Cutworms and Armyworms

Larvae feed on the young, developing plants' tender stems and break them. Larvae bury themselves in the ground during the day and come out at dusk. In the advanced stages, the whole foliage is fed, giving the appearance that cows were grazing in the area (Nagoshi et al., 2021).

Shoot bugs

The adults appear as dark brown to yellowish brown in colour with translucent wings. Both nymphs and adults feed on plant sap, which weakens plants with yellowing in leaves. In extreme circumstances, younger leaves start drying and eventually spread to older ones. A severe infestation during the vegetative stage may twist the upper leaves and stop panicle formation (Kalaisekar et al., 2017).

Aphids

In the middle leaf whorl, stalks, or panicles, colonies of young and adult aphids can be seen feeding plant sap. Nymphal and adult aphids, shoot bugs, and plant bugs wilt and distort young leaves and whorls by sucking sap, which results in shrivelled and chaffy grains. A few sucking pests act as plant disease vectors. A severe infection results in stunted plants, marginal leaf necrosis, and yellowish mottling of the leaves. Moulds develop on honeydew, which produces as a result of aphid feeding (Sasmal, 2015).

Sorghum midge

The adult fly is tiny and delicate, with translucent wings and an abdomen that is bright orange. It releases pollen when it lays a single egg in a floret that is still in development. When fully developed, the larvae turn a dark orange colour from being colourless as larvae. White pupal skin is still present at the tip of the spikelet as the adult emerges because it pupates behind the glumes (Henzell et al., 1994; Oliveira et al., 2013).

Other Minor pests

Leaf caterpillars: At the start of the monsoon, leaf caterpillar moths emerge and lay their eggs in groups. Later stages spread out across the field and feed voraciously, whereas early-stage larvae feed on plants indiscriminately. Reddish-brown and hairy all throughout, fully grown larvae severely defoliate plant tissue.

Head beetles: Recently, a number of beetle species have been recorded in millet-growing regions. They feed the flowers while preventing the growth of grains.

Head caterpillars: These produce frass-filled webbings on the panicle and feed on growing grains.

Head bugs: Head bugs cause deformation and shrinkage by sucking the sap from growing grains. Later, fungus infect grains, which results in blackening (Jagadish et al., 2008).

Diseases of Millets

Grain mold

Sorghum and pearl millet are the main crops affected by grain mold, which can induce disease in moderate to severe disease and cause yield losses of 10 to 30%. Pathogens that cause grain mold disease may spread through plant debris, air, or soil. Fungal infection of the spike and spikelet caused this disease, which led to poor seed germination and the production of shriveled grains in the panicle. Depending on the type of fungus, the seeds become discolored as a result of infection. The market price of the grains may also reduce by 20–30% as a result of fungal colonization of seeds and panicles. The development of the disease is attributed to the rainy conditions during flowering, moderate temperatures (25–35 °C), and high humidity (>90%) (Kange et al., 2015; Cuevas and Prom, 2020).

Blast

Blast disease is a major cause of yield loss in millet. This disease mainly occurs in finger millet, pearl millet, and foxtail millet in severe forms, causing a yield loss of 28-36% depending on prevailing weather conditions during crop growth period and type of cultivar. In finger millet, blast symptoms appear on the seedlings, leaves, panicles, and fingers. Water-soaking and chlorotic halo surrounding the lesions are characteristic symptoms of the leaves. Later, these spots grew larger until they covered the entire leaf, giving it the 'leaf blast' (Jeevan et al., 2023). On the panicle, the symptom of a black-colored elongated lesion below the ear head is called a neck blast. On the fingers, the brown-colored blast symptom starts from the tip to the bottom, and is called a finger blast. Among all blast symptoms, neck blast is mainly responsible for severe yield loss in finger millet (Jeevan et al., 2021). In pearl millet, the symptoms of water-soaked elliptical or diamond-shaped with grey center lesions on leaves later turned brown, and excessive chlorosis caused the drying of young leaves. Symptoms may appear on the leaves, leaf sheaths, and stems of pearl millet (Palanna et al., 2023). Similar to finger millet, foxtail millet also experiences leaf blast, however, there are no neck or finger blasts. Closer spacing, the use of excessive nitrogenous fertilizers, sporadic drizzles, cloudy weather, high relative humidity (93–99%), protracted dew periods, low nighttime temperatures (below 20°C), and the presence of collateral hosts in the field all contribute to the severity of the disease.

Sugary disease/ Ergot

Sorghum and pearl millet are affected by ergot. Sorghum yield losses range from 10–80% and hybrid pearl millet losses from 50–70%, depending on the severity. The exudation of sticky droplets resembling honeydew from the infected florets is the earliest observable sign of ergot infection. Instead of the grain, a wart-like fungal growth called a sclerotium gradually develops. The development of disease is favoured by high rainfall and related humidity during the flowering stage, cool nighttime temperatures, and cloudy weather (Miedaner et al. 2015).

Downey mildew

Sorghum, finger millet, pearl millet, and foxtail millet are frequently affected by downy mildew. Sorghum seedlings that are pale yellow or have light-colored streaks on the leaf, are chlorotic and stunted and may die prematurely, and are systemically affected by the disease. Plants that have been severely diseased have deformed ear heads, which reduces yields. Symptoms in pearl millet appear on both the leaves and the ear head. Chlorosis, or yellowing of the lowest leaves, first appears on the diseased plant and then progresses to the top leaves and the entire plant. A plant that has been severely diseased gets stunted and frequently fails to produce an ear head. Frequently, the diseased plant exhibits "green ear" symptoms on the ear head, which are leafy structures in the case of finger millet and a bush-like appearance in the case of pearl millet. (Jegera et al., 2002; Riethmußller et al., 2002).

Smuts

In India, smuts are sporadically found and are of minor importance. There are different types of smut that occur in all millets *viz*., including head, grain, loose, and long smuts. This phenomenon is more common in sorghum and other small millet species. They can be managed well with seed fungicides (Das, 2017).

Charcoal rot

When crops are under drought stress, charcoal rot is more prevalent, especially in rabi sorghum. Depending on the climate and cultivar growth stage at the time of infection, yield losses may vary. Excessive lodging brought on by charcoal rot can result in a reduction in grain production of 23-64% (Reddy et al., 2010).

Banded sheath blight

All small millets are susceptible to banded sheath blight, which is severe in warm seasons, and humid areas. Oval to irregular, light grey to dark brown lesions on the bottom leaf and leaf sheath are its defining features. A succession of copper colour bands across the leaves, giving them a banded appearance are the characteristic symptoms. (Patro et al., 2020).

Anthracnose and leaf spots

Anthracnose is more common in sorghum. Initially, the development of small, elliptical to circular spots, with a straw-color center and wide margins on the leaves. Defoliation may occur during severe infections, and the plant may die before bearing the ear head. Early infection leads to severe pre-emergence damping-off and wilting of seedlings may occur (Das, 2017).

Integrated Insect Pest management

Cultural methods

- Collect and burn chaffy ear heads and stubbles to prevent the spread of pests that overwinter.
- One month prior to planting, deep ploughing exposes the larval stages of insects, allowing predators to feed on them.
- Deep ploughing exposes insect larvae one month before planting, allowing predators to feed on them. To lessen the harm that shoot flies, midges, and head bugs do, cultivars with a similar maturity should be sown synchronously and at the right time or early.
- It is suggested to rotate crops with cotton, groundnut, or sunflower to lessen the harm that shoot flies, midges, and ear head bugs do. Sorghum can be intercropped with pigeonpea, cowpea, or lablab to lessen the harm stem borers do.
- To reduce shoot fly damage, sow at high seed rates 1.5 times more and postpone thinning (to maintain an ideal plant stand).

Mechanical method

- To track, attract in, and destroy adult stem borers, grain midges, June beetles, and other moth pests, light traps were placed till midnight.
- Until the crop was 30 days old, install 12 insecticide-impregnated fishmeal traps per ha.

Chemical methods

- To reduce damage caused by shoot flies, stem borers, and sucking pests, treat the seeds with thiamethoxam 30 FS @ 10 ml/kg of seeds.
- The crop may be sprayed with cypermethrin 10 EC (750 ml/ha) or quinalphos 25 EC (400 g a.i/ha) when the shoot fly damage reaches 5 to 10% of the plants with dead hearts.
- Spray of cypermethrin 25EC @ 0.5 ml/l at 50% anthesis is advised in midge-endemic locations.
- Carbofuran 3G granules may be applied to whorls at a rate of 8–12 kg a. i./ha to control stem borers.

- When the crop has finished flowering and is at the milk stage, cypermethrin 25 EC @ 0.5 ml/liter may be sprayed on it to control ear head bugs (1–2 bugs per panicle) and head caterpillars (2–3 larvae per panicle).

Use a combination of dimethoate (0.03%), neem seed kernel suspension (0.04%), and soap to control sucking pests like shoot bugs and aphids.

Integrated Disease Management

Cultural practices

- Collection and destruction of any leftover crop remnants, stubbles, etc. acquired from the field.
- Deep summer ploughing: Decreases the diseases downy mildew, smut, and charcoal rot.
- Reduced downy mildew, ergot, smut, charcoal rot, and banded blight are results of crop rotation with non-host crops.
- Changing the date of sowing: Early sowing lessens the severity of blast and rust.
- Plant pathogens (ergot, smut, blast, and grain mould) are spread to the field by contaminated or infected seeds and seedlings. Therefore, the use of ceritified disease-free seeds will reduce disease incidence.
- Reducing the severity of diseases such as downy mildew, blast, rust, and grain mould in millets is made possible by optimizing the plant population.
- Elimination of collateral and alternate hosts: Timely elimination of these hosts aids in the management of diseases including ergot, downy mildew, rust, blast, leaf spots, and bacterial and viral infections.
- Need based application of nitrogenous fertilizer helps to prevent the occurrence of blast, downy mildew, and charcoal rot.

Biological control

- Seed treatment with talc formulation of *Pseudomonas chlororaphis* SRB127 or *Trichoderma* formulations at 4gm/kg seed manage charcoal rot of sorghum.
- Spraying a talc-based formulation of *Pseudomonas* (0.2%) two times increases the seedling growth and reduces the grain mold in sorghum
- Seed treatment (6 g/kg) and first foliar application (2 g/L) of *P. fluorescens* immediately after the symptoms were noticed. The second and third sprays at the flowering stage at 15-day intervals may control the blast in finger millet.

- Soil application of 1 kg/acre talc-based consortia formulation of bio-agents (*Trichoderma viride* + *P. fluorescence* + *Bacillus subtilis*) reduced the banded sheath blight in small millets.
- Root protection of the seedlings by dipping them in a solution of talc-based formulation *T. viride* and *P. fluorescence* at 5 g/L, followed by soil application of FYM (50 kg) enriched with *T. viride* and *P. fluorescence* at 500 g each/acre is helpful for the management of foot rot in finger millet.

Chemical control

- Downy mildew incidence can be reduced by seed treatment with Ridomyl-MZ at 6 g/kg seed followed by one or two need-based applications of Ridomyl-MZ at 3 g/L.
- Carbendazim at 1 g/kg of treated seed. Spray any of the following fungicides: tricyclazole (0.1%), propiconazole (0.1%), or ediphenphos (0.1%), first spray soon after the onset of symptoms. Controlling neck and finger blast infections in finger millet requires second and third sprays as per requirement, applied at 15-day intervals during the flowering period.
- Spray if there is scattered rain during the development of the ear head, a week later, and during the milky stage. Thiram + 0.2% carbendazim and 0.1% propiconazole. To minimize the grain mould, use two to three sprays.
- Seed dressing with sulphur@ 4g/Kg seed reduces the Smut diseases.
- Anthracnose has been successfully managed by treating seeds with Apron-plus (methalaxyl + carboxin + furathiocarp) @1gm/kg of seeds, followed by applications of carbendazim + maneb (0.2%) and mancozeb (0.2%).
- Applying three to four sprays of fungicides, such as bavistin (0.1%), mancozeb (0.2%), tebuconazole (0.1%), and propiconazole (0.1%), can decrease ergot infection. To reduce ergot occurrence and its subsequent spread, spraying during ear head emergence (5-10% flowering), followed by a spray at 50% flowering, and repeating the spray after a week, if necessary.

Summary

The research that is now available indicates that compared to sorghum and other millets, finger millet, and pearl millet are substantially less susceptible to insect pests. It is necessary to gather information on millet crop yield loss caused by major pests in order to assess economic damage levels, the potency of natural enemies, and the integration of these elements into existing ecosystems. Standardizing screening methods for controlling flies and borers is therefore necessary. It is necessary to combine resistance-related traits into cultivars that are agronomically sound. New pests and alterations in the status of minor or sporadic pests should be regularly watched. An integrated strategy for the management of millet pests is necessary for an hour due to the status of pests in changing climates.

References

Chandrashekar, A., & Satyanarayana, K. V. (2006). Disease and pest resistance in grains of sorghum and millets. Journal of Cereal Science, 44(3), 287-304.

Cuevas, H. E., & Prom, L. K. (2020). Evaluation of genetic diversity, agronomic traits, and anthracnose resistance in the NPGS Sudan Sorghum Core collection. BMC Genomics, 21(1), 1-15.

Das, I. K. (2017). Millet diseases: current status and their management. Millets and sorghum: biology and genetic improvement, 291-322.

Henzell, R. G., Franzmann, B. A., & Brengman, R. L. (1994). Sorghum midge resistance research in Australia. Sorghum Improvement Conference of North America, USA; University of Georgia, USA; International Crops Research Institute for the Semi-Arid Tropics, Patacheru 502 324, Andhra Pradesh, India.

Jagadish PS, Mohapatra HK, Chakravarty MK,Srivastava N, Nangia N (2008). A compendium of insect pests ofFinger Millet and other Small Millets. All IndiaCoordinated Small Millets Improvement Project. ICAR,UAS, GKVK, Bangalore, 8-9.

Hosahatti, R., Koti, P. S., Devappa, V. H., Ngangkham, U., Devanna, P., Yadav, M. K., ... & Hossain, A. (2023). Phenotypic and Genotypic screening of fifty-two rice (Oryza sativa L.) genotypes for desirable cultivars against blast disease. Plos one, 18(3), e0280762.

Jeevan B.; Rajashekara H.; Mishra K.K.; Subbanna A.R.N.S.; Singh A.K.; Sharma D. Nayaka S C, Hosahatti R., Prakash G, Satyavathi C T, Sharma R Nayaka S C, Hosahatti R, Prakash G, Satyavathi C T, Sharma R. (2021) Finger millet blast disease: Potential threat to global nutrition security. Blast Disease of Cereal Crops. Fungal Biology. Springer, Cham,51–57.

Jeger, Gilijamse, Bock, & Frinking. (1998). The epidemiology, variability and control of the downy mildews of pearl millet and sorghum, with particular reference to Africa. Plant Pathology, 47(5), 544-569.

Kalaisekar, A., P. G. Padmaja, V. R. Bhagwat, and J. V. Patil. (2017). Insect pestsof millets: systematics, bionomics and management, 1st ed. Elsevier, NewYork, NY.

Kange, A. M., Cheruiyot, E. K., Ogendo, J. O., & Arama, P. F. (2015). Effect of sorghum (Sorghum bicolor L. Moench) grain conditions on occurrence of mycotoxin-producing fungi. Agriculture & Food Security, 4, 1-8.

Maitra, S. (2020). Potential horizon of brown-top millet cultivation in drylands: A review. Crop Research, 55(1and2), 57-63.

Miedaner, T., & Geiger, H. H. (2015). Biology, genetics, and management of ergot (Claviceps spp.) in rye, sorghum, and pearl millet. Toxins, 7(3), 659-678.

Nagoshi, R. N., Koffi, D., Agboka, K., Adjevi, A. K. M., Meagher, R. L., & Goergen, G. (2021). The fall armyworm strain associated with most rice, millet, and pasture infestations in the Western Hemisphere is rare or absent in Ghana and Togo. PLoS One, 16(6), e0253528.

Naylor, R. L., Falcon, W. P., Goodman, R. M., Jahn, M. M., Sengooba, T., Tefera, H., & Nelson, R. J. (2004). Biotechnology in the developing world: a case for increased investments in orphan crops. Food Policy, 29(1), 15-44.

Oliveira, C. M., Auad, A. M., Mendes, S. M., &Frizzas, M. R. (2013). Economic impact of exotic insect pests in Brazilian agriculture. Journal of Applied Entomology, 137(1-2), 1-15.

Palanna, K. B., Vinaykumar, H. D., Prasanna, S. K., Rajashekara, H., Devanna, B. N., Anilkumar, C., ... & Nagaraja, T. E. (2023). Exploring the diversity of virulence genes in the Magnaporthe population infecting millets and rice in India. Frontiers in Plant Science, 14, 1131315.

Patro, T. S. S. K., Georgia, K. E., Kumar, S. R., Anuradha, N., Rani, Y. S., Triveni, U., &Jogarao, P. (2020). Identification of foxtail millet varieties against banded blight disease incited by Rhizoctonia solani Kuhn. Journal of Pharmacognosy and Phytochemistry, 9(5), 1265-1267.

Peter A. Edde. (2022). Arthropod pests of sorghum (Sorghum bicolor (L.) Moench). In: Peter A. Edde. Field Crop Arthropod Pests of Economic Importance, Academic Press, p. 348-408, ISBN 9780128186213, https://doi.org/10.1016/B978-0-12-818621-3.00011-2.

Ramesh, G. V., Palanna, K. B., Vinaykumar, H. D., Arunkumar, Koti, P. S., Mahesha, H. S., ... & Jeevan, B. (2021). Occurrence and characterization of Bipolarissetariae associated with leaf blight of browntop millet (Brachiariaramosa) in India. Journal of Phytopathology, 169(10), 613-622.

Reddy, B. V., Ashok Kumar, A., & Sanjana Reddy, P. (2010). Recent advances in sorghum improvement research at ICRISAT. Kasetsart Journal (Natural Science), 44, 499-506.

Repellin, A., Båga, M., Jauhar, P. P., &Chibbar, R. N. (2001). Genetic enrichment of cereal crops via alien gene transfer: new challenges. Plant cell, tissue and organ culture, 64, 159-183.

Riethmuller, A., Voglmayr, H., Goker, M., Weiß, M., &Oberwinkler, F. (2002). Phylogenetic relationships of the downy mildews (Peronosporales) and related groups based on nuclear large subunit ribosomal DNA sequences. Mycologia, 94(5), 834-849.

Rooney, W. L. (2004). Sorghum improvement-integrating traditional and new technology to produce improved genotypes. Advances in agronomy, 83(10.1016), S0065-2113.

Sasmal, A. (2018). Management of pink stem borer (Sesamiainferens Walker) in finger millet (Eleusine coracana Gaertn.). Journal of Entomology and Zoology Studies, 6(5), 491-495.

Singh, B. U., Rana, B. S., Reddy, B. B., & Rao, N. G. P. (1983). Host plant resistance to stalk-borer, Chilo partellus Swin., in sorghum. International Journal of Tropical Insect Science, 4(4), 407-413.

Chapter 13

Millet Mechanization: Transforming Millet Farming in India

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Introduction:

Millets, often referred to as "nutri-cereals," are a diverse group of small-seeded grains that have played a significant role in global agriculture for millennia. Their importance in the agricultural landscape is undeniable, as they serve as resilient and nutritious staples in the diets of millions around the world. These hardy crops are characterized by their ability to thrive in diverse climates and their remarkable nutritional content, offering an array of vitamins, minerals, and dietary fibre. Millets are known for their drought resistance, making them well-suited for regions with erratic rainfall patterns, which are increasingly prevalent due to climate change. In an era where sustainable farming practices, nutritional security and food security are paramount, millets have emerged as a crucial component of the solution. Their adaptability, nutritional value, and sustainability make them a valuable asset in global agriculture, addressing the twin challenges of providing nourishment to a growing population while preserving the environment. With these advantages, central and state governments are focussing now for increasing cropping intensity and land under the millet. As of 2021, India held the leading position in millet production, accounting for a substantial 41% of the global share, with Niger (~12%) and China (~8%) following closely. Additionally, India secured the 12th position among nations achieving high millet yields (Anonymous, 2023a). In an effort to raise awareness and boost both the production and consumption of millets, the United Nations, in response to the Government of India's initiative, officially designated the year 2023 as the 'International Year of Millet'. Hence, mechanization of millet production and harvesting system could be a better option for fulfilling the demand, generation of employment, timely solution and target of the Governments. This way it will give a better benefit to small and marginal farmers to enhance their livelihood.

Mechanization holds paramount significance in modernizing millet farming, ushering in a new era of efficiency, productivity, and sustainability. Traditional millet cultivation methods, often labour-intensive and time-consuming, have been transformed by the introduction of mechanized techniques. This shift has led to substantial labour savings, reduced drudgery for farmers, and increased crop yields. Mechanization ensures precision in planting and harvesting, resulting in higher-quality millet produce. Moreover, it empowers farmers to adapt to changing agro-climatic conditions, contributing to the resilience of millet farming systems in the face of climate change. With government support and integration into sustainable agricultural practices, mechanization not only boosts economic viability but also plays a pivotal role in preserving the rich tradition of millet cultivation while addressing the challenges of modern agriculture.

Trends in millet cultivation reveal significant changes over the years. The area dedicated to Sorghum has experienced a substantial decline of 76% between 1966 and 2021. Conversely, there has been a strong emphasis on increasing Pearl millet production, with a remarkable rise of over six million tonnes. The yield estimates for all types of millets have demonstrated steady progress, increasing by 600 to 1000 kilograms per hectare.

In the year 2021-22, Pearl millet accounted for the majority of millet production, contributing 58% to the total, followed by Sorghum at approximately 29%, and Finger millet at around 10%. Despite Finger millet having a smaller share of both area and production, its yield estimates are comparable to those of Pearl millet. In 2021-22, their yield estimates were nearly identical, standing at 1436 kilograms per hectare for Finger millet and 1401 kilograms per hectare for Pearl millet.

Millet cultivation and production are notably higher in the western region of India. Rajasthan, in particular, played a significant role in millet cultivation, contributing approximately 36% of the total millet cultivation area in India, which translates to around 4300 thousand hectares. Moreover, Rajasthan holds the distinction of being the largest millet producer in India, accounting for over 26% of the country's millet production, which exceeds 4000 thousand tonnes. It is worth noting, however, that despite its large area and production, Rajasthan's millet yield remains comparatively lower. Similarly, millets (Jawar, Bajra and Ragi) including small millets production in Odisha during 2020-21 has been 159760 MT from an area of 166490 ha with an average productivity of 960 kg/ha (Anonymous, 2023b).

The purpose of the chapter on "Millet Mechanization and Harvesting: Enhancing Productivity and Sustainability" is to provide a comprehensive exploration of the pivotal role that mechanization plays in modernizing millet farming practices. It aims to highlight the significance of adopting mechanized techniques in millet cultivation and harvesting processes, elucidating the benefits it offers in terms of increased efficiency, labour savings, and enhanced crop yields. The scope of this chapter encompasses a wide array of topics, including an introduction to millets and their nutritional importance in global agriculture. It delves into the mechanization technologies utilized in millet farming, offering insights into how these machines streamline the various stages of millet cultivation. Additionally, the chapter discusses the challenges and opportunities associated with the adoption of mechanization, while emphasizing its impact on millet yield, quality, and sustainability. Furthermore, the chapter touches on government initiatives, emerging trends, and innovations in millet mechanization, showcasing real-world case studies of successful implementation. Ultimately, the goal of this chapter is to provide a comprehensive understanding of the subject matter, empowering readers with knowledge to make informed decisions about adopting mechanized practices in millet farming, thereby contributing to the modernization and sustainability of this vital agricultural sector.

Understanding Millet Cultivation:

Millet crops, including pearl millet, finger millet, foxtail millet, proso millet, little millet, and kodo millet, constitute a diverse group of small-seeded grains with significant agricultural importance. These resilient crops have been cultivated for centuries, showcasing their adaptability to a wide range of environmental conditions. Pearl millet, known for its drought resistance, is a staple in arid regions, while finger millet, rich in calcium and protein, is a nutritional powerhouse in Africa and South Asia. Foxtail millet's rapid growth and adaptability make it a versatile choice, and proso millet's round seeds find use in various culinary applications. Little millet, among the smallest millet varieties, is cherished for its iron and calcium content, and kodo millet, another drought-tolerant crop, is a vital component of Indian agriculture. These millet crops not only contribute to food security but also serve as reservoirs of genetic diversity, offering sustainable solutions in the face of climate change and challenging growing conditions. Their versatility and adaptability underscore their significance in global agriculture and nutrition.

Traditional methods of millet farming:

Traditional methods of millet farming have been practiced for centuries and continue to be the foundation of agricultural practices in many regions around the world. These methods often involve age-old, time-tested techniques passed down through generations. Traditional millet farming typically relies on manual labour and simple tools, emphasizing a deep understanding of local ecosystems and weather patterns. Farmers sow millet seeds directly into prepared fields, often using hands or rudimentary hand tools. Weeding is done manually to control competing vegetation. Harvesting involves the use of sickles or scythes, and threshing, the process of separating grains from the stalks, is frequently done by hand or with the help of livestock. Traditional millet farming is characterized by its intimate connection with nature, relying on natural rainfall patterns and traditional knowledge to guide planting and harvesting times. While traditional methods have sustained millet production for generations, modernization and mechanization are gradually complementing these practices to address contemporary challenges such as labour shortages and climate change. Nevertheless, the wisdom and sustainability of traditional millet farming remain invaluable resources in the quest for resilient and productive agricultural systems.

One of the key goals of the Odisha Millets Mission program is to enhance millet productivity by implementing standardized and improved agronomic practices. These practices include the System of Millets Intensification (SMI), Line transplanting (LT), and Line Sowing (LS). By adopting these improved agronomic techniques, there is a significant potential to augment crop yields, expand the area under millet cultivation, and ultimately, enhance the profitability of millet farming for the benefit of farmers (Anonymous, 2023c). Some images are shown in the Fig.1 on the improved agronomic practices promoted/adopted by farmers in millets cultivation.

Standard Seedbed	Marking using wooden marker for SMI planting	Transplanting under SMI using rope marker

		
Weeding using wheel hoe	Preparation of organic manure	Harvesting using Sickle

Fig. 1 Improved agronomic practices followed by farmers in millets cultivation
Source: Annual Report 20-21, Odisha Millets Mission

Challenges faced by millet farmers in the absence of mechanization:

Millet farmers confront a range of formidable challenges in the absence of mechanization, which can hinder their productivity and livelihoods. One of the most pressing issues is the labour-intensive nature of traditional millet farming practices. Tasks such as manual planting, weeding, harvesting, and threshing demand significant physical effort and time, making it increasingly difficult to find and retain agricultural labourers, especially during peak farming seasons. Additionally, the dependence on manual labour can lead to inefficiencies and delays in farming operations, affecting crop yields and overall agricultural productivity. Moreover, the lack of mechanization in millet farming often results in a heavy reliance on weather conditions. Unpredictable rainfall patterns and adverse weather events, such as droughts or heavy rains, can have a devastating impact on millet crops. Without mechanized irrigation systems or efficient means of responding to changing weather, farmers are left vulnerable to crop failures and income loss. Furthermore, the absence of mechanization can hinder the adoption of modern farming practices, such as precision agriculture and resource-efficient techniques. These practices have the potential to enhance crop quality and reduce resource wastage, but they are often challenging to implement without the aid of machinery.

Advantages of mechanization in millet cultivation.

The advantages of using machinery in millet cultivation are transformative, revolutionizing traditional farming practices and offering numerous benefits to farmers and the agricultural sector as a whole. Mechanization brings efficiency and precision to every stage of millet farming, from planting to harvesting and post-production. By streamlining labour-intensive tasks, machinery significantly reduces the physical burden on farmers, addressing the challenge of labour shortages. Moreover, it ensures uniformity in planting and spacing, leading to better crop establishment and higher yields. Mechanized harvesters expedite the often time-sensitive process of harvesting, minimizing post-harvest losses. Additionally, modern machinery enhances the overall quality of millet produce, making it more marketable and financially rewarding for farmers. Beyond immediate advantages, mechanization also contributes to the sustainability of millet farming by promoting resource-efficient practices and reducing the environmental impact. In essence, the adoption of machinery in millet cultivation empowers farmers to meet the demands of modern agriculture while fostering increased productivity, economic viability, and sustainability.

In sum, the challenges faced by millet farmers in the absence of mechanization encompass labor shortages, vulnerability to weather-related risks, and limited access to modern farming technologies. Addressing these challenges and promoting mechanization in millet farming is crucial for improving productivity, enhancing food security, and ensuring the sustainability of millet cultivation in a rapidly changing agricultural landscape.Top of Form

Millet Mechanization Technologies

Millets farming has witnessed a remarkable transformation through the integration of a diverse range of machinery tailored to enhance efficiency and productivity. These indispensable tools include seed drills, which ensure precise and uniform seeding, optimizing germination and crop establishment. Millet threshers have become invaluable for their ability to efficiently separate grains from stalks during harvest, saving farmers time and labour. Mechanical harvesters, such as combine harvesters and reaper-binders, have revolutionized the once labour-intensive harvesting process by swiftly cutting and gathering mature millet plants. In addition, weeders have been employed to combat weed infestations without harming the millet crop, thereby boosting yields. Beyond the field, millet farming benefits from irrigation systems, like drip irrigation and sprinklers, which deliver consistent water to crops, essential in regions with erratic rainfall. These technologies, along with storage facilities and transportation equipment, have modernized millet farming, ensuring efficient post-harvest handling and protecting grains from spoilage. These tools collectively empower millet farmers to overcome labour constraints, enhance crop quality, and bolster the sustainability of millet agriculture in an ever-evolving agricultural landscape.

Equipments/implements for mechanization in millets production

Seedbed Preparation

Tractor-drawn ploughs, cultivators and rotary tillers can be used where a tractor or power tiller is available. Very light tillage is required for millets;

therefore, ploughing up to the depth of 10-15 cm in dry land agriculture is followed by the farmers once a year. On the other hand, the farmers who own the draft animal prefer ploughing by bullocks drawn equipment, either Baliram Iron plough or mould board plough in order to utilize the draft animal power. The average time required for ploughing by the indigenous plough is 23-25 man-h/ha, whereas the cost of operation required for ploughing with mould board plough is as high as Rs. 2800-3000/ha. For seedbed preparation of minor millets, a Blade harrow is used for secondary tillage operation. The use of power-operated equipment such as a tractor-operated mould board plough, cultivator and rotavator to get fine tilth of the soil and avoid repetitive operations could be a good option. In addition, the combined tillage machinery, such as a swipe tyne cultivator attached to a clod crusher and lever, can also be used for seedbed preparation. Performance of different seedbed preparation machinery is given in the Table 1. Prior to these operations land levelling should be done to enhance water and nutrient use efficiency along with reduction in the environmental emissions.

Table 1 Technical specification and performance of the seedbed preparation machinery

Name of Machinery	Overall dimension, m	Weight, kg	Operational speed, km/h	Field capacity, ha/h
Bullock drawn improved plough	350×200 ×800	25	1.2- 1.8	0.039
Bullock drawn improved blade harrow	1200 × 800 × 600	30	1.8-2	0.062-0.075
Power tiller	1000 ×700 × 900	140	2.4	0.079
Sweep type cultivator with clod crusher and leveler	1600 × 1500 × 800	450	3.4	0.48
Power tiller operated rotavator	2000 × 740 × 1200	462	2.1	0.38

Planting/Sowing Machinery

Sowing is a critical operation for ensuring the successful establishment of crops. The precise placement of seeds concerning their depth, the number of seeds per hill, the spacing between plants, and the distance between rows all have a significant impact on achieving a healthy plant population. The machines developed by ICAR-Central Institute of Agricultural Engineering, Bhopal can be used for planting/sowing operations and fertilizer application. Manually operated machines, bullock drawn three row plant planters cum fertidrill, and tractor and power tiller drawn six row planters cum fertidrill with different metering devices (Fig. 2) for sowing minor millet such as kodo millet, little millet, proso-millet, foxtail millet, Barnyard millet, and Finger millet. Use of the multi-millet seed cum fertilizer planters can save up to 90% seeds as compared to broadcasting and 60-70% seeds as compared to drilling by traditional methods (Nandede, 2023). Table 2 depicts performance of different types of planters for millets sowing.

(a) Manual drawn	(b) Bullock drawn	(c) Power tiller dawn	(d) Tractor drawn

Fig. 2 Millets sowing machinery developed by ICAR-CIAE Bhopal

Table 2 Technical specification and performance of the ICAR-CIAE planters

Name of Machinery	Overall dimension, mm	Weight, kg	Operational speed, km/h	Field capacity, ha/h
Manual drawn single/ three row multi-millet seed cum fertilizer planters	1170×450 × 1100	20-30	1.0	0.03-0.09
Bullock drawn three row multi-millet seed cum fertilizer planters	700 ×1000× 900	60-80	2.0	0.10-0.12
Tractor/power tiller drawn six row multi-millet seed cum fertilizer planter	700 × 2100 × 1000	120-150	2-4	0.32-0.52

Machinery for Intercultural Operation

Implementing weed control measures is essential to manage the growth and spread of weeds. Mechanical weed control methods serve as practical alternatives, especially in situations where the environmental consequences of using herbicides or chemical applications make chemical methods unsustainable. The simple and most popular weed management method is manual weeding using khurpi is an expensive, time-consuming and labour-intensive method. During the peak weeding season, a severe shortage of labour can lead to higher labour wages and cause delays in weeding operations. Lightweight mechanical weeders such as wheel hoes or power weeders offer an effective option for intra-row weeding. Mechanical weeding has been shown to enhance crop yields compared to manual hand weeding. Among mechanical options, rotary power weeders perform particularly well in terms of achieving consistent working depth compared to traditional bullock-drawn blade weeders. In millet crops, various choices are available, including manual wheel hoes, animal-drawn hoes, and power-operated weeders, all of which can be utilized to manage weeds efficiently. Improved power weeder working in millet crops is shown in Fig. 3 and specification is given in Table 3.

NRRI- Finger weeder	NRRI-bullock drawn weeder	NRRI-Power weeder	CIAE-Power weeder

Fig.3 Improved manual and power weeders

Table 3 Technical specification and performance of manual and power weeders

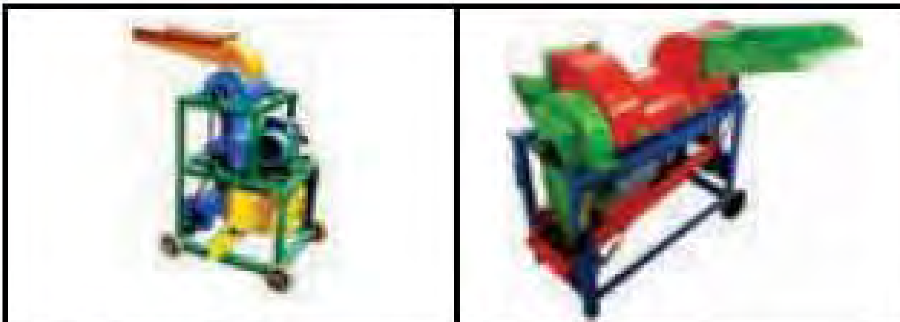
Name of Machinery	Overall dimension, mm	Weight, kg	Operational speed, km/h	Field capacity, ha/h
NRRI- Finger weeder	1850× 380×420	7.5	1.2	0.022 - 0.025
NRRI-bullock drawn weeder	1340× 410 × 320	10	1.5	0.2 ha/h
Twin wheel hoe	250×250×1100	4.5	1.2	0.027
CIAE-Power weeder	450 × 250 × 1000	12	1.7	0.039
NRRI-Power weeder	1800×600×1100	20	1.5	0.025

Millets Harvesting and Threshing Machinery

The sickle is the predominant tool employed for the manual harvesting of crops. Currently, the manual harvesting of millet relies on the use of sickles. This process typically demands approximately 80-100 man-hours per hectare for completion. However, for harvesting multiple types of millets, the adoption of a vertical conveyor reaper and reaper binder can be advantageous. These machines not only help reduce the cost per unit area but also save valuable time during the harvesting process. Some selected harvesting machinery used for harvesting millets is shown in Fig 4. Electric motor operated CIAE-multi-millets thresher works on the principle of impact and shear on the ear head of the crop for the threshing of millets. The dehulling capacity of the thresher is 20-80 kg/h, respectively. Pearling capacity of millets is 200-250 kg/h. Millets like kodo, little, foxtail, proso, barnyard and finger can be threshed with a threshing efficiency between 94-97% in 1 or 2 passes. Power requirement of the machine is 1.5 kW. CIAE multi-millets thresher is shown in Fig 5.

(a) Vertical conveyor reaper | (b) Reaper binder

Fig. 4 Improved harvesting machinery



(a) Thresher cum dehuller | (b) Thresher cum pearler

Fig. 5 CIAE multi millets thresher cum pearler

Table 4 Technical specification and performance of manual and power weeders

Name of Machinery	Overall dimension, mm	Weight, kg	Operational speed, km/h	Field capacity, ha/h
Improved sickle	400 × 150 × 40	0.2	0.5	0.018
Vertical conveyer reaper	2400× 1200 × 1000	245	2.0	0.15-17
Reaper binder	3200 × 1200 × 1100	390	2.0	0.16
Threshing machinery	Threshing output, kg/ha	Threshing efficiency, %		
CIAE Multi millet thresher	1200 × 1000 × 1500	100	80-150	94-97

Innovations in millet harvesting have been developed to address specific challenges faced by farmers. Some notable innovations include:

Small-Scale Millet Harvesters: Given that many millet farmers have small landholdings, innovations in small-scale millet harvesters have emerged. These machines are designed to be more affordable and suitable for small plots, making mechanized harvesting accessible to a broader range of farmers.

Multi-crop Harvesters: In regions where millets are cultivated alongside other crops, multi-crop harvesters have been developed. These machines can harvest multiple crops simultaneously, reducing the need for separate harvesting passes and saving time and labour.

Harvesting attachments for Tractors: Attachments that can be mounted on tractors to harvest millet have been created. These attachments are cost-effective and enable farmers to mechanize the harvesting process without investing in standalone harvesters.

Improved Threshing Mechanisms: Innovations in threshing mechanisms aim to reduce grain losses during the post-harvest process. Threshers equipped with adjustable settings and gentler threshing actions help maintain millet grain quality.

Harvesting Timing Apps: Mobile applications that provide real-time information on the optimal timing for millet harvesting based on weather conditions and crop maturity have been developed. These apps help farmers make informed decisions, reducing the risk of crop damage due to adverse weather.

Harvesting Aids for Marginalized Farmers: Innovations have been designed to address the challenges faced by marginalized and physically challenged farmers. These aids include hand-held harvesting tools and assistive devices that make millet harvesting more accessible.

Mechanized Bagging and Storage Solutions: Innovations in bagging and storage systems facilitate the efficient handling of harvested millet grains, reducing post-harvest losses and ensuring grain quality.

Ergonomic Harvesting Equipment: Ergonomically designed harvesting equipment reduces the physical strain on labourers during the harvesting process. These innovations improve the well-being of farm workers and promote longer hours of productive work.

These innovations demonstrate the ongoing efforts to address specific challenges in millet harvesting, such as labour scarcity, post-harvest losses, and accessibility. By implementing these solutions, farmers can enhance their efficiency and productivity, ultimately contributing to the sustainability of millet cultivation.

Government Initiatives and Supports

Indian government had initiated several policies and programs to promote millet mechanization, recognizing the importance of millets for food security, nutritional diversity, and sustainable agriculture. Here are some key Indian government policies and initiatives:

National Mission on Oilseeds and Oil Palm (NMOOP): While primarily focused on oilseeds and oil palm, this mission also supports the promotion of dryland crops, including millets. It provides financial incentives and subsidies to farmers for the purchase of machinery and equipment for millet cultivation.

National Food Security Mission (NFSM): NFSM includes the promotion of millets to enhance food and nutritional security. It supports the development and dissemination of millet-specific technologies, including mechanization.

Paramparagat Krishi Vikas Yojana (PKVY): This scheme encourages organic farming and sustainable agricultural practices, including millet cultivation. It promotes the use of modern machinery and technology for organic millet production.

Rashtriya Krishi Vikas Yojana (RKVY): RKVY supports the adoption of modern technologies and mechanization in agriculture. It funds projects aimed at increasing millet production and productivity through mechanization.

Millet Promotion Program by State Governments: Several Indian states have launched their millet promotion programs, offering subsidies and support for millet mechanization. These state-level initiatives often complement national programs.

Training and Capacity Building: The government, through various agricultural universities and institutions, conducts training and capacity-building programs for farmers on millet cultivation and mechanization.

Promotion of Farmer Producer Organizations (FPOs): FPOs are encouraged to adopt mechanized millet farming practices to improve their collective productivity and income.

Research and Development Support: The Indian Council of Agricultural Research (ICAR) and state agricultural universities conduct research on millet varieties and mechanization technologies.

Adoption and Challenges for mechanization in millet farming

The adoption of mechanization in millet farming in India is influenced by a complex interplay of factors, including farm size, financial resources, access to credit, infrastructure, education, climate conditions, and government policies. Addressing these factors strategically can promote the sustainable integration of machinery into millet farming practices, leading to increased productivity and improved livelihoods for farmers. Also, transitioning to mechanized farming practices offers numerous benefits, but it also comes with a set of challenges, including financial constraints, the need for training, adjustments to new workflows, maintenance requirements, labour dynamics, and infrastructure limitations. Addressing these challenges through targeted support and policies is essential to ensure a successful and sustainable transition to mechanized agriculture for farmers. Strengthening agricultural extension services is crucial. Continuous support and guidance for farmers adopting mechanization, including troubleshooting and best practices, will help them navigate the transition effectively. By implementing these solutions and best practices, the challenges hindering the adoption of mechanized millet farming can be surmounted, leading to increased productivity, reduced labour intensity, and a more sustainable millet agriculture sector.

Case Studies on Millets Mechanization

Real-world examples of millet farmers who have successfully adopted mechanized techniques.

Mechanized Millet Farming in Rajasthan, India: In the arid region of Rajasthan, India, several millet farmers have adopted mechanized techniques to overcome labour shortages and improve yields. By using tractors and seed drills, these farmers achieve precise and timely planting of millet seeds, resulting in better crop establishment and higher yields. The introduction of threshing machines has also reduced post-harvest losses, leading to improved economic outcomes for these farmers.

Millet Mechanization in Niger: In Niger, where millet is a staple crop, the adoption of mechanization has gained traction among smallholder farmers. By utilizing small-scale millet harvesters, these farmers have significantly reduced the labour required for harvesting and threshing. This not only improves their overall efficiency but also reduces post-harvest losses and ensures better grain quality.

Custom Hiring Centres in Mali: In Mali, the establishment of Custom Hiring Centers (CHCs) has facilitated the adoption of mechanized farming practices, including millet cultivation. These CHCs allow farmers to rent machinery at affordable rates, making mechanization accessible to those with limited resources. As a result, many millet farmers in Mali have been able to increase their yields and income.

Women Empowerment in Burkina Faso: In Burkina Faso, women farmers have embraced mechanized millet farming to reduce the drudgery associated with manual labour. With the support of government initiatives and NGOs, these women have gained access to mechanized equipment like small tractors and seed drills. This not only eases their workload but also enhances their economic independence and contributes to improved millet production.

Summary and Conclusion

The significance of mechanization in millet farming cannot be overstated. Mechanization revolutionizes traditional farming practices by introducing efficiency, precision, and sustainability into every stage of millet cultivation, from planting to harvesting and post-production. It alleviates the physical burden on farmers, addresses labour shortages, and ensures uniformity in planting, leading to better crop establishment and higher yields. Mechanized harvesting minimizes post-harvest losses, enhances grain quality, and expedites the often time-sensitive harvesting process. Beyond immediate advantages, mechanization also contributes to the sustainability of millet farming by promoting resource-efficient practices and reducing the environmental impact. It empowers farmers to meet the demands of modern agriculture, fostering increased productivity, economic viability, and improved livelihoods. In essence, mechanization is a pivotal force in modernizing millet farming, ensuring its resilience and continued growth in the face of evolving agricultural challenges.

Furthermore, mechanization has the potential to attract a new generation of farmers to millet cultivation. Younger individuals, often discouraged by the labour-intensive nature of traditional farming, may find mechanized farming more appealing and economically viable. This infusion of new talent and technology can invigorate the millet agriculture sector and ensure its longevity.

Moreover, as global demand for millets as nutritious and climate-resilient crops continues to rise, mechanization can help meet these demands sustainably. It enables efficient post-harvest processing, reducing losses and ensuring that high-quality millet products reach consumers.

In essence, mechanization has the potential to drive the future of millet agriculture by making it more productive, environmentally friendly, and economically viable. It positions millet farming to play a crucial role in global food security, nutritional diversity, and sustainable agriculture in the years to come. However, to fully realize this potential, it's essential to continue investing in research, training, and supportive policies that promote mechanization in millet farming.

References

Anonymous, 2023a. Millet cultivation in India: History and trends. https://idronline.org/article/agriculture/millet-cultivation-history-and-trends/, accessed on dated 01.10.2023.

Anonymous, 2023b. E-catalogue for export of millets and value added products in Odisha. APEDA, Ministry of commerce and industry, GoI, https://apeda.gov.in/milletportal/files/Odisha_Millet_Value_Added_Products_Catalogue.pdf dated 02.10.2023, accessed on 2.10.2023.

Anonymous, 2023c. Annual report 20-21, Odisha millets mission, https://milletsodisha.com/resources/annualreports, accessed on 02.10.2023.

Nandede, B.M, 2023. Package of machinery for millet production agriculture. Agricultural Engineering Today, 47 (1). https://doi.org/10.52151/aet2023471.1622.

Chapter 14

Glycemic Index Perspectives of Millets: A Nutritional Breakthrough

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Abstract

The glycemic index (GI) is a crucial parameter in the management of blood sugar levels and overall health, and its reduction is a primary concern for individuals with diabetes and those aiming to prevent metabolic disorders. Millets, a group of nutrient-rich grains, have gained attention for their potential to serve as low GI alternatives to conventional cereals. This paper explores various approaches to lowering the GI in millets and millet-based products, with a focus on improving their suitability for glycemic control. Key strategies discussed include the incorporation of dietary fiber, resistant starch, and certain bioactive compounds into millet-based foods. These components, found naturally in millets or introduced during processing, contribute to reduced starch digestion and slower glucose release, resulting in lower GI values. In addition to these technical approaches, the paper highlights the significance of food formulation, structuration, macronutrient interactions and meal combinations in modulating the GI of millet-based dishes. Understanding how different factors influence GI provides valuable insights for individuals seeking to manage blood sugar levels and improve overall dietary choices. Overall, this paper presents a comprehensive overview of approaches to lower the glycemic index in millets and millet-based products. By leveraging these strategies, millets can play a pivotal role in promoting health-conscious diets and supporting individuals in their quest for improved glycemic control and better overall well-being.

Keywords : Glycemic Index; Millets; Macronutrient interactions; Dietary Fiber; Food structuration

Introduction

The glycemic index (GI) is a useful tool for determining how distinct foods affect blood sugar levels, making it essential for people who are worried about their general health and wellbeing. Recognizing the effects of various diets on blood sugar management becomes increasingly crucial as the prevalence of genetic disorders like diabetes and obesity keeps growing worldwide (Walton et al., 2023). As a result of their unique GI properties, millets have become recognized as a nutritional powerhouse that offers an emerging view in the regulation of glucose levels in the blood (Priyadarshini et al., 2021a). Since ancient times, millets, a class of small-seeded, annual cereal grains, have been grown and eaten in many parts of the world, particularly in Asia and Africa. These ancient grains, which come in types including sorghum, pearl millet, finger millet, foxtail millet, and proso millet, have newly attracted renewed interest on a global basis as a nutritious and renewable alternative to conventional staples like rice, wheat, and maize (Yousaf et al., 2021). Millets' low glycemic index, which has the potential to modify nutritional options and have a favorable impact on public health, is one of its most noticeable characteristics. Dr. David J. Jenkins (Jenkins et al., 1982) developed the glycemic index (GI), which rates carbohydrate-rich foods according to how rapidly they elevate the blood sugar level when compared to a standard benchmark food, typically glucose or white bread. While foods with a low GI are digested more slowly and cause a steady rise in blood sugar levels, those with a high GI are quickly absorbed and cause a fast rise in blood sugar (Priyadarshini, Elumalai, et al., 2020). This distinction is essential, particularly for those who have diabetes or who are at risk of getting the disease. When compared to common cereals like wheat and rice, millets have consistently shown low GI values in the general population. This is mostly related to their complex carbohydrate makeup, high fiber content, and slow rate of absorption (Gopirajah et al., 2016). For example, pearl millet, a common food in dry areas of Africa and India, has a remarkable low GI, making it a great option for people who want to efficiently control their blood sugar levels. Similarly, foxtail millet and finger millet have drawn interest for their low-GI qualities due to their specific nutritional compositions. Millets have a low GI, which is advantageous for everyone who wants to have consistent energy levels throughout the day, not just those with diabetes. Low-GI foods deliver continuous energy and encourage feelings of fullness, which can help with weight control and general well-being. Foods with high levels of GI can cause fatigue and increased appetite quickly after eating (Opperman et al., 2004). The abundant nutritious value of millets is another noticeable feature. These grains are an excellent source of dietary fiber, antioxidants, vitamins, and minerals. Their high nutrient content not only helps explain why they have a low glycemic index (GI), but it also has a number of positive health effects, such as better immune system performance, improved digestion, and a lower risk of developing chronic illnesses (Flint et al., 2004). Additionally, millets are very flexible and can be used in a variety of culinary recipes. Millets can effectively substitute high-GI grains in a variety of recipes, from conventional porridges and flatbreads to contemporary fare including salads, soups, and baked goods. Due to their adaptability, millets can be easily incorporated into a person's diet without sacrificing flavor or convenience (Di Cairano et al., 2018). The revival of millets in the global food market in recent years has prompted an upsurge in research and development initiatives targeted at maximizing their nutritional value. Millets are important for combating the twin problems of malnutrition and diseases linked to diet, according to scientists, policymakers, and nutritionists. As a result, campaigns to encourage millet planting and consumption have gained traction, advancing sustainable agricultural methods and better eating patterns. To sum up, millets' thoughts on the glycemic index present a promising response to the rising health issues around the control of blood sugar and general wellbeing (Priyadarshini et al., 2021b). Millets are positioned to be a key player in altering dietary choices and supporting public health thanks to their low GI values, remarkable nutritional profiles, and culinary versatility. This investigation into the GI properties of millets will go further into their possible advantages, offering insightful information to patients, medical professionals, and policymakers alike.

Key determinants of low glycemic index in millets

The relatively low glycemic index (GI) of millets is attributable to a number of important factors that work together to slow down their absorption and digestion, which causes a gradual rise in blood sugar levels.

Carbohydrate Composition

Millets have a distinctive carbohydrate makeup that is dominated by complex carbs, with significant quantities of amylose in particular. Compared to the more straightforward sugars included in high-GI foods, amylose is a kind of starch that is digested more slowly. The low GI of millets is mostly a result of the presence of amylose. The carbohydrate composition had influenced the eGI of millet biscuits in a study (Priyadarshini, Suriyamoorthy, et al., 2020). Here the ragi millet attributing to high resistant starch had a reduced eGI when compared to control biscuits.

Dietary Fiber

Dietary fiber, which millets are high in, is very important in lowering their GI. By creating a gel-like matrix in the digestive tract, fiber slows down the breakdown and absorption of carbs. This causes a steady increase in blood sugar levels by delaying the release of glucose into the bloodstream. Millets' high fiber content also encourages satiety and aids in controlling appetite. When GI was examined in multigrain beverages that contained fructooligosaccharides of about 1%. The multigrain millet loaded beverage was determined to have a glycaemic index of 45, making it a low GI food. The low GI of the beverage may be attributable to the use of whole grains that are high in fiber and other sources of fiber, such as fructooligosaccharide (Arya & Shakya, 2021)a multigrain functional beverage was made using minor millets such as barnyard, foxtail and kodo millet. Millets are rich in dietary fibre, B vitamins and micronutrients like magnesium, iron and have low glycaemic index. Roasted millets were extracted with water and filtered to obtain the beverage. An appropriate ratio of all grain was obtained from D-optimal mixture design. Accordingly, grain amount was varied from 5 to 8 g, 8–12 g, 6–9 g for barnyard, foxtail and kodo millet respectively. The ratio was selected based on pH, phenolic content, antioxidant activity and sensory overall acceptability of resultant multigrain beverages. Beverage was treated with α-amylase enzyme, fructooligosaccharide, galactooligosaccharide, and maltitol to improve the sensorial properties. The final multigrain functional beverage was prepared from 7 g barnyard, 10 g foxtail and 8 g of kodo millet along with 1.2 g/100 g w/v of fructooligosaccharide, containing 5.72 g/100 g total dietary fibre, 47.69 mg ferulic acid equivalents (FAE.

Protein Content

In general, millets contain more protein than other grains like wheat and rice. Because protein slows down the digestion of carbohydrates, it can help lower the GI of a meal. Additionally, it encourages satiety, which helps prevent blood sugar rises after meals. According to a study, the maximum protein content was found in foxtail and barnyard millets. The non-starch components, such as total dietary fiber and arabinoxylan, had an impact on protein weakening (Sharma & Gujral, 2019).

Lipid Content

There are several millets that contain a significant level of lipids (fats), including finger millet (ragi). Because fats take longer to digest and delay the absorption of carbohydrates, their presence in a meal can lower the total GI. Similar research has been done to alter wheat starch by linking it with different fatty acids and germ oil (Vidhyalakshmi et al., 2023).

Phytate Content

The substances known as phytates, which are found in millets, can prevent digestive enzymes from breaking down carbohydrates. Millets' low GI is a result of this inhibition, which causes a slower release of glucose into the bloodstream. Starch digestibility was enhanced by the conversion of starch to oligosaccharides and the decrease in phytate level brought on by enzymatic hydrolysis during fermentation (Suma & Urooj, 2017).

Cooking Method

The preparation of millets can also affect how well they digest. Millets' low GI is better maintained when they are cooked using techniques like boiling, steaming, or baking rather than when they are ground into flour, which can raise their GI (Rice et al., 2019).

Particle Size

Compared to whole millets or coarsely ground millet flour, finely ground millet flour often has a higher GI. This is because the faster spike in blood sugar is brought on by the finer particles' easier absorption and digestion. A reduced glycaemic response was observed in foods cooked with finger millet (kurakkan) flour that had a wider particle size distribution (Jayasinghe et al., 2013).

Variety and Maturity

The GI of millet can vary depending on the variety and ripeness at harvest. Millets that are not fully grown typically have a lower GI than those that are. Additionally, because to changes in their carbohydrate makeup, certain millet types may have slightly varying GI ratings. The GI of 11 different varieties of millet was recently examined in a meta-analysis of 65 trials. Millet had an average GI of 52.7. Low GIs were found in teff, fonio, Barnyard millet, foxtail millet, and Job's tears. The middle GIs were found in finger millet, Kodo millet, small millet, pearl millet, and sorghum (Anitha et al., 2021). In comparison to waxy proso millet, the non-waxy variety had larger levels of resistant starch and a smaller amount of rapidly digestible starch (Yang et al., 2018). One can infer from this study that waxy and non-waxy proso millet have different qualitative attributes.

Antioxidants

Antioxidants included in millets, such as polyphenols, may also help lower a food's GI. Polyphenols have been demonstrated to slow down the breakdown of carbohydrates and increase insulin sensitivity. In a study, compared to rats fed with finger millet, those fed the kodo millet diet had lower blood sugar.

Antioxidants like superoxide dismutase, catalase, glutathione peroxidase, glutathione reductase, and glutathione reductase levels, as well as lipid peroxides, were dramatically reduced in diabetic mice and returned to normal in the millet-fed group (Hegde et al., 2005).

Processing

The GI of millet-based goods might vary depending on the degree of processing. Millet products that are whole or have undergone minimum processing often have lower GIs than millet products that have undergone extensive processing. Millets are frequently processed using a variety of techniques to reduce GI such as soaking germinating etc. Millet that has been treated and given better attributes is suitable for creating new foods, enhancing the food security (Akinola et al., 2017).

Low glycemic index of millets is a combination of their high fiber, protein, and carbohydrate content, as well as the inclusion of substances like phytates and antioxidants. Millets are a beneficial dietary option for people who want to control their blood sugar levels and improve their general health because of these features, which work together to decrease the digestion and absorption of carbohydrates.

Binary and ternary interactions approaches to lower GI in millet products

In order to lower the starch digestibility, the resistant starch (V) involves associations between starch and other grain components like protein, lipid, or polyphenol to form binary, ternary, or quaternary complexes (Kaimal et al., 2021). The idea of a "food matrix" demonstrates the interactions between many nutrients, both major and small. These interactions can be divided into binary, ternary, and quaternary (containing starch, proteins, lipids, and phenolics) combinations, such as starch interacting with lipids, proteins interacting with lipids, and starch interacting with proteins. These interactions, which are dependent on the particular food's composition, are essential for controlling how each nutrient is digested and broken down. Additionally, they affect the food's microstructure, molecular composition, a number of physical and chemical characteristics, and total nutritional value. The interaction between millet fiber and polyphenols is an intriguing illustration of this. This combination can slow the rise in blood sugar levels following a meal, primarily by preventing the enzyme amylase from working. It also performs a protective role for the body. According to a 2019 study by Jin and colleagues (Jin et al., 2019), foxtail millet's ability to reduce blood sugar is greatly influenced by the interaction of starch with naturally occurring amino acids and lipids. By lowering the rate of action of digestive and hydrolytic enzymes, fiber from food and other non-starch polysaccharides, like arabinoxylan, have been demonstrated to limit the uptake and degradation of starch (Sharma & Gujral, 2019). Additionally, the research showed a negative correlation between the presence of several substances, such as lipids, phenolic compounds, and antinutritional elements like phytic acid and tannins, and the in vitro digestibility of proteins and starch. This negative association suggests that when these elements rise, proteins and carbohydrates are less digestible. The amounts of resistant starch (RS) and slowly digested starch (SDS) are positively correlated with this observation. When the protein, fat, or both removed from the samples, we observed significant increases in in vitro starch digestibility and the eGI. It's worth noting that the in vitro starch digestibility of kodo millet was more profoundly influenced by the removal of lipids than by the elimination of proteins. In instances where both fat and protein were taken out of millet, the eGI increased from 49.4 for cooked millet flour to 62.5. This is in stark contrast to cooked rice flour, which had a notably lower eGI compared to cooked kodo millet starch. Among all the samples, cooked rice had the lowest Resistant Starch (RS) content at 1.61%. Remarkably, rice exhibited significantly higher in vitro starch digestibility and eGI compared to millet flour. It is important to highlight that treatments applied to kodo millet, such as decortication, which involves the removal of proteins, lipids, or both (with an emphasis on lipids), led to an increase in its in vitro starch digestibility and eGI (Annor et al., 2013).

Structuration approach lower GI in millet products

Euryale ferox seed shell extract was discovered to efficiently inhibit enzymes like alpha-amylase and alpha-glucosidase in a research study. The GI of bread was significantly reduced as a result of this inhibition. Particularly, the GI of the bread was lowered from 95 to 61 by the addition of merely 2% of this extract (Maibam et al., 2023). Larger starch molecules are reduced by -amylase into smaller maltooligosaccharides, which are then broken down by alpha-glucosidase into glucose monomers. Given the crucial roles of these enzymes, using plant-based polyphenols is a technique for regulating the rate of starch digestion. These polyphenols successfully block a certain enzyme, enabling a thorough and quick digestion of starch in the ileum. The double bond between the second and third carbon atoms in the heterocyclic ring and the hydroxyl group at positions A5 and B3 in the phenyl groups are both implicated in flavonoids' ability to inhibit alpha-amylase. Flavonoids can efficiently situate themselves within the alpha-amylase active catalytic space thanks to this configuration. The hydroxyl group at positions B3 and C3 in the phenyl groups, which offers a particular entryway for the B-ring into the alpha-glucosidase catalytic active site, is responsible for the critical inhibitory activity in the case of alpha–glucosidase (Lim et al., 2022).

The in-vitro digestibility and estimated glycemic index (eGI) of cowpea starch were influenced by physical modifications such as steam sterilization and cooling cycles. The eGI of cowpea starch decreased when subjected to the autoclaving-cooling cycle, which can be attributed to the transformation of its crystalline structure from the A type to a combination of the B and V types. This current study suggests that a single autoclaving and cooling process for cowpea starch may be a superior approach for achieving several benefits, including higher resistant starch (RS3) content, improved pasting properties, enhanced temperature stability, superior crystallographic quality, and a reduced glycemic index (GI) (Ratnaningsih et al., 2020). In a research study, a low glycemic food product was developed through an extrusion process. This process involved the use of two different types of corn starch: the normal type, which typically has a higher amylose content, and the waxy type, which has a higher amylopectin content. Esterification was performed during extrusion, with sodium propionate serving as the precursor. Interestingly, the waxy type starch exhibited lower levels of esterification due to its tightly knit amylopectin network. As a result, the final extruded product had a low glycemic index, primarily because the esterified starch structure encountered hindrance from steric factors. This occurred even though the A-type starch structure was predominant and extended further compared to the V-type starch structure (Hernandez-Hernandez et al., 2022). Various cooking and additives can influence GI of food products.

By utilizing polyphenol interactions either with the enzymes responsible for starch breakdown or with the molecular structure of starch itself, it is possible to modify the process of starch digestion. One potential mechanism through which phenolic compounds can influence the efficiency of starch hydrolysis is by vying for the binding sites of α-amylase and α-glucosidase, essentially competing with starch molecules for these locations. Moreover, phenolic compounds possess the capacity to alter the semi-crystalline structures of starch. This alteration leads to the formation of a complete V-type amylose structure and the displacement of starch-amylopectin complexes. Both of these interactions ultimately result in a reduction in the rate at which starch is digested (Li et al., 2018). Increased resistant starch (RS) levels in modified starches offer evident advantages in terms of their dietary properties, including a low glycemic index. Additionally, this promotes the growth of beneficial probiotic bacteria like Bifidobacterium sp. and Lactobacillus sp. (Zailani et al., 2023). In a fascinating study, it was observed that despite buckwheat having a lower amylose content compared to wheat, both types of starch exhibited similar digestibility. Nevertheless, what proved to be significant in determining digestibility was the starch's structure, particularly the degree of polymerization of long and medium amylopectin branches (Du et al., 2022).

Traditional and novel treatments for lowering GI of millet based products

Barnyard millet flour exhibited a notably lower glycemic index (GI) of 50.17 when compared to wheat biscuits, which had a GI of 73.58. Surprisingly, this difference in GI was observed despite only minor variations in nutrient composition between the two. Furthermore, both dehulled grains and grains that underwent a heat treatment process showed lower GI values than pure glucose. Dehulled grains exhibited GI values within the range of 45.2 to 54.8, with an average of 50.0. On the other hand, dehulled grains subjected to the additional heat treatment process displayed an even lower mean GI of 41.7, with values ranging from 38.4 to 45.3. This reduction in GI can be attributed to the formation of resistant starch during the heating and cooling processes applied to the dehulled and heat-treated millet. Previous research has suggested that heat processing can render specific starch components resistant to mammalian enzymes, allowing them to evade digestion (Anju & Sarita, 2010).

The process of amylose retrogradation is recognized for its role in generating resistant starch, as reported by (Jenkins et al., 1981). It has been proven that the intermittent application of heating and cooling cycles can substantially enhance the proportion of resistant starch in wheat, as demonstrated by (Shaikh et al., 2020). Interestingly, native wheat starch that underwent five cycles of autoclaving and subsequent cooling contained a substantial 11.5% resistant starch, a remarkable increase compared to the mere 0.5% found in the untreated native samples.

The grain meals in our study, whether they were dehulled or dehulled and subjected to heat treatment, are categorized as low glycemic index (GI) foods, as suggested in the classification in 2005 (Barclay et al., 2005). It is worth noting that the health mix made from barnyard millet, had a relatively higher GI of 59.80, even though it contained notable amounts of hypoglycemic ingredients. In contrast, the plain grain meal in our study, which did not include any hypoglycemic agents, displayed a significantly low GI of 41.7. This finding has important implications for the development of specialized foods for individuals with diabetes. There are also other barnyard millet based muffins having nutritional value (Goswami et al., 2015). Additionally, barnyard millet exhibited improved carbohydrate tolerance among the participants in our experiment, both those with diabetes and those without. This improvement was demonstrated by a significant decrease in fasting plasma glucose levels, with individuals with diabetes experiencing an average reduction of 6.0% after the dietary intervention (Ugare et al., 2014).

A comparative research study examined the changes in the structure and physiochemical properties of millet starch when exposed to microwave and ultrasound treatments at equivalent power levels. Both methods brought about alterations, but their impacts differed. Microwave treatment resulted in heightened crystallinity, a decrease in amylose content, and changes in granule structure. Conversely, ultrasound treatment caused only minor changes in crystallinity while enhancing the amylose content. Both techniques showed promise for modifying millet starch, with microwaving favoring structural adjustments and ultrasound improving the starch's physiochemical properties. Recognizing these distinctions can guide their application in food processing and product development for a wide range of culinary and industrial uses (Wang et al., 2020). The presence of fatty acids in millet starches plays a significant role in determining their hypoglycemic properties. Both the type and quantity of fatty acids in millet flours are crucial factors in maintaining the low digestibility of millet starches. Specifically, oleic acid has been identified as particularly effective in slowing down the breakdown of millet starch, whereas millet starches containing elaidic acid are more susceptible to enzymatic hydrolysis compared to those with oleic acid. Preserving the beneficial low hypoglycemic property of millet involves safeguarding the fatty acids during processing and avoiding procedures that could convert unsaturated fatty acids into the trans form. This careful handling is essential for maintaining millet's valuable hypoglycemic characteristics. The effects of millet's in vitro starch digestibility and estimated glycemic index (eGI) are influenced by the type and quantity of fatty acids present in these grains. Over the storage period, there was a subtle interplay between reheating-induced gelatinization and the aging process induced by frozen storage, both competing factors influencing starch digestibility. Interestingly, when compared to their counterparts stored at -18°C, the frozen millet products stored at -40°C exhibited qualities similar to freshly prepared items. Notably, it was the freezing method that had the most significant impact on the digestive properties of products made from delicate foxtail millet (Ren et al., 2016).

Low Glycemic Millet Product Advancements

Another exploration showed the effects of traditional recipes created from the millet-based food mix we developed on individuals with pre-diabetes. The millet-based food mix we formulated contained a substantial amount of protein (19.41 g/100 g) and dietary fiber (21.11 g/100 g). Traditional dishes like roti, dosa, and dumplings (mudde), which were prepared using this mix, received high approval ratings and exhibited favorable sensory qualities similar to regional dishes. The glycemic index values for dosa, mudde, and roti were determined to be 37, 48, and 53, respectively, with corresponding glycemic loads of 11.05, 18.43, and 18.09. Importantly, all three of these developed products had a relatively low glycemic index (less than 55) and a moderate glycemic load (less than 20). Furthermore, when pre-diabetic individuals participated in a dietary intervention involving these products, significant reductions were observed in their fasting blood sugar levels (from 120.50 ± 18.73 to 97.81 ± 20.00) and HbA1c levels (from 6.14 ± 0.30 to 5.67 ± 0.40), indicating that these products are suitable for managing diabetes mellitus (Geetha et al., 2020).

Female participants who ingested the product (Dambu) created from maize experienced a greater blood glucose response of 5.20.8, whereas those who consumed the product made from millet experienced the lowest blood glucose response of 5.140.53. Male participants who consumed the product (Dambu) made from maize had the lowest blood glucose reaction, which was 4.51%, whereas those who consumed the product (Dambu) created from millet saw a greater blood glucose response of 4,940.9. With percentages of 41.51% and 40.33%, respectively, the male and female participants that drank the product (Dambu) manufactured from maize had the lowest glycemic index values (Aliyu et al., 2020). The properties of starch primarily hinge on the composition and distribution of amylose and amylopectin chains. Among both waxy and non-waxy cultivars, a remarkably diverse range of starch structures and morphologies were observed. The amylose content varied considerably across different varieties, spanning from 0.75% to 28.3%, with the Hongmeizi variety notably reaching 32.3%, according to available records. There exists a positive correlation between amylose content and various factors such as cooking quality, thermal characteristics, and pasting properties. The size and shape of starch granules within these varieties also exhibited significant variability, ranging from 0.3 to 17 μm in size and from round to polygonal in shape. Non-waxy starch varieties of proso millet find extensive application in food processing due to their notable resistance to swelling during heat treatment (Bangar et al., 2021). Millet biscuits are crafted using a blend of 45% millet flour and 55% refined wheat flour. These biscuits received favorable reviews from a trained panel and were well-received by diabetic participants. As per findings from a shelf-life investigation, biscuits made from both millet flour varieties can be safely stored for up to 60 days at room temperature when placed in a single thermally sealed polyethylene bag. Compared to biscuits produced with refined wheat flour, those created with millet flour contain elevated levels of crude fiber, total ash, and overall dietary fiber. The glycemic index (GI) values varied among the biscuit types, with the lowest GI recorded at 50.8 for biscuits made from foxtail millet flour, while the highest GI reached 68 for those composed of barnyard millet flour and refined wheat flour (Lestari et al., 2017). According to sensory assessment, it was determined that noodles enriched with 30% finger millet had a notably lower glycemic index (GI) of 45.13, in contrast to the control noodles, which had a GI of 62.59. Noodles made from finger millet flour were recognized as not only rich in nutrients but also possessing properties that help lower blood sugar levels (Shukla & Srivastava, 2014). The little millet flakes displayed a median GI of 52.11, with values reported by healthy individuals spanning from 41.57 to 61.80. Additionally, the flakes had a small glycemic load (GL) of 9.24 (Patil et al., 2015). Cookie bars made from a combination of 15% foxtail millet, 15% arrowroot flour, and 30% kidney beans may be considered as falling into the category of low glycemic index foods, given their glycemic index of 37.6 (Lestari et al., 2017).

Conclusion

In conclusion, adopting a low glycemic approach to incorporating millets into our diets holds significant promise for promoting better health and managing conditions like diabetes. Millets, with their inherently lower glycemic index compared to many other grains, offer a valuable option for individuals seeking to control blood sugar levels. Studies have shown that millets, such as foxtail millet, finger millet, and others, can be effectively utilized in various food products to create low glycemic options. These millet-based foods not only provide sustained energy but also have a positive impact on glycemic control, making them suitable for those with diabetes or individuals aiming to prevent blood sugar spikes. Furthermore, the presence of specific compounds like dietary fiber, resistant starch, and certain fatty acids in millets contributes to their hypoglycemic properties. Careful processing and preservation of these compounds during food preparation are crucial to retaining the low glycemic benefits of millets. Incorporating millets into our diets can help diversify our food choices, improve nutrition, and support overall well-being. As awareness of the importance of low glycemic foods grows, millets offer a versatile and nutritious solution for health-conscious individuals and those looking to manage blood sugar levels effectively.

References

Akinola, S. A., Badejo, A. A., Osundahunsi, O. F., &Edema, M. O. (2017). Effect of preprocessing techniques on pearl millet flour and changes in technological properties. International Journal of Food Science & Technology, 52(4), 992-999.

Aliyu, M. L., Tijjani, S. A., Ameh, D. A., & Babagana, A. (2020). Glycemic Index of Traditional Meal (Dambu) from Pearl Millet and Maize. Science, 8(1), 29-32.

Anitha, S., Kane-Potaka, J., Tsusaka, T. W., Botha, R., Rajendran, A., Givens, D. I., Parasannanavar, D. J., Subramaniam, K., Prasad, K. D. V., Vetriventhan, M., & others. (2021). A systematic review and meta-analysis of the potential of millets for managing and reducing the risk of developing diabetes mellitus. Frontiers in Nutrition, 386.

Anju, T. J., & Sarita, S. (2010). Suitability of Foxtail Millet (Setariaitalica) and Barnyard Millet (Echinochloa frumentacea) for Development of Low Glycemic Index Biscuits. Malaysian Journal of Nutrition, 16(3), 361–368.

Annor, G. A., Marcone, M., Bertoft, E., & Seetharaman, K. (2013). In vitro starch digestibility and expected glycemic index of kodo millet (Paspalum scrobiculatum) as affected by starch--protein--lipid interactions. Cereal Chemistry, 90(3), 211–217.

Arya, S. S., & Shakya, N. K. (2021). High fiber, low glycaemic index (GI) prebiotic multigrain functional beverage from barnyard, foxtail and kodo millet. LWT, 135, 109991. https://doi.org/https://doi.org/10.1016/j.lwt.2020.109991

Bangar, S. P., Ashogbon, A. O., Dhull, S. B., Thirumdas, R., Kumar, M., Hasan, M., Chaudhary, V., &Pathem, S. (2021). Proso-millet starch: Properties, functionality, and applications. International Journal of Biological Macromolecules, 190, 960–968.

Barclay, A. W., Brand-Miller, J. C., & Wolever, T. M. S. (2005). Glycemic index, glycemic load, and glycemic response are not the same. Diabetes Care, 28(7), 1839–1840.

Di Cairano, M., Galgano, F., Tolve, R., Caruso, M. C., &Condelli, N. (2018). Focus on gluten free biscuits: Ingredients and issues. Trends in Food Science & Technology, 81, 203–212. https://doi.org/https://doi.org/10.1016/j.tifs.2018.09.006

Du, J., Pan, R., Obadi, M., Li, H., Shao, F., Sun, J., Wang, Y., Qi, Y., & Xu, B. (2022). In vitro starch digestibility of buckwheat cultivars in comparison to wheat: The key role of starch molecular structure. Food Chemistry, 368, 130806. https://doi.org/https://doi.org/10.1016/j.foodchem.2021.130806

Flint, A., Møller, B. K., Raben, A., Pedersen, D., Tetens, I., Holst, J. J., & Astrup, A. (2004). The use of glycaemic index tables to predict glycaemic index of composite breakfast meals. British Journal of Nutrition, 91(6), 979–989. https://doi.org/10.1079/BJN20041124

Geetha, K., Yankanchi, G. M., Hulamani, S., & Hiremath, N. (2020). Glycemic index of millet based food mix and its effect on pre diabetic subjects. Journal of Food Science and Technology, 57, 2732–2738.

Gopirajah, R., Keshav, R., Wadhwa, R., &Anandharamakrishnan, C. (2016). Glycemic response to fibre rich foods and their relationship with gastric emptying and motor functions: An MRI Study. In Food Funct. (Vol. 7). https://doi.org/10.1039/C6FO00659K

Goswami, D., Gupta, R. K., Mridula, D., Sharma, M., & Tyagi, S. K. (2015). Barnyard millet based muffins: Physical, textural and sensory properties. LWT-Food Science and Technology, 64(1), 374–380.

Hegde, P. S., Rajasekaran, N. S., & Chandra, T. S. (2005). Effects of the antioxidant properties of millet species on oxidative stress and glycemic status in alloxan-induced rats. Nutrition Research, 25(12), 1109–1120. https://doi.org/https://doi.org/10.1016/j.nutres.2005.09.020

Hernandez-Hernandez, O., Julio-Gonzalez, L. C., Doyagüez, E. G., & Gutiérrez, T. J. (2022). Structure-digestibility relationship from noodles based on organocatalytically esterified regular and waxy corn starch obtained by reactive extrusion using sodium propionate. Food Hydrocolloids, 131, 107825.

Jayasinghe, M. A., Ekanayake, S., & Nugegoda, D. B. (2013). Effect of different milling methods on glycaemic response of foods made with finger millet (Eucenea coracana) flour. Ceylon Medical Journal, 58(4).

Jenkins, D. J., Wolever, T. M., Taylor, R. H., Barker, H., Fielden, H., Baldwin, J. M., Bowling, A. C., Newman, H. C., Jenkins, A. L., & Goff, D. V. (1981). Glycemic index of foods: a physiological basis for carbohydrate exchange. The American Journal of Clinical Nutrition, 34(3), 362–366. https://doi.org/10.1093/ajcn/34.3.362

Jenkins, D. J., Wolever, T. M., Taylor, R. H., Griffiths, C., Krzeminska, K., Lawrie, J. A., Bennett, C. M., Goff, D. V, Sarson, D. L., & Bloom, S. R. (1982). Slow release dietary carbohydrate improves second meal tolerance. The American Journal of Clinical Nutrition, 35(6), 1339–1346. https://doi.org/10.1093/ajcn/35.6.1339

Jin, Z., Bai, F., Chen, Y., & Bai, B. (2019). Interactions between protein, lipid and starch in foxtail millet flour affect the in vitro digestion of starch. CyTA-Journal of Food, 17(1), 640–647.

Kaimal, A. M., Mujumdar, A. S., & Thorat, B. N. (2021). Resistant starch from millets: Recent developments and applications in food industries. Trends in Food Science & Technology, 111, 563–580. https://doi.org/https://doi.org/10.1016/j.tifs.2021.02.074

Lestari, L. A., Huriyati, E., &Marsono, Y. (2017). The development of low glycemic index cookie bars from foxtail millet (Setariaitalica), arrowroot (Maranta arundinacea) flour, and kidney beans (Phaseolus vulgaris). Journal of Food Science and Technology, 54(6), 1406–1413.

Li, M., Pernell, C., & Ferruzzi, M. G. (2018). Complexation with phenolic acids affect rheological properties and digestibility of potato starch and maize amylopectin. Food Hydrocolloids, 77, 843–852. https://doi.org/https://doi.org/10.1016/j.foodhyd.2017.11.028

Lim, J., Ferruzzi, M. G., & Hamaker, B. R. (2022). Structural requirements of flavonoids for the selective inhibition of α-amylase versus α-glucosidase. Food Chemistry, 370, 130981. https://doi.org/https://doi.org/10.1016/j.foodchem.2021.130981

Maibam, B. D., Chakraborty, S., Nickhil, C., & Deka, S. C. (2023). Effect of Euryale ferox seed shell extract addition on the in vitro starch digestibility and predicted glycemic index of wheat-based bread. International Journal of Biological Macromolecules, 226, 1066–1078. https://doi.org/https://doi.org/10.1016/j.ijbiomac.2022.11.223

Opperman, A. M., Venter, C. S., Oosthuizen, W., Thompson, R. L., & Vorster, H. H. (2004). Meta-analysis of the health effects of using the glycaemic index in meal-planning. British Journal of Nutrition, 92(3), 367–381. https://doi.org/10.1079/BJN20041203

Patil, K. B., Chimmad, B. V, &Itagi, S. (2015). Glycemic index and quality evaluation of little millet (Panicum miliare) flakes with enhanced shelf life. Journal of Food Science and Technology, 52(9), 6078–6082. https://doi.org/10.1007/s13197-014-1663-5

Priyadarshini, S. R., Elumalai, A., Moses, J. A., &Anandharamakrishnan, C. (2020). Predicting human glucose response curve using an engineered small intestine model in combination with mathematical modeling. Journal of Food Engineering, 293, 110395. https://doi.org/10.1016/j.jfoodeng.2020.110395

Priyadarshini, S. R., Moses, J. A., &Anandharamakrishnan, C. (2021a). Determining the glycaemic responses of foods: conventional and emerging approaches. Nutrition Research Reviews, 1–27.

Priyadarshini, S. R., Moses, J. A., &Anandharamakrishnan, C. (2021b). Prediction of in-vitro glycemic responses of biscuits in an engineered small intestine system. Food Research International, 110459. https://doi.org/https://doi.org/10.1016/j.foodres.2021.110459

Priyadarshini, S. R., Suriyamoorthy, P., Moses, J. A., &Anandharamakrishnan, C. (2020). Mass transfer approach to in-vitro glycemic index of different biscuit compositions. Journal of Food Process Engineering, e13559. https://doi.org/10.1111/jfpe.13559

Ratnaningsih, N., Suparmo, Harmayani, E., &Marsono, Y. (2020). Physicochemical properties, in vitro starch digestibility, and estimated glycemic index of resistant starch from cowpea (Vigna unguiculata) starch by autoclaving-cooling cycles. International Journal of Biological Macromolecules, 142, 191–200. https://doi.org/https://doi.org/10.1016/j.ijbiomac.2019.09.092

Ren, X., Chen, J., Wang, C., Molla, M. M., Diao, X., & Shen, Q. (2016). In vitro starch digestibility, degree of gelatinization and estimated glycemic index of foxtail millet-derived products: Effect of freezing and frozen storage. Journal of Cereal Science, 69, 166–173.

Rice, R., Keawsompong, S., & Ph, D. (2019). Effect of Processing Procedures on in Vitro Digestibility and Colonic Fermentation of Riceberry Rice. Journal of Microbiology, Biotechnology and Food Sciences, 8(3), 940–946. https://doi.org/10.15414/jmbfs.2018-19.8.3.940-946

Shaikh, F., Ali, T. M., Mustafa, G., & Hasnain, A. (2020). Structural, functional and digestibility characteristics of sorghum and corn starch extrudates (RS3) as affected by cold storage time. International Journal of Biological Macromolecules, 164, 3048–3054. https://doi.org/https://doi.org/10.1016/j.ijbiomac.2020.08.105

Sharma, B., & Gujral, H. S. (2019). Influence of nutritional and antinutritional components on dough rheology and in vitro protein & starch digestibility of minor millets. Food Chemistry, 299, 125115. https://doi.org/https://doi.org/10.1016/j.foodchem.2019.125115

Shukla, K., & Srivastava, S. (2014). Evaluation of finger millet incorporated noodles for nutritive value and glycemic index. Journal of Food Science and Technology, 51(3), 527–534.

Suma, F. P., & Urooj, A. (2017). Impact of household processing methods on the nutritional characteristics of pearl millet (Pennisetum typhoideum): A review. Journal of Food Processing and Technology, 4(1), 28–32.

Ugare, R., Chimmad, B., Naik, R., Bharati, P., &Itagi, S. (2014). Glycemic index and significance of barnyard millet (Echinochloafrumentacae) in type II diabetics. Journal of Food Science and Technology, 51, 392–395.

Vidhyalakshmi, R., Prabhasankar, P., & Meera, M. S. (2023). Ultrasonication assisted pearl millet starch-germ complexing: Evaluation of starch characteristics and its influence on glycaemic index of bread. Journal of Cereal Science, 112, 103686. https://doi.org/https://doi.org/10.1016/j.jcs.2023.103686

Walton, J., Bell, H., Re, R., & Nugent, A. P. (2023). Current perspectives on global sugar consumption: definitions, recommendations, population intakes, challenges and future direction. Nutrition Research Reviews, 36(1), 1–22. https://doi.org/DOI: 10.1017/S095442242100024X

Wang, M., Wu, Y., Liu, Y., & Ouyang, J. (2020). Effect of Ultrasonic and Microwave Dual-Treatment on the Physicochemical Properties of Chestnut Starch. Polymers, 12(8). https://doi.org/10.3390/polym12081718

Yang, Q., Zhang, P., Qu, Y., Gao, X., Liang, J., Yang, P., & Feng, B. (2018). Comparison of physicochemical properties and cooking edibility of waxy and non-waxy proso millet (Panicum miliaceum L.). Food Chemistry, 257, 271–278. https://doi.org/https://doi.org/10.1016/j.foodchem.2018.03.009

Yousaf, L., Hou, D., Liaqat, H., & Shen, Q. (2021). Millet: A review of its nutritional and functional changes during processing. Food Research International, 142, 110197. https://doi.org/https://doi.org/10.1016/j.foodres.2021.110197

Zailani, M. A., Kamilah, H., Husaini, A., Awang Seruji, A. Z. R., &Sarbini, S. R. (2023). Starch Modifications via Physical Treatments and the Potential in Improving Resistant Starch Content. Starch - Stärke, 75(1–2), 2200146. https://doi.org/https://doi.org/10.1002/star.202200146

Chapter 15

Consumer Perception, Misconception and Barrier Towards Millet Foods

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Abstract

Millet's foods are part of healthy diets and Indian tradition. Increasing awareness about healthy diet and lifestyle leads to shift food preferences and consumption pattern. Despite, the abundant nutrients availability and health benefits, consumption of millets food is not much appreciable due to various misconceptions and myths about millets. Particularly millets foods have no taste and cause digestive problem. Besides the millet food preferences is affected by various social, cultural, and economic factors. So, the consumer perception about millets foods has a significant role in the choice to buy and consumption. Consumer perception will influence whether consumers intend to purchase and eat the goods. Understanding the consumer perception on millets foods is critical. Hence, in this chapter consumer perception, misconception and barriers towards millets foods are discussed. Also, the methodology and statistical techniques used to determine the consumer perception are discussed as well.

Key words: Millet, consumer perception, Focus Group Discussion, Garret ranking and Determinants

Introduction

One of the healthiest foods in the world is millets foods. Millets are commonly referred to as Nutri-cereals. Years ago, these were common foods in many nations, they are raised as cereal grains for both human and animal nourishment. Millet is vitamin-rich and packed full of nutrients and contains essential macro and micronutrients, vitamins such as Vitamins B6, C, E, and K, niacin, riboflavin and minerals such as calcium, Folate, Folic acid, magnesium, manganese, Pantothenic acid, copper, selenium, potassium, phosphorus and essential amino acids, dietary fiber, carbs, phytochemicals, and proteins in 100 grams [Parameswaran & Sadasivam, 1994][Sarita & Singh, 2016]. Additionally carries many health-promoting bioactive components. Millets are nutritionally dense and include a number of useful components that are health-promoting when compared to traditional cereals [Sarita & Singh, 2016]. Foxtail millet-based goods exhibited higher quantities of protein, dietary fiber, resistant starch, and a lower glycemic index than wheat, rice, and barley-based products. Millet starch digested starch more slowly as well. Consuming millets has been demonstrated the improved health outcomes because they have a balanced nutritional composition. Millets have the ability to increase diversity while also ensuring security in terms of food and nutrition. The health improving properties of millets are getting increased attention worldwide. However, there has been a dramatic decline in both their usage and production. So, now millets are reviled as "minor grains." The major reasons for the declining of both usage and production of millets are due less preferences towards the millet's foods. In addition, there are no regulations for millet production, processing, or the publicly funded supply of nutritious cereals.

So, considerable attention is now being given to the millet's foods for its positive health and environmental effects. Food processers and markets are using more product diversification techniques to draw customers with a variety of product attributes. The processed Foxtail millets foods fall within the category of medium glycemic index foods and can be used as diabetics' therapeutic foods and to prevent osteoporosis. Foxtail millet food is eaten as nutritious snack due to its high fibre, resistant starch, and reduced glycemic index and it is said to be preventing non-communicable disorders including diabetes and obesity[Arora et al., 2023]. The value of millets foods is connected to wide range of features as well as circumstances. The goodness of the millet's foods must have a value that recognised by consumers. The millets foods were assessed to be comparable to the regular products and received respectable sensory scores The values of the millet's foods can be measured by analysing consumer behaviour in existing markets. Perception about the millets foods determines the consumer behaviour. Key problems in millet food production are a lack of knowledge about the consumer perception, misconception and barrier towards millets foods. Therefore, the perception of consumer behaviour is very essential to assess the values of millets foods in the market and consumers likeness towards millets foods.

Consumer perception

The perception is process of reaction of sense receptors (such as the eyes, ears, nose, mouth, and fingers) to such fundamental stimuli as light, color, odor, texture, and sound by which people choose, organize, and interpret sensations. A stimulus is something that causes a receptor to become active. The focus of the perception is what we add to unprocessed sensations to give them significance. Every person reads a stimulus in a way that is compatible with his or her particular biases, wants, and experiences. The perception process has three stages 1. exposure, 2. attention, 3. and interpretation. The perception acts as a strainer between the consumer's internal and external stimuli. Perception is influenced by the consumer preference, decision-making, and attitude of a consumer [Verbeke, 2003]. The process of perceiving the quality of food by consumers is explained by Issanchou [Issanchou, 1996]. The gathering and classification of both intrinsic and extrinsic product features serves is the initial step of the consumer perception. The Intrinsic features includes cues like appearance, color, shape, and presentation and extrinsic features includes price, brand name, quality seal, country of origin, retailer, manufacturing data, and nutritional information.

The beliefs about the qualities of the product are created using the perceived quality cues. Additionally, there is a distinction between experience and credibility qualities. The experience qualities including convenience, freshness, and sensory features that can be directly perceived at the time of consumption while the credibility qualities including healthiness and naturalness, need a high level of abstraction. Credibility qualities are not immediately perceptible to the customer. The overall quality assessment is presummit in the last stage based on views of the quality attributes of the products. Food attributes (sensory qualities, health benefits, and safety features), sociodemographic factors (Age, gender, family status (kids), and family size), cultural factors (Religion and tradition) and environmental factors (Economic variables (pricing) and marketing stimuli (quality, traceability, and nutrition labeling)) all play a role in perception of foods[Biloukha & Utermohlen, 2000; Issanchou, 1996; Roux et al., 2000].

The color, appearance, texture, taste, and flour of millet-based Rusk, Sattu, and Papads were found to be comparable to those of their control counterparts, but other commodities scored lower on these criteria. The Foxtail millet and cereal-based products' sensory characteristics (color, look, texture, taste, flavor, and overall acceptability) were the same ($p > 0.05$)[Arora et al., 2023].

The consumer's beliefs and attitudes influence the food choice[Biloukha & Utermohlen, 2000] [Roux et al., 2000].Consumers' beliefs connect attributes, benefits, and aims in their minds. The emotions or affective reactions to a product's qualities are known as attitudes. Consumers assess whether a food product meets their needs and expectations using a variety of product characteristics. Customers develop attitudes toward food products based on the various aspects they observe in a product [Mowen, 1988]. The determinants of consumer perception are the consumer's objectives and driving forces.

Consumer perception of millets foods refers to how people acquire opinions about the millets foods and it is a process of how consumers receive and process sensory stimuli through their five senses while eating and buying the millets foods. Consumer perception includes the sensory and marketing features of millets foods. It is used to find out how their consumers view the millets foods in terms of nutritional and sensory characteristics, packaging, pricing and circumstances. Consumer perception theory is used to create marketing and advertising campaigns in order to retain the current clientele and draw in new ones[Barratry & Rajapushpam, 2018]. Consumer perception depends on eating habits and an abundance of replacements, including breakfast cereals and fast food. The consumption of bread decreased by 13.8% between 1999 and 2003 due to altered eating habits (Pra tta la et al., 2001; Siega-Riz et al., 2000).

Three types of measures of consumer perception, 1. Customer satisfaction surveys (CSAT), 2. Net promoter score (NPS), 3. Customer Effort Score (CES). CSAT is method asking direct question to customers to find out what they perceived. Customers can score your product or service quantitatively by completing customer satisfaction questionnaires. NPS is a number that measures how likely it is for customers to tell others about particular brand or product. It focuses more on how your customers feel about other brand while purchases. CES is an additional indicator for measuring consumer perceptions. It describes the product's usability and how simple it would be for a consumer to find a solution.

Factors related to consumer perception are price, taste, texture, nutritional composition, packing and health claims, convenience of the food are the important factors of consumer perception of millets foods[Klopčič et al., 2020]. Besides this demographic, age and education of consumers influence the consumers perception[Bech-Larsen & Grunert, 2003][Lähteenmäki et al., 2010]. Products perceived as healthy and labelled with health claims are easily accepted. Processing methods also influences the consumers[Lampila et al., 2009]. Location, variety of menu, social relationships and lead time also determines the perception towards millets foods. Some of the rational for acceptance of millets foods is given in the table 1.

Table 1. Rationales for the acceptance of millets foods

Sl.no	Rationale
	Millets foods makes the consumers healthy
	Millets foods are low glycemic and reduces the risk of diabetes
	Millets foods contains more fibre and lowers the cholesterol
	Millets foods contains more fibre and good for Gut microbiome
	Millets foods are tasty
	Millets foods are available at all time
	Millets foods are cheaper than the other staple foods

Misconception towards millets foods

There are five misconceptions towards millet food. 1. Millets foods is consumed by people only with health issues and dietary limitations, 2. Millets have little flavour and bland taste, 3. Preparation of millets foods are challenging, 4. Millets has very acute recipes, 5. Millets foods causes digestive issues. This is a widespread misconception that frequently shapes how millets are seen. Many individuals mistakenly think that millets are only appropriate for people who adhere to particular dietary restrictions, such gluten-free or vegan diets, but this is untrue. Millets are excellent for people with dietary restrictions, but they can also help others who want to live better lives. The idea that millets are bland and tasteless is one of the most prevalent misconceptions about them. This misunderstanding might be originated from the idea that millets are only suitable for those with dietary limitations who are unable to eat appetizing items. One of the most widespread misconceptions about millets foods is that they are challenging to prepare. But In actuality, preparing millets is really easy and doesn't need for any specialized knowledge or methods. Millets can be cooked simply by giving them a thorough rinsing and soaking them in water for a few hours. Millets can be cooked the same way as rice or any other grain after being soaked. For quicker results, you can pressure cook them, steam them, or even boil them.

Barriers towards millets foods

The greatest obstacle to consumers accepting millets foods is their lack of familiarity with them and prior opined about millets foods has also connected limited knowledge to acceptance. Consumers gives priority to accept the food which are well-known to them than that of the foods have been introduced newly or recently [Bech-Larsen et al., 2001]. Food neophobia has been linked to familiarity with food products. Food phobia reduces one's inclination to consume any foods, but especially foreign ones[Tuorila et al., 2001]. Although the tendency for food neophobia differs among consumers, it is a basic defence mechanism to keep us safe from any allergic ingredients[Pliner & Hobden, 1992].

General conception is that the foods made from millet are too expensive, take too long to prepare, uninteresting, and not tasty. Lack of motivation for millets foods, meal options for millet at canteens and restaurants and in locations where people live and do business are limited. People at work and at home, friends discourage or are unsupportive to millet foods. There are no different types of millet food recipes or that people don't know how to make more millets foods[Mc Morrow et al., 2017]. Lack of awareness about millets foods is affects the preference of millets foods and access to nutritious foods is frequently limited[Blanck et al., 2009][Baskin et al., 2016][Freedman & Rubinstein, 2010].

Sometimes the systems that control hunger and satiety, the sensory experience that food delivers, and a person's innate preferences for sweet and salty foods are linked to physiologically based behavioural predispositions. These are the primary variables that affect food preferences; as a result, people frequently choose foods and beverages based on their personal tastes. The second level of sensory-affective components comprises familiarity with something, as well as feelings and sensations related to food. Similar to interpersonal variables, which involve family, friends, and other social networks, intrapersonal factors—a person's thoughts, attitudes, knowledge, abilities, and social norms—come after the preceding elements in determining the choice of food. The final level of influencing factors on food consumption is the environment. Environmental factors are the most difficult to change even though they are the furthest away from the individual. They include access to and availability of food as well as resources, the state of the economy, social, environmental, and cultural standards. Along with the previously described components, the psychological state of the individual is thought to be one of the most important influencers of the act of eating. Situations involving rejection or loneliness, worry, stress, and emotional pain may have an impact on a person's eating habits in more fragile individuals. Customers' main barriers to healthy eating were time constraints, inadequate cooking abilities, food costs, or a lack of healthy selections at restaurants [Bos et al., 2016][de Mestral et al., 2016].

Sampling and Data Collection

Sampling

The procedure of collecting data from a small group or subgroups is known as sampling. The information collected from the samples is analysed and used to inform a wider audience or target customers. There are two types of sampling techniques 1. Probability sampling and 2. non-probability sampling. The classification of probability and non-probability sampling techniques are given in the fig. 1.

Fig.1. Types of Sampling Techniques

Data Collection

Collection of data is the most important phase in consumer perception analysis. The method of data collection varies depend on type of research. Data collection is a systematic approach of collecting information in the form of numbers or phrases from the targeted samples or Population through interviews, questionnaire, group discussion and feedback forms. Collected data undergoes the data pre-processing and statistical analysis for further useful in the development of data-driven decisions for research. There are two types of data.1. Primary data, and 2. Secondary data. Primary data are data that are new, fresh, and are obtained for the first time while the secondary is the data that are collected already and subjected to statistical analysis.

Primary data are gathered by observation or direct contact with respondents in one way or another for descriptive research and surveys (including sample surveys or census surveys). Observational technique, interview technique, questionnaire technique, schedule technique other techniques include using mechanical devices, projective technique, depth interviews, consumer panels, pantry audits, laboratory audits, distributary audits, and content analysis are the primary data collection technique. Secondary data is collected from published and unpublished sources. Consumers' perceptions of front of package food labels (FOPL) in India from 14 Indian states were analysed using a physical questionnaire-based survey was conducted using a purposeful sampling technique, and quota sampling designs (for age) were utilized in each center and state [Bhattacharya et al., 2022]

Focus group discussions

Focus group discussions is one of the primary data collection techniques majorly used to assess the consumer perception before product development. It mainly focusses to investigate consumer impressions rather than fresh produce or novel processing and production techniques. Customers can communicate concerns they don't understand or queries they have using this way[Krueger, 2014; Morgan, 1998]. Focus group talks are appropriate for identifying potential obstacles in the acceptance of millets foods because they can effectively address potential concerns and questions of consumers. The possible questions arise from the focus group discussion are listed in the table 2.

Table 2. Possible questions from the Focus Group Discussion

Sources and supply recommendations
Are there any daily consumption recommendations of millets foods?
Is there maximum limit for the daily consumption?
What amount of daily intake of millets foods is required to reap the possible health benefits?
How do individual millets food recommendations differ? What is the purpose of millets in my diet?
Any veggies, fruits, or berries have more nutrients than millets foods?
What form should millets be consumed in?
Do we consume enough millets in our typical diet?
What effects do millets foods have?
What specific health advantages do millets foods offer?
What are the impacts of various millets food types?
What are the drawbacks or unfavorable features of millets foods?

What are the millets foods' long-term effects?
Are the health benefits of foods made with millets supported by science? Who conducted these studies and how were they done?
Are foods made of millets necessary for health?
What effects does this have on the product's sensory qualities (taste)?
Do millets foods in organic products have more millets?
Brand and reputation
It's crucial to consider the manufacturer's reputation.
What is the product's brand?
Feelings of loyalty to the brand
Price
Do millet products have any price discounts?

Best-worst scaling

The best-worst scaling (BWS) is a method of collecting information about the declared preferences that are chosen by the consumers to choose the best and worst alternatives from a set of millets foods based on various attributes. The Random Utility Theory of Decision-Making serves as the foundation for the BW method [McFadden, 1974]. In BWS method asks participants to rank the importance of each product attribute out of all possible options and, ask them to rank the most (best) and least (worst) essential attributes[Pérez y Pérez & Gracia, 2023]. Using the best-worst scaling approach, the preferences of Spanish customers for olive oil were assessed. It was found that consumers value the product's price, geographic origin, protected designation of origin mark, and olive variety (Liu et al., 2018; Merlino et al., 2018). The BWS method enables to transform the qualitative data into a quantitative data by score the qualitative statement, to avoid the constraints, mistakes, and to classify (ranking) or to declare a point (rating) using Likert scale (Lee et al., 2008;Lee et al., 2007;Liu et al., 2018).

Choice experiment

The customer preferences for porridge based on several qualities were evaluated using the choice experiment approach[Wanyama et al., 2019]. Choice experiments are frequently used in consumer perception and environmental investigations. According to choice tests, consumer preferences are a mixture of a product's attribute levels (Veettil et al., 2011; Meemken et al., 2017). To investigate consumer preferences for non-market commodities, a choice experiment technique is used to construct a false market. The choice experiment, which has the ability to analyze various attributes and their levels, is used to analyze the key characteristics of non-market goods or services from a variety of attributes (Huang et al., 2021reducing food waste is a global concern and campaigns to reduce food waste have been launched. For example, the term & ldquo; food sharing & rdquo; has originated from Germany and promotes sharing food instead of wasting. & ldquo; The Guerilla Kitchen & rdquo;, which originated from Netherlands, is an organization that also promotes avoiding wasting food. Consequently, more and more people are paying attention on this issue and we think it is necessary to understand people’s acceptance of suboptimal food, as discarded suboptimal food represents a significant proportion of food waste. Additionally, at least one-third of the food globally produced each year is classified as suboptimal and cannot be sold in the market because of a poor appearance, damaged packaging, or near expiration date, thus presenting challenges for environmental, social, and economic sustainability. Previous studies on suboptimal food have focused more on appearances and packaging dates and less on investigating traceable agricultural and price discounts, which is where food classified as suboptimal entails a discount. Moreover, citrus product attributes such as appearance, size, freshness indicators, traceable agricultural products, and price discounts were determined in terms of consumer preference through pre-measurement here, then using a choice experiment method to clarify which attributes consumers care about most (N = 485 respondents).

Willingness to Pay

The price that customers are willing to pay for a product that they believe to be most acceptable is known as the Willingness to Pay (WTP). Consumer buying behaviours must be evaluated in terms of their intention to purchase the millets foods or willingness to pay rather than just their attitude and preference toward the goods. It is was found that a WTP for a product declines when the shelf life of the product is poor (Tsiros & Heilman, 2005). In recent years, WTP of consumers for quality of food is grown quickly. This WTP is based on the consents of knowledge about the nutritional and sensory value of food, followed by environmental factors such as organic, low carbon foot print, less preservatives, freshness (Lima et al., 2021). Consumers in Nairobi and Kampala were likely to pay an extra for composite flour made from millet and either maize or beans due to the increased nutrition, whereas in Kampala, are unfavorable for composite flour made from beans or amaranth grain

(Wanyama et al., 2019). Indian consumers are willing to pay more WTP for fruits and vegetables farmed sustainably (Nandi et al., 2017). Price reductions will entice consumers to make purchases, according to prior research on consumer WTP for subpar food [Verghese et al., 2013]. WTP is calculated by multiplying by dividing the attribute's coefficient by the price coefficient (eqn.1)(Hole & Kolstad, 2012).

$$WTP_j = \frac{\partial P}{\partial A_j} = \frac{\text{Attribute's coefficient}}{\text{Price coefficient}} \quad ...(1)$$

Perceptual mapping

Perceptual mapping often referred to as positioning mapping to visually assess how your target customers perceives the millets foods. A perceptual map is a straight forward graph with a vertical and horizontal axis. These axes stand in for the dimensions need to be examined and axes are labelled with each of the standards of target consumer to decide whether or not to purchase the product.

Statistical analysis

Descriptive Analysis

Descriptive analysis is used to sum up the data either from sample of a population or from a complete population. The two primary types of descriptive statistics are measurements of central tendency (mean, median, and mode) and measures of variability (standard deviation, variance, minimum and maximum variables, kurtosis, and skewness). The likelihood ratio test and the chi-square test of homogeneity are used to examine the relationship between millet food consumption and other sociodemographic factors (Bhattacharya et al., 2022).

Regression analysis

Regression analysis builds an equation (eqn.2) to describe how an independent variable impacts the value of a dependent variable (linear regression or multiple regression) with changing data information. It uses consumer perception data. By understanding the link between each variable, regression analysis aids in outcome prediction and future decision-making.

$$U_{ij} = \alpha A_j + \beta X_i + \varepsilon_{ij} \quad ...(2)$$

This model suggests that the utility (U) of the consumer (i) connected to the chosen porridge flour (j) can be split into a deterministic and a stochastic component. The deterministic component is divided into a vector of consumer i's socioeconomic factors (X) and porridge flour properties (A) that may affect the consumer choice. ε is an error term with independently and identically distributed error that accounts for unobserved variables affecting customer decision-making. The and are parameters need to be estimated.

Probit and logit models

In the case of binary outcome analysis, the probit (eqn.3) and logit models (eqn.4) are among the family of generalized linear models that are most frequently utilized. The logit model is assessing the data using logistic function (sigmoid function). logistic function can model the binary and dichotomous dependent variables, and categorical data and creates the link between the predictors and the likelihood that an event will occur, spans from 0 to 1 on a continuous scale. The logit model can be used to find the probability of the occurrence of the events. The model's objective is to calculate the likelihood that an observation with a given set of features would fall into a certain category; furthermore, categorizing observations according to their expected probabilities is a sort of binary classification model. The probit analysis was chosen because it is better consistent with the normality assumption of the equation's error components. Probit regression models are quite similar to logit models (Franses & Paap, 2001). Since a probit model's predicted coefficients may only be read as positive or negative, marginal effects were computed to yield probabilities that can be quantitatively interpreted (Hagle & Mitchell, 1992). The random utility framework can be used to model the consumer's selection of a specific porridge flour is given in the equation (Wanyama et al., 2019).

$$Pr(Y = 1|X) = \Phi(Z) = a_0 + a_1X_1 + a_2X_2 + \cdots + a_nX_n \quad ...(3)$$

$$logit(I) = log\left[\frac{P}{(1-P)}\right] = Z = a_0 + a_1X_1 + a_2X_2 + \cdots + a_nX_n \quad ...(4)$$

Testing of regression analysis

The ANOVA technique separates systematic components from random factors to explain for the apparent aggregate variability within a data set. In a regression analysis, the effect of independent variables on the dependent variable is examined using the ANOVA test. Similar to this, the likelihood-ratio test assesses the degree to which two statistical models, one of which was created by maximizing across the entire parameter space and the other by imposing a constraint, fit the data. If the observed data are consistent with the constraint, the two likelihoods should not differ by more than the sampling error. (i.e., the null hypothesis).

Factor analysis

The factor analysis (FA) is a dimension reduction method of data analysis. By correlating all the original variables without losing any information, this technique describes variations among all factors. Finding independent latent variables, which simplify all variables' information, is the aim of FA. An example would be a consumer review of a product based on the color, form, wearability, current trends, materials, comfort, place of purchase, and frequency of usage. To group all of these characteristics into homogeneous groups in this case, factor analysis is used. For instance, a new latent variable of design is formed by grouping color, materials, quality, and trends.

Garret Ranking

The preference, order change of constraints, and advantages were studied using Garrett's Ranking Technique and converted into numerical scores. The main benefit of this method over a straightforward frequency distribution is that the limitations are ranked according to respondents' perceptions of their seriousness. As a result, it's possible that the same number of respondents on two or more limitations gave different rankings. The pigeon pea-based products are organized using Garret ranking methodologies (Majili et al., 2022). Utilizing Henry Garrett rating methodologies, the issue with household food consumption was assessed and found that approximately 72% of households spend more than 50% of their income on food. 60.4 percent of households have cut back on their food consumption from previous levels. Reduced consumption of food products such pulses, eggs, meat and fish, cereals, fruits, and vegetables are found in 58.4% of BPL households. Just 48.67% of APL households have cut back on their intake of pulses, eggs, meat and fish, cereals, fruits, and vegetables (Nadu, 2015). Garrett's formula used for converting ranks into per cent (eqn.5).

$$\text{Per cent position} = 100 \times \left(\frac{R_{ij} - 0.5}{N_j}\right) \quad \ldots(5)$$

Where,

R_{ij}=rank given for i^{th} constraint by j^{th} individual

N_j=number of constraints ranked by j^{th} individual

Other methods

Hierarchical Bayes (HB) and choice-based conjoint analysis (CBC) were used to estimate the utilities (Klopčič et al., 2020). By giving subject-level, part-worth ratings, the HB estimation is aided in the investigation of how utilities put on certain attribute levels may be modified by other consumer-specific factors, in our case, by gender or age (Wellman & Vidican, 2008). A descriptive analysis is conducted, and the Shapiro-Wilk Test is used to determine whether the major variables are normal. Using the chi-square and Kruskal-Wallis tests test, associations between nominal variables, and associations between ordinals and nominal variables are examined, respectively. Spearman correlation is carried out between ordinal variables or between ordinal and cardinal (Jones, 2007). The cohort technique of data analysis investigates and contrasts a particular sample of user behaviour so that it may be compared to other user groups with comparable characteristics. This methodology can be used to gain a deep grasp of a broader target market or a wealth of knowledge about what customers want. Because it may show you how your efforts are affecting certain client demographics, cohort analysis may be very useful for marketing research.

Conclusion

Food selection is a complex process that involves preferences for sensory qualities as well as the effect of non-sensory elements, such as expectations and attitudes about food, health claims, price, ethical considerations, and mood. Political ideology, cultural, religious, and ethnic values, product packaging clarity and environmental responsibility, and dietary recommendations from doctors all influence food choices. To encourage healthy eating and combat chronic disorders like obesity, healthier environments should be encouraged. Reduced access to healthy foods and more opportunity for employees to make healthier food choices are the goals of strategies to encourage better eating habits. Implementation entails the provision of healthier options, greater accessibility, and the creation of laws requiring the provision of healthy options or limiting the availability of less healthy options at work. Studies of consumer perception, misconception and barriers toward millets foods encourage millet food consumption in various situations and demonstrate how, once impediments are seen differently by different target groups, different strategies are required to remove them.

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References

Arora, L., Aggarwal, R., Dhaliwal, I., Gupta, O. P., & Kaushik, P. (2023). Assessment of sensory and nutritional attributes of foxtail millet-based food products. Frontiers in Nutrition (Vol. 10). https://www.frontiersin.org/articles/10.3389/fnut.2023.1146545

Barrairy, D., &Rajapushpam, R. (2018). A study on perception of millet products among houshold consumers in Salem District. IOSR Journal of Business and Management, 20(8), 67-76.

Baskin, E., Gorlin, M., Chance, Z., Novemsky, N., Dhar, R., Huskey, K., & Hatzis, M. (2016). Proximity of snacks to beverages increases food consumption in the workplace: A field study. Appetite, 103, 244-248.

Bech-Larsen, T., & Grunert, K. G. (2003). The perceived healthiness of functional foods: A conjoint study of Danish, Finnish and American consumers' perception of functional foods. Appetite, 40(1), 9-14.

Bech-Larsen, T., Grunert, K. G., & Poulsen, J. (2001). The acceptance of functional foods in Denmark, Finland and the United States: A study of consumers' conjoint evaluations of the qualities of functional foods and perceptions of general health factors and cultural values (No. 73). University of Aarhus, Aarhus School of Business, The MAPP Centre.

Bhattacharya, S., Bera, O. P., & Shah, V. (2022). Consumers' Perception About Front of Package Food Labels (FOPL) in India: A Survey of 14 States . In Frontiers in Public Health (Vol. 10). https://www.frontiersin.org/articles/10.3389/fpubh.2022.936802

Biloukha, O. O., &Utermohlen, V. (2000). Correlates of food consumption and perceptions of foods in an educated urban population in Ukraine. Food Quality and Preference, 11(6), 475–485.

Blanck, H. M., Yaroch, A. L., Atienza, A. A., Yi, S. L., Zhang, J., &Mâsse, L. C. (2009). Factors influencing lunchtime food choices among working Americans. Health Education &Behavior, 36(2), 289–301.

Bos, C., van der Lans, I. A., van Rijnsoever, F. J., & van Trijp, H. C. M. (2016). Heterogeneity in barriers regarding the motivation, the opportunity and the ability to choose low-calorie snack foods and beverages: Associations with real-life choices. Public Health Nutrition, 19(9), 1584–1597.

de Mestral, C., Stringhini, S., & Marques-Vidal, P. (2016). Barriers to healthy eating in Switzerland: A nationwide study. Clinical nutrition, 35(6), 1490-1498.

Franses, P. H., & Paap, R. (2001). Quantitative models in marketing research. Cambridge University Press.

Freedman, M. R., & Rubinstein, R. J. (2010). Obesity and food choices among faculty and staff at a large urban university. Journal of American College Health, 59(3), 205–210.

Hagle, T. M., & Mitchell, G. E. (1992). Goodness-of-fit measures for probit and logit. American Journal of Political Science, 762–784.

Hole, A. R., & Kolstad, J. R. (2012). Mixed logit estimation of willingness to pay distributions: a comparison of models in preference and WTP space using data from a health-related choice experiment. Empirical Economics, 42, 445–469.

Huang, W.-S., Kuo, H.-Y., Tung, S.-Y., & Chen, H.-S. (2021). Assessing Consumer Preferences for Suboptimal Food: Application of a Choice Experiment in Citrus Fruit Retail. In Foods (Vol. 10, Issue 1). https://doi.org/10.3390/foods10010015

Issanchou, S. (1996). Consumer expectations and perceptions of meat and meat product quality. Meat Science, 43, 5–19.

Jones, A. (2007). Applied econometrics for health economists: a practical guide. CRC Press.

Klopčič, M., Slokan, P., & Erjavec, K. (2020). Consumer preference for nutrition and health claims: A multi-methodological approach. Food Quality and Preference, 82, 103863.

Krueger, R. A. (2014). Focus groups: A practical guide for applied research. Sage publications.

Lähteenmäki, L., Lampila, P., Grunert, K., Boztug, Y., Ueland, Ø., Åström, A., &Martinsdóttir, E. (2010). Impact of health-related claims on the perception of other product attributes. Food Policy, 35(3), 230–239.

Lampila, P., van Lieshout, M., Gremmen, B., & Lähteenmäki, L. (2009). Consumer attitudes towards enhanced flavonoid content in fruit. Food Research International, 42(1), 122–129.

Lee, J. A., Soutar, G., & Louviere, J. (2008). The best–worst scaling approach: An alternative to Schwartz's values survey. Journal of Personality Assessment, 90(4), 335–347.

Lee, J. A., Soutar, G. N., & Louviere, J. (2007). Measuring values using best-worst scaling: The LOV example. Psychology & Marketing, 24(12), 1043–1058.

Lima, J. P. M., Costa, S. A., Brandão, T. R. S., & Rocha, A. (2021). Food Consumption Determinants and Barriers for Healthy Eating at the Workplace—A University Setting. In Foods (Vol. 10, Issue 4). https://doi.org/10.3390/foods10040695

Liu, C., Li, J., Steele, W., & Fang, X. (2018). A study on Chinese consumer preferences for food traceability information using best-worst scaling. PloS One, 13(11), e0206793.

Majili, Z., Nyaruhucha, C. N., Kulwa, K., Mutabazi, K., Rybak, C., & Sieber, S. (2022). Identification and prioritization of pigeon pea-based products tailored to consumer preference perspective: A mixed method assessment approach. Legume Science, 4(3).

Mc Morrow, L., Ludbrook, A., Macdiarmid, J. I., & Olajide, D. (2017). Perceived barriers towards healthy eating and their association with fruit and vegetable consumption. Journal of Public Health (Oxford, England), 39(2), 330–338. https://doi.org/10.1093/pubmed/fdw038

McFadden, D. (1974). Frontiers in Econometrics, chapter Conditional logit analysis of qualitative choice behavior. Academic Press New York, NY, USA.

Meemken, E.-M., Veettil, P. C., & Qaim, M. (2017). Toward improving the design of sustainability standards—a gendered analysis of farmers' preferences. World Development, 99, 285–298.

Merlino, V. M., Borra, D., Girgenti, V., Dal Vecchio, A., & Massaglia, S. (2018). Beef meat preferences of consumers from Northwest Italy: Analysis of choice attributes. Meat Science, 143, 119–128.

Morgan, D. L. (1998). Practical strategies for combining qualitative and quantitative methods: Applications to health research. Qualitative Health Research, 8(3), 362–376.

Mowen, J. C. (1988). Beyond consumer decision making. Journal of Consumer Marketing, 5(1), 15–25.

Nadu, T. (2015). impact of food inflation on BPL and APL household consumption-a study in Kannur District, Kerala. Indian Journal of Economics and Development, 3, 11.

Nandi, R., Bokelmann, W., Gowdru, N. V., & Dias, G. (2017). Factors influencing consumers' willingness to pay for organic fruits and vegetables: Empirical evidence from a consumer survey in India. Journal of Food Products Marketing, 23(4), 430–451.

Parameswaran, K. P., & Sadasivam, S. (1994). Changes in the carbohydrates and nitrogenous components during germination of proso millet, Panicum miliaceum. Plant Foods for Human Nutrition, 45, 97–102.

Pérez y Pérez, L., & Gracia, A. (2023). Consumer Preferences for Olive Oil in Spain: A Best-Worst Scaling Approach. In Sustainability (Vol. 15, Issue 14). https://doi.org/10.3390/su151411283

Pliner, P., & Hobden, K. (1992). Development of a scale to measure the trait of food neophobia in humans. Appetite, 19(2), 105–120.

Roux, C., Le Couedic, P., Durand-Gasselin, S., &Luquet, F.-M. (2000). Consumption patterns and food attitudes of a sample of 657 low-income people in France. Food Policy, 25(1), 91–103.

Sarita, E. S., & Singh, E. (2016). Potential of millets: nutrients composition and health benefits. Journal of Scientific and Innovative Research, 5(2), 46–50.

Tsiros, M., & Heilman, C. M. (2005). The effect of expiration dates and perceived risk on purchasing behavior in grocery store perishable categories. Journal of Marketing, 69(2), 114–129.

Tuorila, H., Lähteenmäki, L., Pohjalainen, L., & Lotti, L. (2001). Food neophobia among the Finns and related responses to familiar and unfamiliar foods. Food Quality and Preference, 12(1), 29–37.

Veettil, P. C., Speelman, S., Frija, A., Buysse, J., & Van Huylenbroeck, G. (2011). Complementarity between water pricing, water rights and local water governance: A Bayesian analysis of choice behaviour of farmers in the Krishna river basin, India. Ecological Economics, 70(10), 1756–1766.

Verbeke, W. (2003). Consumer perception of food safety: role and influencing factors. New Approaches to Food-Safety Econ, 6–21.

Verghese, K., Lewis, H., Lockrey, S., & Williams, H. (2013). The role of packaging in minimising food waste in the supply chain of the future: Prepared for: CHEP Australia. RMIT University Report.

Wanyama, R., Gödecke, T., Jager, M., & Qaim, M. (2019). Poor consumers' preferences for nutritionally enhanced foods. British Food Journal, 121(3), 755–770.

Wellman, G. S., & Vidican, C. (2008). Pilot study of a hierarchical Bayes method for utility estimation in a choice-based conjoint analysis of prescription benefit plans including medication therapy management services. Research in Social and Administrative Pharmacy, 4(3), 218–230.

Chapter 16

Market Challenges and Strategies for Promoting Millet Consumption

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Abstract

Millet a miracle food being utilized for its numerous health potential, therapeutic, and bioavailability of macro and micronutrients. Besides its advantages,it meant for feeding world population of 2050 with sustainability in the agricultural sector. Though, few challenges were prevailing while commercializing millet were namely crop yield/ productivity, poor consumer acceptance, inclined pricing, weed and pest management. The improvement of land area for production of millet, promotion, branding, ready to eat food products, traditional and ethic food products, improved processing aids could possibly be the marketing aids to promote millet consumption. To overcome these disadvantages, steps were taken by government and non-governmental organizations and to improve the marketing strategies were also discussed.

Keywords : Millet, constraints, consumer acceptance, consumer preference, marketing strategies

Introduction

Growing population, food insecurity, malnutrition, global climate change, communicable and non-communicable diseases (NCDs) were major concern in 21st century. To overcome or address few of such issue people turned to have a mind for healthy food and food-based remedies. There turns up millet or nutria cereals, a group of ancient, climate-resilient grain have huge remedy potential for dietary problems and NCDs (Srivastava et al., 2023).The potential and significance of millets heads up & hits 2023 as international year of millet, concern to raise awareness of its benefits from nutrition, environmental sustainability and economic development. Millets works on various solutions such as affordability, sustainability in crop production (given in table 1), resilient value chains and consumer access to varied diets. The majorly benefited country and have great market potential were Africa, Russia, China and Asia. India is one among the largest producer and consumer of millet in the world, producing pearl millet, sorghum, finger miller, small millet and proso millet. They contain rich source of protein, phosphorous, fiber, niacin, manganese, magnesium, potassium, iron, methionine, essential amino acids and vitamin E. The therapeuticeffect of millet was remarkable namely controls/prevent heart disease, migraine, asthma, atherosclerosis, blood pressure, diabetics, obesity, various types of cancer, premature death and asthma. Millets not only provide micro and micronutrients but also gave huge phenolic components with antioxidant, metal chelating and metal reducing powers namely phenolic acids (dehydrodiferulates, dehydrotriferulates, flavonols, flavones, flavan-2-ol monomers) and its derivatives (Birania et al., 2020).This chapter deals with the production scenario, consumer preference & consumer acceptance of millet, potential market, marketing strategy and challenges prevailing in millet.

Table 1 Millet and its cultivation traits

Millet name	Cultivation traits
Banyard millet	Instant/ fast growing and possess huge fodder volume
Finger millet	Adaptability, great source of calcium
Foxtail millet	Short duration, grows even at low fertile soil and tolerate drought
Kodo millet	Long duration, cultivated in shallow and deep soil, contains enormous amount of folic acid
Pearl millet	Rich in folic acid, cultivated in arid and semi-arid areas.
Proso millet	Tolerates heat & drought, short duration crop
Sorghum	Tolerate moisture, stress and remarkable temperature resistant crop

Millet production scenario and trade

Millets were produced by 93 countries and only 7 countries produce higher than 1M ha acreage. Millet productivity were increased by 36% in the past seven decades.Among which pearl millet from sub-saharan Africa and finger millet from sub-humid uplands of east Africa were accountable for world millet production and trade. Most millets of around 97% were cultivated by developing nations by poor and marginal farmers were used for domestic uses. However, its import and export increased slowly from 1960s to 2017s by 25.4% and 25.9% respectively. Global import and export increased during 2011-2017 of about 374.5 and 376.4 thousand tons. According to APEDA, India is the largest producer of millet worldwide. Pearl millet (40.51%) and sorghum (8.09%) contributes to world production, whereas the major producing states of India were Rajasthan, Karnataka, Maharashtra, Uttar Pradesh. Haryana, Gujarat, Madhya Pradesh, Tamil Nadu, Andhra Pradesh and Uttarakhand. Next to India, USA contributes about 11%, Nigeria 9%, China 7%, Ethiopia 7%, Niger 6%, Mexico 5%, Mali 4%, Sudan 4%, Brazil 3% and other countries about 25 % respectively(APEDA, 2021). Though India being largest producer, America contributes to the largest exporter of millet, whereas pearl millet export dominated in pearl millet export, US dominates the proso millet export market and China dominates the foxtail millet export(Chakraborty & Chakraborty, 2021). The production scenario worldwide for millet were displayed in figure 1 data adopted from (APEDA, 2021).

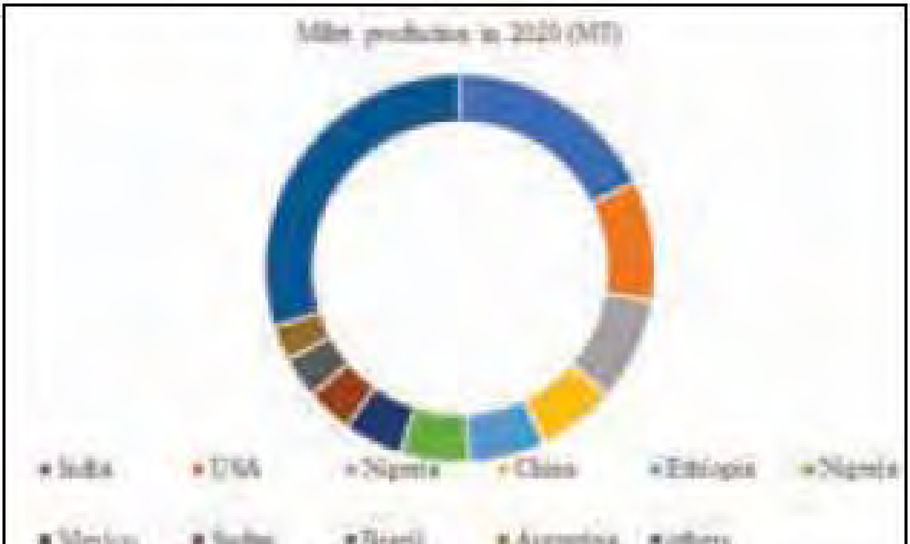

Fig. 1 World-wide production scenario of millet

Consumer preference, marketing strategies and behavior

The preferences on food intake varies from one consumer to the other, based on various factors namely taste, branding, promotions, purchasing power, cost and health concern.Health awareness, environmental sustainability and culture shifts were the main reason for millet conception in recent years (Alekhya & Shravanthi, 2019). Consumer behavior were greatly influenced by education, awareness campaigns promoting millets benefits, workshop, cooking demonstrations and marketing efforts highlighting the advantages of millets contributes to consumer adoption. The availability of millet-based products in various platforms like supermarkets, health food stores and online platforms influences consumer behavior in greater extent. Increased accessibility to millet-based products like flour, snacks, ready to eat products, millet beverages etc. attracts consumer to incorporate millets into their daily diet. The understanding of consumer behavior towards millet and its value-added products now become important in framing marketing strategies, developing new products and promoting the benefits of millet to a wider-spectra. These consumer preferences were described with few case studies in various countries as described below.

A study on consumption pattern and nutritional assessment of minor millet among rural women in TN was performed by (Senthamarai Selvi & Malathi, 2019). Around 120 participants were investigated and found that the majorly consumed millet were finger millet (30%), sorghum (28%), kodo millet (17%), barnyard millet (16.7%) and pearl millet (8.3%) respectively. Among the consumer around 80% prefer millet as flour, 5% as germinated/sprouted crop and 10 % as malted millet. Majority of the responded 77.5% prefer millet incorporated in Indian sweets. The frequency of millet consumption was monthly once where finger millet, kodo millet and barnyard was consumed twice a month. The data collected was also correlated with RDA of various nutrient and the respondents were benefited by consumption of millets.

Millet consumption in India was analyzed by (Kumar Yadav, 2023) in which the consumption of millet increased over the period of time. The majority of millet produced in India were subjected to human consumption over past decades, followed by feed and distilleries. Only meagre amount of production was utilized by start up FMCG and were increased over the period of time and expected to hit higher in 2030. Finally, the export of millets was very low and steps were taken by government to overcome these issues, the major reason was its production and human consumption makes the product unavailable for export.

Kane-Potaka et al., (2021)malnutrition, diabetes, and some other major issues. To understand public knowledge and practices of consuming millets in urban areas, a survey was conducted with 15,522 individuals from seven major cities of India using a structured questionnaire, and after data cleaning 15,139 observations were subjected to analysis using descriptive and inferential statistics. It was found that the largest group among early adopters of millets were people with health problems (28% made an survey on millet consumption pattern in India with around 15,522 individuals from seven cities in seven states of south, west, north and east India. The participants were provided with an information flyer and a link to an app about millet at the end of the survey. The results suggest that people with health issues (28%)adopt millet, followed by people with weight loss aspects (15%) and only 14% select millet for taste. The study found significant gap between people those where health conscious and the people who were sure about millet being healthy. The major reason for non-consumption of millet at home (40%) was observed and 22% reported to dislike the taste of it. The recommendation was to provide knowledge on nutritional and health benefits on millets, enhance the accessibility of millet un urban market and develop high sensory perspective product to satisfy the consumer acceptance.

According to a survey face to face with 15,500 people by International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) the reason for consumption of millet was the health and wellness in urban India of about 58% (Food, n.d.). A study conducted by (Alekhya & Shravanthi, 2019) with 100 consumers towards millet based food products in Telangana, India. The results revealed that the income of the consumer doesn't have any influence over the millet-based products, whereas the social media influence and health benefits were found to be their choice of preference. However, there was slight variation in purchasing decision of the millets based on their variation in price of various millets. It was also found that demand for brown top millet was high owing to its health benefits despite of high price, though the supply was limited. The consumer acceptance of the millet-based products was found to be low owing to its flavor and steps must be taken for flavor enhanced products in order to make the millet-based product more consumer acceptable.

Cultivation, processing and Marketing Challenge

Though the production were remarkable in developing countries, their average production was dominatingly below the world average demand. In various countries, the marketing of millet grains was found to be less or meagerly established owing to its poor economic returns to the farmers. The seed supply chain of millet was found to be dependent on informal seed chain in most of the developing countries. Though the cultivation of millet by India and China betterments the socioeconomic status of farmers with well-developed marketing system, better accessibility to inputs including improved varieties, it was found to be insufficient for end use.Millet cultivation constrains and measures has been tabulated in Table 2.

Other major missing was its non-availability of improved seed quality, less production land, improper or less availability of large-scale production of millet grains, heterogeneity in land aces or local cultivars. With respect to minor millets the adaptability was found to be meagre in modern agroecosystems and mechanization. The smaller grain size of small millets makes it difficult for mechanical planting, harvest and yield makes it less fit for commercialization. Dehulling of minor millets by traditional manual method was found to be labor intensive and time consuming(Chakraborty & Chakraborty, 2021) which in turns higher the cost of production and marketing. Mechanical dehullers were found to damage the grain, less efficient owing to its small grain size makes it unfit and follows traditional method. This drudgery in manual processing is major trait for reduced consumption and commercialization of small millets at large scale.

The unexpected climatic conditions, biotic constraints and soil nature includes rainfall patter, distribution, soil type, soil fertility, socioeconomic farming status, diseases, insects, pest, birds, parasitic plants and weeds influences the millet production. The weed infestation was the major threat for global millet production and reduced millet yield, which has to be addressed in the international millet year 2023. Though the major market potential of millet with respect to cultivation was its lack of improved cultivars, agricultural inputs and policy support. Well planned and long-term public sector investment for multidisciplinary research activities by developing and developed countries, national and international multi-disciplinary public sector initiatives were required to promote health benefits of millet, improved crop management pattern, enhance consumption and value-added products of millet. More startup, FMCG, MSME for millet and its products has to be strengthened with better marketing aids and promotions to strengthen the millet belt production, processing and marketing.

Table 2. Millet cultivation constrains and measures.

Constraints	Measures
Production/ cultivation area	• Steps has to be taken to increase land area for cultivation. • Intercropping could also be implemented
Weed	• Weed management
Storage	• Pest control • Rodent control • Prevent lipid oxidation

Packaging	• Attractive • Effective against lipid oxidation • Pest/ infestation resistant
Antinutritional factors	• Research on elimination of antinutritional factors • Low-cost elimination method could be done
Seed quality	• Government initiatives • Genome improvement
Cultivation	• Pest control • Organic farming • Yield improvement
Value addition	• Sensory improvement • Promotion • Branding
FMCG/MSME/ Start ups	• Quality end product • Consumer acceptable product • Traditional/ethnic food alternatives
Lack of infra-structure	• Government Initiatives
Limited aware-ness	• Promotion • Government Initiatives
Low income for farmers	• Improve seed quality • Government policies and subsidies
Price variation throughout the year	• Balanced supply and demand
Lack of famil-iarity	• Promotion • Branding

Government Initiatives – A marketing strategy

The marketing strategies of millet could be in one of creating awareness about millet in terms of novel food, nutritional security crops across regions, countries, communities, farmer groups and networks. Enhance the production and productivity of millet, improve research and development to improve the value chain of millet and millet-based products. Adopting improved crop variety for yield factor, improved processing, product development aids. In this modern era, busy world ready to eat or ready to cook products will support the group of people for instant food, helps working women in better ways with healthy alternatives (Opole, 2019). Apart from these steps and measures government of various countries setup various programs to promote millet consumption are as follows.

1. International year of millet–2023 declared by Food and Agriculture organization and United nations to improve awareness about health and nutritional benefits of millets.

2. Millet mission –launched in 2018 by India to improve the area, millet cultivation, productivity and promote value addition and marketing of millets. This mission pawed a way for creating millet-based enterprises, setting up of processing units and marketing infrastructure.

3. National Food Security Mission (NFSM): launched in 2007 to increase the production of food grains including millets by adopting best practices and new interventions. This mission also supports for inputs in seeds, fertilizers, pesticides and integrated farming pattern.

4. MIDH – the Mission for Integrated Development of Horticulture (MIDH) promotes the cultivation of millets to improve horticulture production and productivity also follows similar agenda of NFSM(Madhu D.M, Gangadhar.K, 2023).

Conclusion

Despite the health potential of millet, the awareness on millet and its production, promotion was less. The fear of farmers in loss of their income makes the millet less available. The other factor for less productivity was its less land for cultivation. The government policies and marketing strategies by International millet year and Millet mission was potential efforts to feed population 2050. Though the startups have to be strengthened and export has to be made to improve the economic aspect of developing countries. The developing countries were majorly targeted owing to their high-end production of millets. Research and development activity on improved processing aids could be efficient in near future. The government enforcement and polies on each millet has to be enhanced and steps to reduce antinutritional factor in millet could be the driving research.

References

Alekhya, P., & Shravanthi, A. R. (2019). Buying Behaviour of Consumers towards Millet Based Food Products in Hyderabad District of Telangana, India. International Journal of Current Microbiology and Applied Sciences, 8(10), 223–236. https://doi.org/10.20546/ijcmas.2019.810.023

APEDA. 2021. https://apeda.gov.in/milletportal/Production.html

Birania, S., Rohilla, P., Kumar, R., & Kumar, N. (2020). Post harvest processing of millets: A review on value added products. International Journal of Chemical Studies, 8(1), 1824-1829.

Chakraborty, S. K., & Chakraborty, S. (2021). Rural Entrepreneurship Development in Millet Processing. Millets and Millet Technology, 345-361.

Food, S. (n.d.). Consumer survey about millets. 1–8.

Kane-Potaka, J., Anitha, S., Tsusaka, T. W., Botha, R., Budumuru, M., Upadhyay, S., ... & Nedumaran, S. (2021). Assessing millets and sorghum consumption behavior in urban India: A large-scale survey. Frontiers in sustainable food systems, 5, 680777.

Kumar Yadav, K. (2023). Millets Production and Consumption in India. 3(January), 275–283.

Madhu D.M, Gangadhar.K, V. H. (2023). In: Exploring The Untapped Potential of Millets In India's. 04(05), 2021–2024.

Opole, R. (2019). Opportunities for enhancing production, utilization and marketing of finger millet in Africa. African Journal of Food, Agriculture, Nutrition and Development, 19(1), 13863-13882.

Senthamarai, L., & Malathi, D. (2019). Consumption Pattern and Nutritional Assessment of Minor Millets among Rural Women in Madurai District of Tamil Nadu, India. International Journal of Current Microbiology and Applied Sciences, 8(11).

Srivastava, P., Mondal, K., Banga, U., Vishwavidyalaya, K., & Bharti, S. D. (2023). Unleashing the Potential of Millets Promoting Nutritious Grains as Vital Cereal Staples during the International Year of Millets : A Review. January. https://doi.org/10.9734/IJPSS/2023/v35i183469

Chapter 17

Rice Processing and Fortification

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Introduction

Micronutrient malnutrition (MNM) is a serious issue that affects the lives of billions of people worldwide. MNM is a deficiency of micronutrients (vitamins and minerals) in the daily diet, and is a source of various health issues and diseases. One of the most prevalent micronutrient deficiencies is iron deficiency, which leads to anemia, a health disorder that lowers hemoglobin levels and reduces the quantity of oxygen in the blood (Vishwakarma et al., 2023). The World Health Organization estimates that 36.5% of pregnant women and 60.2% of children under the age of five are anemic globally (WHO, 2021). In India, the situation is particularly concerning, with a staggering 68.9% of children and 57.2% of women suffering from anemia in the year 2020 (NFHS reports, 2020). These alarming statistics underscore the urgent need for targeted interventions and improved nutritional access to address this widespread health issue. Food fortification can address this issue by adding the required nutrients to the commonly consumed foods for a wider reach and tackle this problem effectively in minimum time. Salt, wheat, corn, rice, and edible oils are staple foods that are commonly chosen for fortification. This fortification can be either synthetic by incorporating chemicals or natural, that is, food-to-food fortification (FtFF), by using different combinations of ingredients and their formulations.

Rice is a staple food for half of the world's population (Timmer, 2010). It is a rich source of macro-and micronutrients as a whole grain, but the removal of the bran layer during the polishing process causes loss of minerals and vitamins. White rice is the main product of the rice milling industry, while broken rice, bran, and husk are by-products. Broken rice fetches a much lower price than white rice does. Therefore, it can be used as a raw ingredient for the development of various nutritionally rich products. Broken rice has the potential for reuse and enhancement by fortification with replenished nutrients, including iron, zinc, vitamin A, and B complex vitamins. Technologies such as dusting, coating, and extrusion have been suggested for incorporating micronutrients into rice, with extrusion being recognized as a promising technology. Nevertheless, the rice fortification process presents several challenges in terms of extrusion and various unit operations that require attention and resolution.

Rice Processing

The rice structure includes the hull, pericarp, bran layer, aleurone layer, embryo, and endosperm. The endosperm is the major edible portion of the rice. The rice milling process involves several steps to remove the outer husk, bran layer, and germ from the rice grains. Depending on the type and extent of processing, the obtained rice can be classified as brown rice, parboiled brown rice, parboiled rice, and white-milled rice (Figure 2.1). Brown rice is obtained when only the husk is removed, while white-milled rice is obtained by removing the bran layer and germ, leaving behind polished and refined grain. As brown rice retains bran, it takes a longer time to cook, and because of the higher content of fatty acids, it undergoes rancidity. Thus, the bran layer is removed to produce visually appealing white rice, resulting in the loss of micronutrients present in the bran. Parboiled rice, on the other hand, undergoes a steaming process before hulling, which helps retain some of the nutrients from the bran layer within the grain. All rice types have unique characteristics and are used in various culinary dishes.

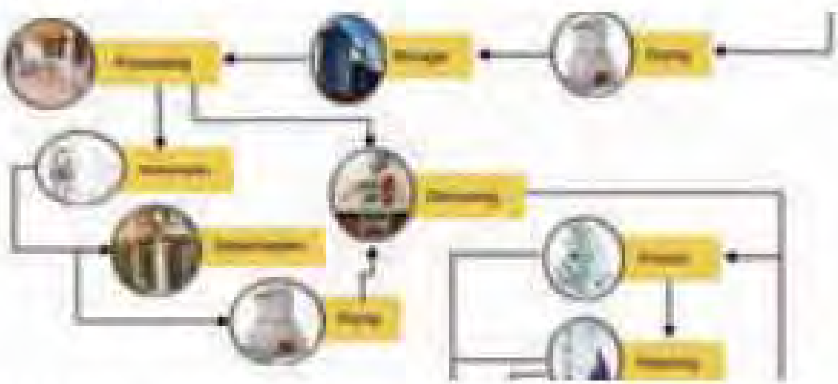

Fig. 2.1 Schematic diagram of postharvest processing of rice (Reproduced from Müller et al., 2022)

Brown rice & white milled rice

The different unit operations involved in the processing of rice are pre-cleaning, drying, de-husking, paddy separation, milling, whitening, rice grading, weighing, and bagging. The two basic unit operations that differentiate brown rice and white milled rice are de-hulling and milling, whereas all other processes remain almost the same for both rice types.

Pre-cleaning

Pre-cleaning is necessary to remove undesired extraneous foreign matter from the paddy. This is of great importance for the proper operation of rice milling machinery. The open double-sieve cleaner uses a series of oscillating sieves and suction fans to remove impurities. The single-scalper drum cleaner consisted of horizontal rotating drums with an aspirator and vibrating sieves to remove sand, stones, straws, and other impurities.

De-husking

De-husking or de-hulling is the process of removing husks without causing any damage to the bran and kernels. The paddy passes between two abrasive surfaces that move at different speeds. It is done manually by stone or by modern machinery, such as rubber rolls, discs, and centrifugal shellers. Brown rice is produced at this stage by removing the husk from the paddy, followed by milling to produce white rice.

Paddy separation

During this process, the paddy that was not de-husked was separated from brown rice. The paddy separator comprised multiple identical slanted trays with dimples across their surfaces. These dimpled trays moved back and forth. As a mixture of husked rice and paddy was introduced at the upper edge of the tray, the denser husked rice settled in the lower layer and made contact with the dimpled tray, whereas the lighter paddy remained afloat on top of the husked rice.

Milling

In the milling step, two huller machines pass through brown rice, removing the outer bran layers of the grain. The bran layers were removed as the grains were brushed against the interior wall of the huller and rotating core. The grain was then cooled and polished with a brush, followed by a second hulling. The broken kernels are sorted from the smooth white rice over a wire mesh screen in a brewer's reel. Even Brown rice undergoes a degree of milling, about 2-4%

by weight, which leads to scratching of the inner bran layer, to enable the adequate hydration of the rice to undergo cooking (Bhar et al., 2022). It can also be termed "under-milled rice" or "brown rice".

Whitening

Whitening is the process of removing germ, pericarp, tegmen, and aleurone layers. This is also known as pearling or polishing. Typically, two types of polishers are used for the whitening process: abrasives and friction. The degree of whiteness is determined by factors such as the radial velocity of the stone wheels, size of the stones in the grid, clearance between the stone surface and adjacent screen, and external pressure applied to the outlet chamber of the whitening machines. The bran layer removed during this process is transported pneumatically to a separate room for additional processing or storage.

Mist polishing

The polishing steps involved rubbing milled white rice with other rice surfaces, while air mist acted as a lubricant. This process is performed to improve the luster of rice and its visual appeal for consumers.

Grading and sorting

Broken rice and discolored rice grains were removed during the grading and sorting processes. The grains were passed through a series of rotating cylinders with indented screens to remove the small and broken grains. Photo sensors and a charged coupled device were used to differentiate the discolored grains by the voltage difference, which was promptly removed by an air jet.

After the grading and sorting process, the enrichment process is encouraged to restore the nutrients lost during the milling process back to rice. At this stage, rice is either coated or dusted with the required micronutrients or blended with fortified rice kernels. Enriched rice was packed, stored, and distributed.

Parboiled rice

Some paddy varieties break more during milling, reducing head yield owing to poor inherent milling quality or uneven processing. Parboiling, a pre-milling treatment involving soaking, heating, and drying, has been proven to enhance grain structure through partial gelatinization, increasing head rice yield (Muchlisyiyah et al., 2023). During soaking, the paddy absorbs water via molecular and capillary absorption. Subsequent steaming partially cooks the rice, inactivates enzymes, turns the endosperm translucent and pasty via gelatinization, and seals grain cracks (Eyarkai Nambi et al., 2017). Parboiling enhances the micronutrient movement from bran to grain, thereby improving the nutritional value of rice. parboiled paddy was dried to 14-16% moisture for milling and storage. Traditional open-yard drying takes up to five days, while modern mills use rapid and hygienic hot-air drying. Figure 2.2 illustrates the various parboiling techniques. The parboiling process can also be used for rice fortification by adding deficient micronutrients to soaking water and steaming. Previous studies have shown that the parboiling process improves the zinc, iron, and folic acid content of rice by parboiling process (Wahengbam et al., 2019).

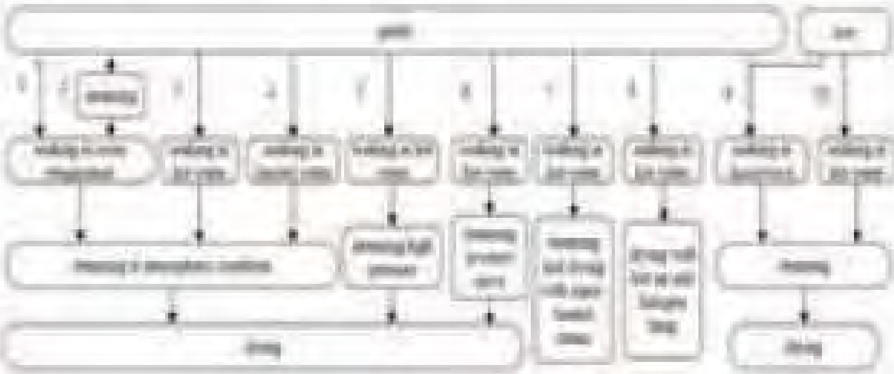

Fig. 2.2 Rice Parboiling Techniques [Reproduced from Muchlisyiyah et al., 2023]

Rice by-products

Rice industry waste, including rice straw, husks, bran, germ, and broken rice, is abundant. The amount produced varies based on rice type and milling rate. Typically, rice milling produces approximately 50-52% (dried paddy basis) of milled rice, out of which 66-72% is quality milled rice, 26-32% is broken rice, and 1.23-1.78% is groats. The Milling also yields 18-20% rice husk, 5-15% rice bran, and 2% rice germ (Rachmat et al., 2022).

Rice husk

Rice husk consists of 15% carbon, 18% ash, and 67% volatile matter. The ash content could be reclaimed through combustion. During burning, various temperatures yield different forms of silica in the ash, namely, amorphous silica and crystalline silica. These distinct forms have diverse properties and can be used in various applications. Another major utilization of rice husks is the conversion of rice husks to fuel. Thus, husks undergo thermal processes such as combustion, pyrolysis, or gasification to be used as biomass fuel. Rice husk fibers mainly include lignin, hemicellulose, cellulose, and hydrated silica, which allow them to be used as additives in poultry and animal feed. Although it is not commonly used for human consumption, it is frequently included in pet foods. This addition serves as a dietary fiber source for pets and helps them feel satiated (Bodie et al., 2019). Phenolic compounds extracted from rice husks using methanol have demonstrated strong antioxidant properties, effectively combating singlet oxygen scavengers and preventing DNA damage in human lymphocytes induced by high hydrogen peroxide levels (Rachmat et al., 2022).

Rice bran

Rice bran is a nutritionally rich by-product of the rice milling industry. It contains 15–22% lipids, 34–52% carbohydrates, 7–11% fiber, 6–10% ash, 8–12% moisture, and 10–16% protein. Rice bran is abundant in vitamins from both E and B complexes, and it stands out as the exclusive natural source of γ-oryzanol. Many key nutraceutical compounds derived from rice bran are rich in phytochemicals, which exhibit potent antioxidant properties. Studies have suggested that rice bran has anti-cancer properties and can prevent many chronic diseases (Ling-Tan and Norhaizan, 2017; Gul et al., 2015). Owing to its nutritional and nutraceutical properties, rice bran is used in the food, nutraceutical, and pharmaceutical industries.

Rice bran is commercially used for the production of rice bran oil (RBO). Hydraulic pressing, X-M milling, and solvent extraction are the commonly used methods for RBO extraction. RBO is hypoallergenic and beneficial to human health; thus, it is commonly used as a cooking oil in countries such as Japan, China, and India. Rice bran is also used as an additive in pastries and baked products to produce low-fat, high-fiber products. Defatted rice bran was used as a filler in poultry feed. Bran is used as a high-energy feed for broiler chickens and other livestock to increase their weight gain.

Broken rice

During the grading step of rice milling, the broken rice is separated based on its size. Rice that falls below the required size is categorized as 'broken,' typically measuring less than three-fourths of the entire kernel length. Broken rice is commonly used in the pet food industry and breweries. Brewer rice consists of broken rice with rice bran and rice germ and is popularly used in the pet food industry because of its high fiber content. Brewer's rice is frequently used as an ingredient in beer brewing. It contributes to the flavor, aroma, color, and texture of beer. In addition, brewer's rice supplies essential raw components that serve as substrates for yeast to ferment and produce alcohol.

In countries such as Vietnam, broken rice is used in dishes. It can also be ground into flour and used in the production of gluten-free products. The economic value of broken rice is low compared to that of head rice, which makes it a great by-product for utilization in rice fortification. This provides a sustainable and economical edge for food fortification programs. Broken rice can be cleaned, ground, mixed with micronutrients, and extruded to produce fortified rice kernels (FRK). This FRK is further mixed with normal rice to significantly reduce the cost of fortified rice, thus making it accessible to populations belonging to all income sectors.

Rice Fortification

Rice fortification technologies

Rice fortification involves the addition of limiting vitamins and minerals to rice. This is performed commercially in three ways: (a) dusting, (b) coating, and (c) extrusion. In dusting, deficient micronutrients are mixed with rice in the form of powder, which sticks to the surface of rice using electrostatic force. Because the electrostatic force is weak, this can cause nutrient leaching during washing or cooking. Coating refers to the addition of a nutrient-rich, water-resistant layer on the surface of rice grains. Materials such as waxes, gums, starches, and polymers have been used for coating. However, this method can also lead to the loss of vitamins and minerals during cooking, and it changes the taste, color, and appearance of the rice. Compared to these methods, rice fortification by extrusion is preferred, as it keeps the nutrients intact during washing and cooking.

Extrusion is a versatile process involving mixing, kneading, shearing, cooking, shaping, and forming (Gujral and Singh, 2002; Xu et al., 2016). It is a multifaceted technique in which moistened starch and protein materials undergo various process conditions to create unique products (Liu et al., 2011). During extrusion, starch gelatinization, protein denaturation, lipids, starch, and proteins form complexes that lead to changes in the microstructure, chemical properties, and overall shape of the product (Hagenimana et al., 2006). This method is the most effective way of adding vitamins and minerals to rice. It involves a two-step process: first, creating a dough from rice flour, water, and the required micronutrients, and then passing the dough through an extruder to produce fortified rice kernels (FRK), which are dried to a moisture content of 14% or less, ensuring better storage stability. These FRKs were then mixed with regular milled rice to produce micronutrient-fortified rice. FRKs produced through extrusion are more resistant to nutrient loss during cleaning, washing, and cooking compared through methods such as dusting or coating. Furthermore, the use of brokens for FRK development provides an opportunity for the value addition of rice mill by-products.

Steps in rice fortification

The manufacturing process for FRK was developed using a twin-screw extruder (TSE) as shown in Fig. 3.1. First, the broken rice was ground into a fine flour using a pulverizer. Specific amounts of water and vitamin-mineral premix (VMP) were then mixed uniformly, and the mixture was conditioned in a blender to ensure even moisture distribution. The conditioned mixture was then fed into a twin-screw extruder, where it was shaped into rice kernels using a suitable die, resulting in the creation of FRK. Afterward, it was dried to achieve the desired storage moisture content, polished to give it a shiny surface, and blended with regular rice in specific proportions to prepare micronutrient-fortified rice (MFR).

Fig. 3.1 Process flow chart of the fortified rice kernels and micronutrient-fortified rice

Pulverizing

Fine rice powder was obtained by grinding the broken rice in a micropulverizer (hammer mill). The micropulverizer was composed of food-grade stainless steel (SS304). It involves a high-speed rotor that rotates in the cylindrical casing while the feeding of the grain is carried out at the top, and crushing is achieved by the rotating hammers (Figure 3.2). The fine powder obtained was passed through a sieve of the desired pore size and collected at the bottom of the micro-pulverizer. The fineness of the powder was regulated by the screen.

Fig. 3.2 Hammer mill

Mixing and conditioning

The quantity of rice flour and VMP was calculated according to the formulation, and a uniform micronutrient flour mix or blend was formed by mixing them in a paddle blender-cum-conditioner. Reverse osmosis and ultraviolet-treated pure water were added to the flour mix to achieve the desired moisture content before extrusion. The paddle-blender-cum-conditioner was made of food-grade stainless steel, and U- or W-shaped mixing chambers were used for mixing (Figure 3.3). The blend was discharged by tilting the mixing chambers upside-down.

Figure 3.3 Paddle blender-cum-conditioner

Extrusion

The extruder is used to make FRK, as it combines several operations such as mixing, shearing, heating, kneading, and more into one machine. Extruders may be classified into two types based on their make: a single-screw extruder and a twin-screw extruder (TSE). The latter is preferred for FRK production because it provides better conveying properties (Fig 3.4). Similarly, warm extrusion is preferred to hot or cold extrusion because it provides better physicochemical and cooking properties to FRK. Inside the extruder, the moistened starch in the mixture undergoes gelatinization and turns into a molten viscous mass because of heat. The molten mass is pushed out of the machine through a die designed to match the dimensions of the desired rice variety to produce FRK. To ensure the quality of FRK, the extrusion process conditions, such as temperature, feed rate, screw speed, and cutter speed, and product parameters, such as moisture content particle, size of the flour, and the ratio of ingredients, need to be optimized.

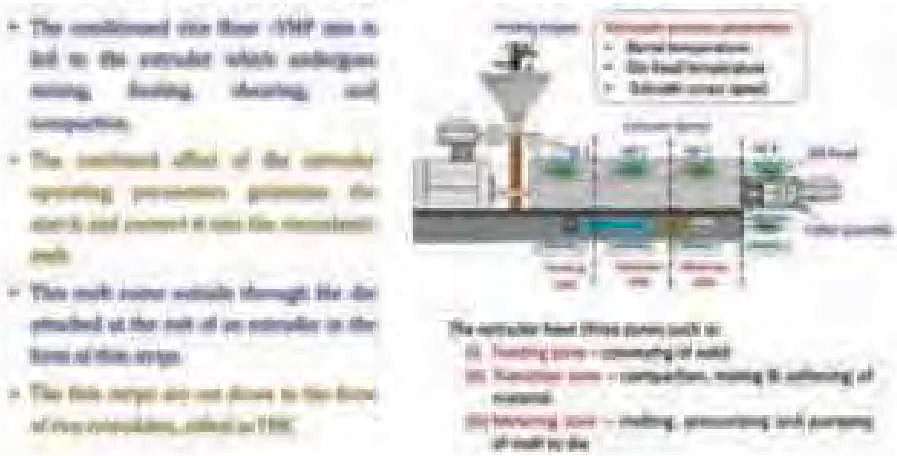

Fig. 3.4 Twin screw extruder used for FRK development

Drying

Drying removes moisture from FRK, thus making it safe to store for a longer period of time. It also significantly affects the color and cooking properties of FRK. After the extrusion process, the FRK is required to dry it to the right moisture level, which is approximately 11-12%. Different types of dryers like tray dryers, fluidized bed dryers, conveyor belt dryers, tumble dryers, or rotating cylinder dryers can be used to do this. Tray dryers or fluidized bed dryers are the preferred drying methods to reduce moisture in FRK compared to other methods.

Polishing

During polishing, FRK was rubbed between the abrasive surfaces of the emery stone rollers. This removes any protrusions from the FRK and makes it appear smooth and shiny, thus making it more similar to natural rice kernels. After polishing, the FRK was packed and distributed for blending to manufacture the MFR.

Blending of FRK and normal rice

Blending involves mixing the FRK with natural rice in a ratio between 0.5% and 2%, depending on the concentration of the micronutrients added to the FRK. It can be either a batch or a continuous process. Constant verification of the blending ratio is required to ensure uniform blending at the correct ratio. The bending equipment is selected based on factors such as the blending capacity and type of pre-blending system. The most popular batch blender is the Forsberg blender. It is a paddle-type mixer that mixes the two rice types in a closed chamber. The blending system consists of a horizontal mixing drum with a paddle arrangement, vibratory dozer, bucket elevator, and conveyor. When the demand is high, a continuous blending system is used, which matches its capacity with that of the pre-blending system.

Fig. 3.5 FRK and normal rice blending unit

Packaging and storage

FRK can be packed in an automatic fill-and-sealing (FFS) packaging machine to the desired packet sizes. In the case of manual packaging, the fortified rice is stored in a storage tank and packed in suitable packaging bags in a hygienic environment and by following personnel safety protocols.

Continuous production of FRK, FRN and LGR

As discussed in the earlier section, various unit operations are required in the extrusion process for fortification. These unit operations must be customized and optimized for a particular raw ingredient, and the final product is required. With the optimization of these unit operations, especially extruders, a variety of fortified (synthetic and natural) food products such as FRK, fortified rice noodles (FRN), and low GI rice (LGR) have been developed in the Food Chemistry and Technology Laboratory (FCTL), Agricultural and Food Engineering Department, IIT Kharagpur (Figure 4.1).

A pilot plant for the manufacture of FRK and MFR was indigenously designed and fabricated, and was used to conduct trials on FRK quality characteristics and produce FRK for clinical studies.

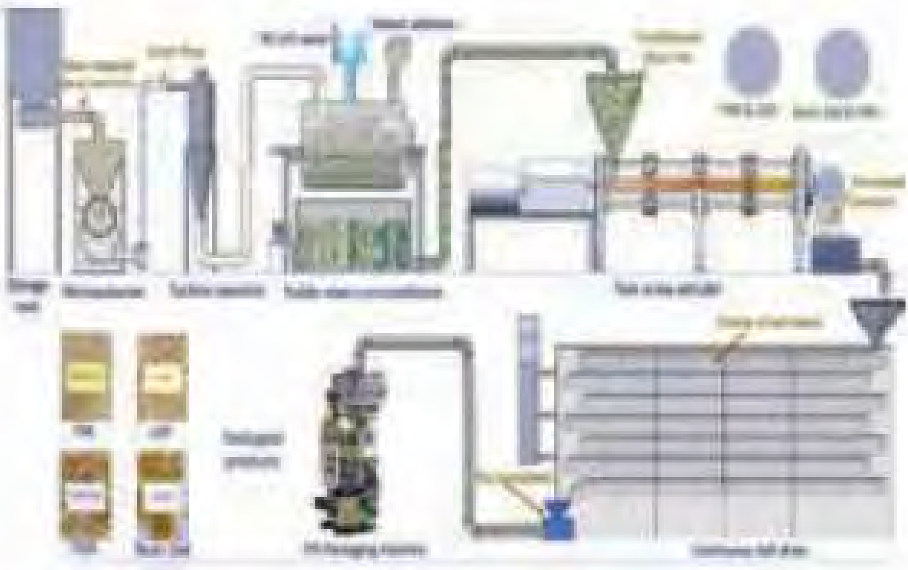

Fig. 4.1 Continuous production of fortified rice, rice noodles and millet based low glycaemic rice

FRK was prepared with broken rice and vitamin-mineral premix (VMP) using extrusion technology. The concentrations of iron, folic acid, and vitamin B_{12} in FRK were maintained according to the FSSAI guidelines, as shown in Table 4.1 (2018).

Table 4.1 The fortification level of the micronutrients in rice per 100 g

Micronutrient	FRK	MFR
Iron (mg/ 100g)	425	4.25
Folic acid (µg/100 g)	1250	12.5
Vitamin B_{12} (µg/100 g)	12.5	0.125

VMP was mixed with rice flour using multistage mixing to achieve uniform mixing, and a paddle blender was used for the homogenous distribution of VMP and moisture content. After mixing and conditioning, the extrusion was carried out at an optimized range of die head temperature of 88-90 °C, screw speed of 30-32 rpm, feed speed of 7-8 rpm, and moisture content of 30-32 % wet basis (wb) (Nithya et al., 2022). The extrudate obtained was further dried at 40 °C with a forced hot-air tray dryer until the moisture reached is 12% wb. Dried FRK showed physical and cooking characteristics similar to those of raw rice. The retention of micronutrients in cooked rice is more than 90% for iron and 70% for vitamin B_{12} and folic acid. The sensory evaluation showed no significant difference in quality attributes such as appearance, color, aroma, texture, taste, and overall acceptability between unfortified rice and MFR (FRK + Natural rice:1+99). In addition to the standardization of FRK to match the characteristics of natural rice (Swarna), studies have been conducted to manufacture FRK using different rice varieties, including waxy rice, parboiled rice, and a mixture of rice varieties.

Fig. 4.1 Virtual appearance of (a) Fortified Rice Kernels (FRK), (b) Low GI Rice (LGR), and (c) Fortified Rice Noodles (FRN)

Diabetes, a lifestyle disease, results from elevated blood sugar levels, negatively impacting individuals' health, and potentially leading to fatal outcomes if not managed. To reduce the occurrence of diabetes and its related illnesses, one can adopt a diet with low glycemic index (GI) or utilize a product with a low GI value. One such product has been produced in our laboratory using the manufacturing setup for the FRK, where rice was mixed with a combination of millets namely foxtail millet, barnyard millet, and quinoa to develop low GI rice (Yadav et al., 2021). The composition of multigrain flour (100 g) consisted of broken rice (43 g), foxtail millet (28.18 g), quinoa (18.47 g), and barnyard millet (10.35 g) to obtain GI ≤ 55. Using a method similar to FRK, millet-based rice was manufactured by optimizing the extrusion process parameters and using a suitable die. However, the low-GI rice produced has different physical and textural properties from the raw rice and FRK, as seen in Figure 4.1 (b). Moreover, the crystallinity of LGR was lower than that of raw rice. This product would help reduce blood sugar levels in diabetic individuals and provide an opportunity for the industry to commercialize such a novel product.

Generally, noodles prepared from plain maida are deficient in nutrients and affect the health of growing children and teenagers, who are the targeted consumers of noodles in India. Noodles made from maida cannot be consumed by patients with celiac disease because of the presence of gluten. Adding micronutrients to rice flour and producing noodles could overcome these issues. One such product utilizing FtFF has been developed in our laboratory (Vishwakarma et al., 2023). Marjoram was added as a natural fortificant to rice noodles, and fortified rice noodles (FRN) were developed using the existing technology for FRK by simply changing the die of the extruder.

The iron, calcium, protein, and fiber levels significantly increased as a result of marjoram addition. The overall phenolic, antioxidant, and flavonoid content increased after fortification. However, a reduction in crystallinity was observed in the noodles. The Sensory evaluation of the noodles revealed that the samples enriched with 2-4% MLP were more acceptable than the other samples. This application of marjoram or herb opened a new door to fortification by implying a natural fortificant to replace synthetic ones.

Conclusions

Fortification is a successful and widely accepted method for enhancing the nutritional value of food products. Fortification of staple foods is needed today because of the deficiency of various micronutrients in the body. Rice consumption is deeply ingrained in the culture of many countries, including India, where it is the main staple food. Being a staple food for nearly half of the world's population, it presents a unique opportunity as a vehicle to deliver these essential micronutrients through fortification. Numerous rice products can be manufactured using these novel technologies. Extrusion has shown promising results in the global development of fortified foods. The fortified foods developed from rice in our laboratory include FRK, low-GI rice, and FRN, which can help enhance the nutritional status of the Indian population without changing their eating habits.

Reference

Bhar, S., Bose, T., Dutta, A., Mande, S.S. (2022). A perspective on the benefits of consumptionof parboiled rice over brown rice for glycaemic control. European Journal of Nutrition. 1-10.

Bodie, AR., Micciche, AC., Atungulu, GG., Rothrock Jr, MJ., Ricke, SC. (2019). Current trends of rice milling byproducts for agricultural applications and alternative food production systems. Frontiers in Sustainable Food Systems. 3, 47.

Eyarkai Nambi, V., Manickavasagan, A., Shahir, S. (2017). Rice milling technology to produce brown rice. Brown rice. 3-21.

Gujral, H.S., Sharma, P., Kumar, A., Singh, B. (2012). Total phenolic content and antioxidant activity of extruded brown rice. International Journal of Food Properties. 15(2), 301–311.

Gul, K., Yousuf, B., Singh, AK., Singh, P., Wan, A. (2015). A rice bran: nutritional values and its emerging potential for development of functional food—a review. Bioactive Carbohydrates and Dietary Fibre. 6, 24–30.

Hagenimana, A., Ding, X., Fang, T. (2006). Evaluation of rice flour modified by extrusion cooking. Journal of Cereal Science, 43(1), 38–46.

https://asutoshcollege.in/new-web/Study_Material/processsing_of_rice_03042020.pdf

https://course.cutm.ac.in/wp-content/uploads/2020/06/Session-4.2_Rice-Milling.pdf

International Institute for Population Sciences & National Family Health Survey (NFHS-5). (2019–20). National Family Health Survey (NFHS-5) 2019–20: India. http://rchiips.org/nfhs/NFHS-5Reports/NFHS-5_INDIA_REPORT.pdf (accessed on 25 September 2023).

Ling-Tan, BL., Norhaizan, ME. (2017). Scientific evidence of rice by-products for cancer prevention: chemopreventive properties of waste products from rice milling on carcinogenesis in vitro and in vivo. Biomed Research international. 20, 1–18.

Marshall, WE., Wadsworth, JI. (1993). Rice science and technology. CRC Press.

Muchlisyiyah, J., Shamsudin, R., Kadir Basha, R., Shukri, R., How, S., Niranjan, K., Onwude, D. (2023). Parboiled rice processing method, rice quality, health benefits, environment, and future perspectives: a review. Agriculture. 13(7), 1390.

Müller, A., Nunes, M. T., Maldaner, V., Coradi, P. C., de Moraes, R. S., Martens, S., Marin, C. K. (2022). Rice drying, storage, and processing: effects of post-harvest operations on grain quality. Rice Science. 29(1), 16-30.

Nithya, A., Dalbhagat, CG., Mishra, HN. (2022). A comparative study on the physicochemical, cooking and textural properties of fortified rice kernels prepared from raw and parboiled rice. International Journal of Food Science & Technology. 57(2), 1325-1332.

Rachmat, R., Rahayu, E., Darniadi, S., Hadipernata, M. Enhancement of quality and milled rice yield recovery through the improvement of polishing process and configuration. In IOP Conference Series: Earth and Environmental Science(2022).1024, 1, p. 012008. IOP Publishing.

Timmer, C.P. (2010). Reflections on food crises past. Food Policy. 35, 1–11.

Vishwakarma, S., Mandliya, S., Dalbhagat, CG., Majumdar, J., Mishra, HN. (2023). Effect of marjoram leaf powder addition on nutritional, rheological, textural, structural, and sensorial properties of extruded rice noodles. Foods. 12(5), 1099.

Wahengbam, ED., Das, AJ., Green, BD., Shooter, J., Hazarika, MK. (2019). Effect of iron and folic acid fortification on in vitro bioavailability and starch hydrolysis in ready-to-eat parboiled rice. Food Chemistry. 292, 39-46.

World Health Organization. (2021). Anaemia in Women and Children: WHO Global Anaemia Estimates(2021 Edition). https://www.who.int/data/gho/data/themes/topics/anaemia_in_women_and_children (accessed on 25 September 2023).

Xu, E., Pan, X., Wu, Z., Long, J., Li, J., Xu, X., Jiao, A. (2016). Response surface methodology for evaluation and optimization of process parameter and antioxidant capacity of rice flour modified by enzymatic extrusion. Food Chemistry. 212, 146–154.

Yadav, GP., Dalbhagat, CG., Mishra, HN. (2021). Development of instant low glycemic rice using extrusion technology and its characterization. Journal of Food Processing and Preservation. 45(12), e16077.

Innovations in Millet Processing, Packaging, and Marketing

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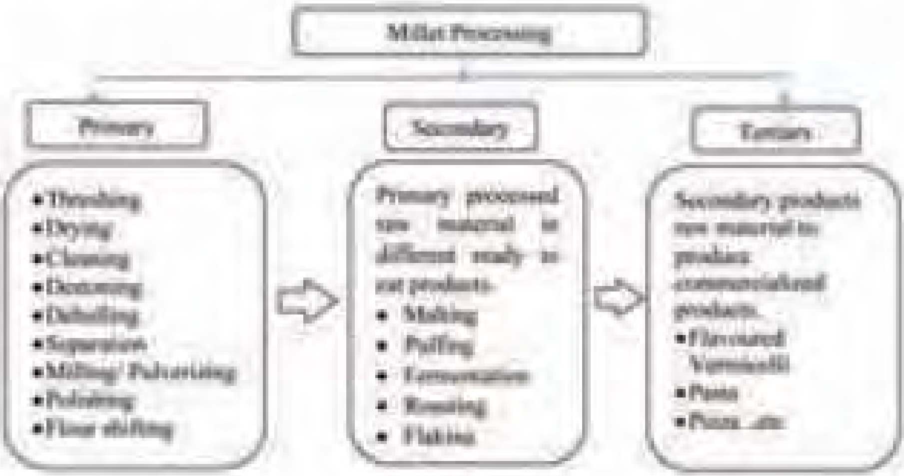
Millets are widely grown in India and in a foreign country. After harvesting, millets are not eaten as uncooked whole seeds, hence processing is required to make grains edible and digestible. Millets are good sources of nutrients and calorie. There is increasing demand for processing of millets to fetch higher prices and utilization of millets leading to profitable cultivation and sustainable(Rajendra R. Chapke, G. Shyam Prasad, I.K. Das, Hariprasanna K., Avinash Singode, B.S. Kanthi Sri 2020).

Why processing of millets?

In general, Millet processing involves the separation of dirt, foreign material, pericarp, the germ from the edible portion, drying, pulverizing, value added products, packaging and storage. The outer tough seed coat of millets, characteristic flavour, cultural attachments and non-availability of processed millet products are limiting factors unlike rice or wheat. The farmers are getting very less price (Rs.15-20/kg) to their un-processed produce compared to process one (Rs.80-100/kg). Unfortunately, there is no well-proven industrial process available for processing of millets. Now a days many innovations in terms of machinery, processing methods, technology, value added products developed. There is a shift in processing and equipment from traditional to modern methods and optimize processing condition to make quality products that are affordable. Millets processing aids in Digestibility, provides food safety by cooking inactivates natural toxins and heat prevents bacterial and food spoilage. Improves the Organoleptic properties-optimizes the appearance, taste and texture of foods to meet the needs of consumers. Ready to eat (RTE) and convenience. To meet consumer demand for quick and easy meal solutions and also nutritional supplement. Maximize nutritional availability Processing can make it easier for nutrients from grains to be digested. Nutrients lacking in the diet can be added to staple grain-based foods (food fortification) (e.g. thiamin added to flour).



Owing to its nutrients composition and technological properties of small millet grains, many Institutions like ICAR – IIMR, Hyderabad, CIAE, Bhopal, CIPHET, Ludhiana, SAUs associated with AICRP on PHET, CSIR-CFTRI, Mysuru, IIFPT, Tanjavur, GBP UA&T, Pantnagar, ICAR-VPKAS, Almora, etc and NGO, private sectors have developed various technologies for post-harvest handling and processing of millets. It offer a number of opportunities for processing and value-addition to use as next generation foods to satisfy the consumers' choice of different culture, location, choice and society (Rajendra R. Chapke, G. Shyam Prasad, I.K. Das, Hariprasanna K., Avinash Singode, B.S. Kanthi Sri 2020).

Primary processing

Primary processing mainly involves Threshing, drying, destoning, cleaning, sorting, dehusking, dehulling, grading and pulverizing and their technique presented in Table 1.

Unit Operations	Processing techniques
Threshing – Grain and Husk segregation	**Mechanical threshing equipment:** These devices rotate threshing cylinders or drums with connected teeth. They can handle a lot of millet and are quick and effective. Motorised threshers to massive combine harvesters, modern mechanical threshing equipment is available in a variety of sizes and capabilities. **Pneumatic threshing:** Using air. The air is blown through the millet stalks as they are fed into the apparatus, this process can handle big amounts of millet and is less harmful to the grains. **Electrostatic separation:** using electrostatic charges. The grains of millet break from the husks after being run through a machine that charges them with static electricity. This process yields grains of excellent quality and is quick and effective. **Vibratory threshing:** using mechanical vibrations. The stalks of millet are fed into a device that vibrates them, separating the grains from the husks. This process can manage a lot of millet while being kind to the grains. **Laser-based threshing:** using lasers. The millet stalks are fed through a device that burns the husks with lasers while leaving the grains unharmed. Although it is still in the experimental stage, this procedure is quick and effective (Kunkari, Lokhande, and Gaikwad 2023)
Drying	**Reduce the moisture to a safe storage level** **Mechanical drying system:** Continuous flow hot air dryers- LSU dryer Deep bed batch type of dryers
Cleaning	**Removing impurities** **Destoner cum grader cum aspirator**-Stones are collected on back side, cleaned grains to the front and lighter particles by air.

Dehullers removing husk	**Shear abrasion** – friction and abrasion forces on grain surfaces Centrifugal impact (Single), Centrifugal impact (double time) - Centrifugal force Roller mills- a pair of steel rollers that roate inside a chamber at constant /varying speeds in a counter directional manner CIAE millet mill – conventional approach – two stones rotating with cyclone separator etc. Tangential Abrasive Dehulling Devices (TADD)
Pulverizing	Separating bran and germ from the starchy endosperm so that the endosperm can be ground into flour and rawa using different types of sieves **Hammer milling:** use of a hammer mill. The millets are ground into flour using a high-speed rotating hammer in this process. A hopper is used to feed the millets into the hammer mill, which then turns them into fine flour **Roller milling:** Another technique for preparing millets is roller milling. With this technique, the millets are put through a succession of rollers to be crushed and ground into flour. Compared to conventional techniques, the roller milling process is more effective and results in a more reliable output. **Jet milling:** This technique entails pulverising millets into flour with high-pressure air jets. High-quality millet flour products are frequently made using this procedure, which yields very fine, homogenous flour. **Ultrasonic milling:** It is a more recent technique for processing millets. The millets are broken down into flour using ultrasonic vibrations in this process. Ultrasonic milling is a very effective technique that generates very little heat while producing very fine grain (Kunkari, Lokhande, and Gaikwad 2023)

Secondary Processing

Millet is predominantly starchy and the bran layer of millet is a good source of b-complex vitamins. It also serves as a source of antioxidants in our diets. Thus, the presence of all the required nutrients in millets makes them suitable for large scale utilization in the manufacture of food products such as baby foods, snack foods and dietary food. (Millet and Snack 2021)

Secondary processing is a process converting primary processed raw material into product which is suitable for food uses or consumption such as ready-to-eat (RTE) and ready-to-cook (RTC) products, minimize cooking time and make it convenient foods (Tonapi and Sangappa 2020). The traditional (popping and flaking) as well as contemporary methods of cereal processing could be successfully applied to millets to prepare ready-to-eat products, thereby, increasing its utilization as a food using following technique presented in table.

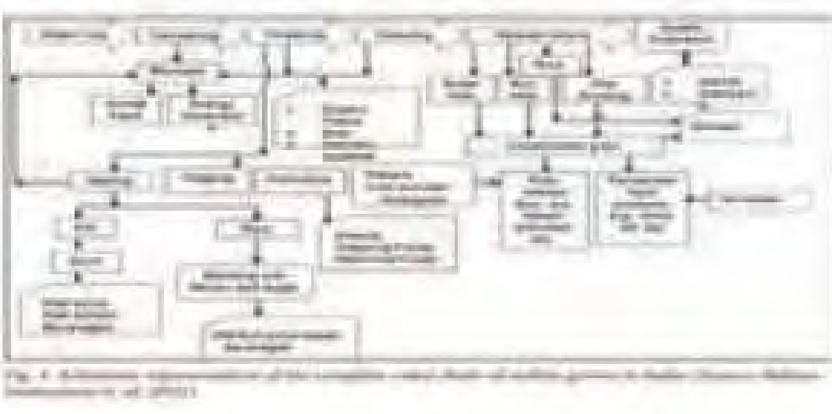
Unit Operations	Processing techniques
Puffing	• Desired popping and expansion, millets are soaked to the necessary moisture level before being exposed to hot sand at a 1:6 ratio and high temperature (230-250 C) for a short duration (20-30 seconds) • **Gun puffing** : process of filling the closed spinning chamber with superheated steam after preheating the milled grains in the cannon or high-pressure chamber is known as "gun puffing" (Luh, 1991) • **HTST Fluidized Bed Puffing / Popping**: g is a process where a solid particle substance is placed in a holding vessel and is subjected to certain conditions that cause the mixture of solid and fluid to behave like a fluid. at a temperature between 240°C and 270°C, with equivalent exposure. • **Microwave**: Thermal energy that has significant potential for processes like cooking, tempering, drying, heating, baking, blanching, popping, and puffing (Buffler 1993; Roussy and Pearce, 1995)
Malting	• Steeping (immersing grains in water), germination (encouraging sprout growth and enzymatic activity), and kilning (drying the grains and halting enzymatic activity). This process has been shown to

	improve the nutritional content, fiber, crude fat, vitamins B and C availability, minerals, and sensory qualities of grains. • **an integrated single unit is extremely common because** it is quick, simple, and inexpensive to process. To ensure a uniform layer thickness in the integrated single malt, the grains are spread out on grain retaining sieves (Kumar et al. 2016).
Fermentation	• One advancement in millet fermentation technology is mixed-culture fermentation, where the use of multiple strains of microorganisms can increase the output of the finished product while enhancing its sensory qualities. Another novel technology is "Very High Gravity" (VHG) fermentation, which can boost ethanol production and profitability on an industrial scale. • extrusion and other technologies can be combined with millet fermentation to create unique products while streamlining the time-consuming fermentation process. • application of thermal and non-thermal modern approaches to millet fermentation has not been fully explored. (Kumar et al., 2021)
Roasting	• Grains that have been roasted are easier to digest, have improved flavour and aroma, and it helps to remove the husks from the grains. • Fluidized bed roasting: Millet grains are suspended in a stream of hot air or gas, which swiftly and evenly roasts them. To achieve the required level of roasting, the grains are cooked for a set amount of time and at a certain temperature. When compared to conventional roasting techniques, this process is effective, consistently provides high-quality results, and uses less energy. (Shingare et al., 2013) • Infrared roasting:- Using infrared radiation. The grains are put on a conveyor belt and moved through an infrared radiation chamber where they are heated for a predetermined amount of time and at a predetermined temperature. This process yields

	roasted millets of a consistent quality and is quick and effective. (Shingare et al.,2013) • Microwave roasting: Using a microwave in this technique. The grains are roasted in a microwave oven at a particular power level and timing. This process yields roasted millets of a consistent quality and is quick and effective. • Drum Roasting-Millet grains are roasted in a rotating drum. The grains are tumbled inside the drum while it is heated from the outside to guarantee equal roasting. This process yields roasted millets of consistently high quality and is effective. • Vacuum roasting: Millet grains are roasted in a low-pressure setting. The grains are roasted at a certain temperature and duration in a vacuum chamber. This process gives the millets and other grains a distinct flavour and scent. (Kaur et al.,2022)
Flaking	• Heavy duty roller-flaker

Tertiary Processing

Several studies recommended, millets as the nutritional composition, biological and sensory characteristic values are found to be on par with wheat-based products. This has come as a morale-booster and has boost-up the demand for millet-based food products. Different value-added food products of millets instantly ready-to-eat (RTE) products can be prepared reducing the cumbersome time for fermentation. It is gluten free, low calorie, rich source of phenolic compounds, causes satiety resulting in slower digestibility and reduces oxidative stress.



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Advantages of Processing:

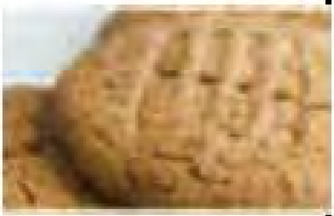
- Reduce the levels of phytates and tannins using dehulling
- Increase bioavailability of amino acids and mineral elements and improve protein and starch digestibility using fermentation, soaking, steaming and germination
- Nutritional supplements, quick, easy meal solutions using value addition
- Optimizes the appearance, taste and texture of foods using secondary processing techniques.
- Nutrients lacking in the diet could be added to staple grain based foods.
- Easy for package and handling the product
- Increase the shelf life
- Reduce the losses
- Reduce the pest/insect attack etc.

Processing of millets – Value added Products

• **Sorghum based ready to cook mixes** - Sorghum upma mix and masala sorghum dry mix have been developed using fermented, steamed and flaked sorghum grains. • The products has been well received by a sensory study conducted considering 80 consumers.	
Millets puffs- • The sorghum puffs using gun puffing, are white in colour and are crispy in nature, similar to the puffed rice. The shelf life is for 4 months when packed in air tight MET pouches at ambient temperatures (Puffs yield – 94%; By-product yield – 6% (small puffs and unpuffed grains). • The puff gun machine is loaded with dehulled foxtail grain onto a rotating barrel and the mixture is roasted for and fired resulting in a puffed sorghum product (Puffs yield – 92%; By-product yield – 82% (small puffs and unpuffed grains)	

Extruded snacks • The mixture is combined and passed through twin screw extruder to produce expanded snacks which are ready to eat. The snack can be coated with desired spices to create variations in the taste and flavour (Ingredients - sorghum grits, rice, ragi, wheat and corn flour). • Snacks yield – 90%; By-product yield – 10% (Extrudate byproduct) • The shelf life of the product was 6 months and the shelf life analyses are still in progress	
Extruded flakes • Semolina (Sorghum: Wheat: Corn Flour) Conditioning, Water Extrusion, Roller flaker machine, Extruded flakes,Packaging • Flakes yield – 88%; By-product yield – 12% (Extrudate byproduct, un-flattened flakes)	
Instant sorghum idli mix • Instant sorghum idli mix sorghum fine semolina, blackgram dhal, salt and food grade additives; citric acid and sodium bicarbonate were used as main ingredients. All the ingredients were mixed uniformly in a blender. The formulated mix was packed in a MPET packing material, he shelf life of idli mix is 3 months.	
Instant dosa mix • Instant sorghum dosa mix sorghum flour, blackgram dhal (2:1), salt; citric acid and sodium bicarbonate were used as main ingredients and mixed uniformly in a blender. The formulated mix was packed in a MPET packing material. The shelf life of dosa mix is 6 months.	

Instant pongal mix • Instant pongal mix using processed sorghum, green gram dhal, spices & condiments. The mix has to be added to three cups boling water and cooked in pressure cooker for upto three whistles mixed with ghee or milk to make round balls before serving. The formulated mix was packed in a MPET packing material.	
Kodo rice based ready to cook mixes • Ready to cook kheer and halwa mixes have been developed using decorticated and fermented kodo rice	
Millet instant laddu mix • Millet laddu mix is developed from roasted sorghum fine rawa, finger millet flour, pearl millet flour; adding to it powdered low calorie sugar, dry fruits and cardamom are added. The mix has to be mixed with ghee or milk to make round balls before serving. The formulated mix was packed in a MPET packing material.	
Retort pouch processed ready to cook little millet halwa • The optimized roasting time was 17min with 1000 ml of water to prepare the Halwa from 200g of little millet. • Halwa was packed in retort pouches and retort processed to achieve lethality rate of the product (F0 value: 6.1). • Analysis of variance revealed that the treatments significantly influence the moisture content, fat, protein and total sugar ($p \leq 0.01$).	 

• Also observed that as the days of storage increased at all storage conditions there was increasing trend with NEB, FFA and PV.	
Millets vermicelli • Finger millet /Foxtail millet /Pearl millet semolina and refined wheat semolina are blended in the mixing compartment of the vermicelli-making machine and blended with water for 30 minutes and extruded using a round die. The vermicelli is allowed to temper in room temperature for 8 hours and then dry in a cabinet drier for 6 hours	
Millet cookies • Millets were incorporated indifferent variations from 10% to 50% levels to standardize cookies (100%), bread/bun (50%) and cake (100%) by replacing refined wheat flour or using 100% millet flour at IIMR. It is the need of the hour to develop bakery foods as convenience foods and IIMR has carried out research in developing millet based RTE bakery foods	
Millet bread/bun • Millet breads have been prepared at IIMR of replacing 50% wheat in bread with pearl millet, finger millet or foxtail millet flour of varied proportions and adding superior quality yeast, trans-free fat, salt and sugar. The dough is proofed and then baked in oven to get bread. Round balls of the dough is made and baked to get bun. It has a shelf life of 6 days when packed in LDPE packets.	

Millet cake • Millet cakes have been prepared at IIMR using 100% pearl millet, finger millet or foxtail millet flour and adding superior quality fat, sugar, eggs and chocolate/ vanilla essence; and also adding all the millets together with varied proportions. Of all the cakes made finger millet cake was highly acceptable	
Millet pizza • Millet pizza have been prepared at IIMR using 50% sorghum, pearl millet, finger millet or foxtail millet flour, 50% fine wheat flour, adding superior quality fat,yeast, salt and sugar; and also adding all the millets together with varied proportions. Of all the pizza base made sorghum pizza base was highly acceptable. • It has a shelf life of 4 days when packed in MET packets.	

Millet Processing Machinery

Millet Cleaner, Washing Machine (Capacity: 1000-1200 kg/hr)

Flexib Millets Destoner Cum Grader Cum Aspirator

Millet mill dehuller - Type I

Millet mill dehuller - Type II

Dehuller different types: Continuous type – M/s. Perfura Technologies Pvt. Ltd.

Specification	Vertical Dehuller	Centrifugal Dehuller (Single Stage)	Centrifugal Dehuller (Double Stage)
Working Principle	Abrasive force	Centrifugal	Centrifugal
Capacity	100 kg/hr	200 kg/hr	200 – 250 kg/hr
Efficiency	50-70 %	30-80%	80-85%
Suitable grains	All millets	All millets (Best suitability for Barnyard and proso)	All millets (Best suitability for Little and foxtail)
Overall dimensions	2 x 2.5 x 5 feet	4 x 2.5 x 5 feet	4x 3x 7 feet

Millet pulverizer

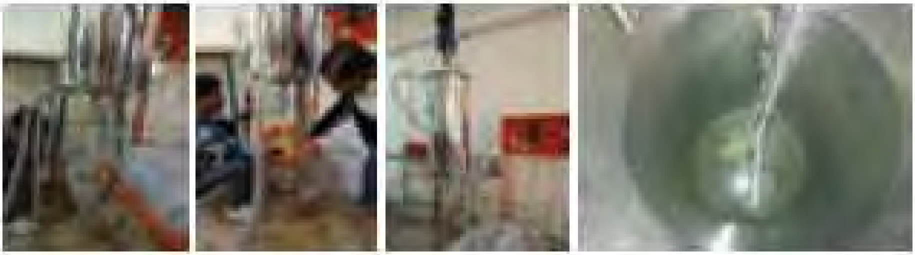
Small millets polisher

Flack Millet Dehusker

Single Stage Centrifugal Dehuller

BATCH TYPE MILLET FERMENTOR

The SS 304 batch stirred tank millet fermentor (150 litre) consists specially designed agitator with paddle and wiper. Fermenter evaluated with 1:3 ratio sorghum + water (16oC) and pump the hot water and circulated through outer jacket pipe. The special designed discharge valve for draining off water with wire mesh and same outlet for fermented grain and also temperature sensors and EC set up the system. Observed that wet grains were falling freely, average mass flow rate is high (25 kg / 2 min) and average discharge of water was 20 l/ min.



Millet Flaking machine

- Produces flakes from pre-treated/ fermented whole sorghum grains with a min gap of 0.5 mm between the rolls, min flake thickness that can be obtained was 0.5 mm. Flaking efficiency: 92%.
- Comprises of two sets of stainless steel rolls running at a differential speed of 1:1.5 with corresponding speeds of 400 and 600 rpm in opposite direction. Power is drawn from a 0.5 hp single phase motor running at 1440 rpm. Polygonal teflon feeder provided for controlled feeding rate of the raw materials into the flaking rolls runs at 260 rpm.

Millet Roti Making Machines- jointly developed by IIMR with private entrpeneur

- Foot operated
- More space required
- Capacity 40 rotis/hr
- Low speed (150 rpm)
- Cost- Rs. 25,000/-

- Hand operated
- Less space required
- Capacity – 50-60 rotis/hr
- Medium speed (200 rpm)
- Cost- Rs. 10,000/-

- Hand operated
- Less space required
- Capacity 80-100 rotis/hr
- High speed (250 rpm)
- Cost- Rs. 8,000/-

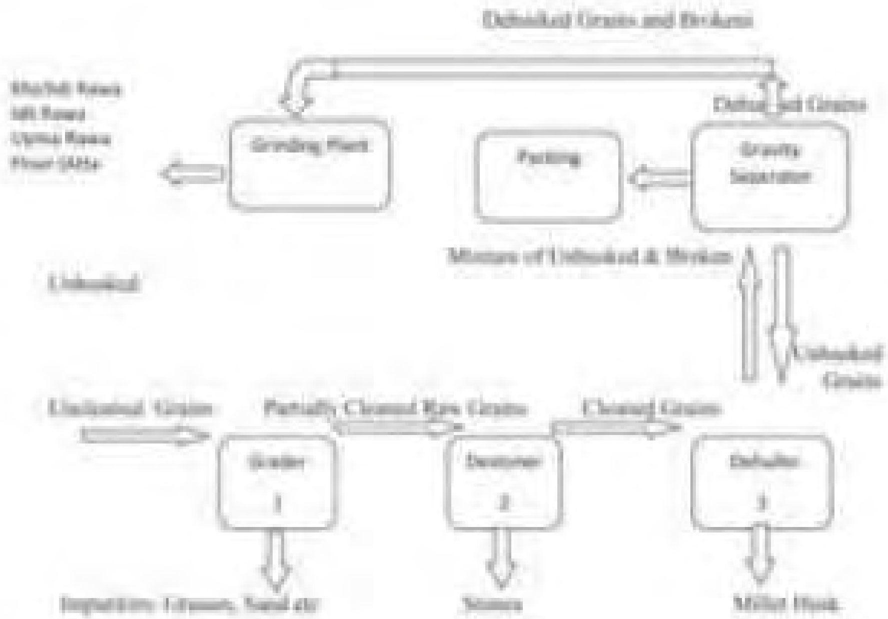
Area requirement of primary processing unit

Scale	Machinery space	Storage space	No of Machinery selection
Small (100-500 kg/hr)	100-150 Sq. ft	600 Sq. ft	4-5
Medium (600-1000 kg/hr)	400-600 Sq. ft	5000 Sq. ft	8-10
Large (1000-2000 kg/hr)	800-1000 Sq. ft	10000 Sq. ft	8-10

Machinery requirement: approximate cost

Machinery	Specifications	Manufacturers	Cost (Rs.)
Grader	1-2 HP 500-1000 kg/hr	• Perfura Technologies (India) Private Limited • Borne Technologies Private Limited • Bhavani Industries • AVM Engineering Industries	2.0-2.5 lakh
Grader cum aspirator	1-2 HP, 3-5 HP 500-1000 kg/hr		0.4-2.5 lakh
De-stoner cum aspirator	2-6 HP		0.5-3.5
De-stoner cum grader cum aspirator	2-4 HP		0.9-6.0
Elevators	1-2 HP	• Perfura Technologies (India) Private Limited	1.0-1.6
Double stage dehuller with blower/ Pulverizer	3 -7 HP 100-300 kg/hr	• Perfura Technologies (India) Private Limited • Borne Technologies Private Limited • Bhavani Industries • AVM Engineering Industries	1.6-7.0
Gravity separator	2-3 HP 100-250 kg/hr	• Borne Technologies Private Limited	1.0-1.2
Polisher	100 kg/hr	• AVM Engineering Industries	0.90

Flow chart for Primary processing unit



Case Study

A Millet Processing Centre has been established with the following millet processing machinery viz., Destoner, Millet Mill, Grain Polisher, Pulveriser, Flour Sifter and Packaging Machinery for enhancement of tribal livelihood in Tamil Nadu. Based on the performance evaluation, the output capacity of destoner cum cleaner was found to be 230 kg/h and 233 kg/h for little and foxtail millet respectively with a cleaning efficiency of 89 and 90% respectively for the above millets. The performance of millet mill revealed that the output capacity was 90-92 kg/h for little and foxtail millet with a dehulling efficiency of 86 and 87% respectively with small percentage of brokens (< 5 %). The capacity of grain polisher was 60-61 kg/h with a polishing efficiency of 85% & 86% respectively for little and foxtail millet. The pulveriser was evaluated for finger millet flour making whereby the output capacity of the machine was 75 kg/h with a milling efficiency of 90% respectively. The cost economics revealed that the tribal farmers could save 85% of the processing cost. The benefit cost ratio was found to be 2.05.The total profit to the tribal Society through Millet Processing Centre was Rs. 21,000/- during the first harvesting season of millets.(Ambrose et al. 2017)

Fig. 1. *Millet processing centre in tribal area, [illegible] Tamil Nadu.*

Fig. 2. *Hands on training on operation of millet processing machineries.*

Fig. 1. *Millet processing centre in tribal area, [illegible] Tamil Nadu.*

Fig. 2. *Hands on training on operation of millet processing machineries.*

Effect of processing on nutritional Properties of millets

Different processing methods of foxtail millet made an effect on the total phenolic content (TPC), total flavonoid content (TFC), and the six kinds of phenolic acids. Compared with whole millet, the TPC of dehulled millet decreased and 64 TFC of dehulled millet increased. Compared with dehulled millet, the TPC and TFC of cooked and steamed millet decreased. However, the total phenolic content and cinnamic acid content were rich in cooked millet. In addition, cooked millet demonstrated remarkable radical scavenging capacity, which was associated with its high contents of natural antioxidants found in the samples, such as phenolic compounds, cinnamic acid, and phytic acid. Correlations between the antioxidant activity and cinnamic acid ranged from 0.75 to 0.89, while the antioxidant activity and total phenolic content ranged from 0.83 to 0.91. Therefore, cooked millet was a good choice for human consumption.

Table 1: Nutritional composition of millets, rice and wheat (per 100 g edible portion, 12% moisture)

[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Rice (brown)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Wheat	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Maize	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Sorghum	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Pearl millet	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Finger millet	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Foxtail millet	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Common millet	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Little millet	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Barnyard millet	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Kodo millet	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

(Gowda et al. 2022)

Packaging

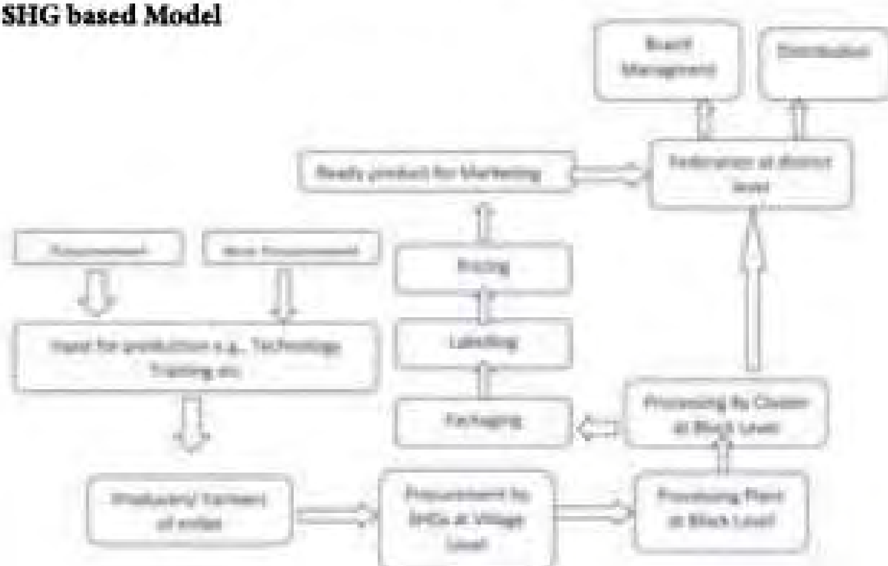
Millet grains with the safer level of moisture content can be stored for a longer period. Traditionally millets are stored in indigenous systems like kothis, baskets, bins etc. especially constructed using locally available materials like wooden strips, planks, ropes, cow dung etc. Jute bags are recommended for storage of cleaned millet grains in a cool and dry place. Jute bags must be disinfected before use. Tailor made LDPF or HDPE polyethene lm bags are used based on the type of the value added product to be stored. A film with very low oxygen permeability and water vapour permeability, less light transmission is mostly recommended for the packaging of dehulled millets. The packaging and storage requirement varies with the different forms of millet products.(Kotwaliwale et al., 2022.)

For values added products: Aluminium laminate storage of snacks at lower temperatures is desirable to maintain the microbial quality of snacks .It reported that packaging of snack in Aluminium laminate is better than in HDPE as low count of bacterial, mold and lab were observed in snack packed in Aluminium laminate as compared to HDPE. Cold temperature storage of snack resulted in better microbiological characteristics as compared to room temperature storage. (Millet and Snack 2021)

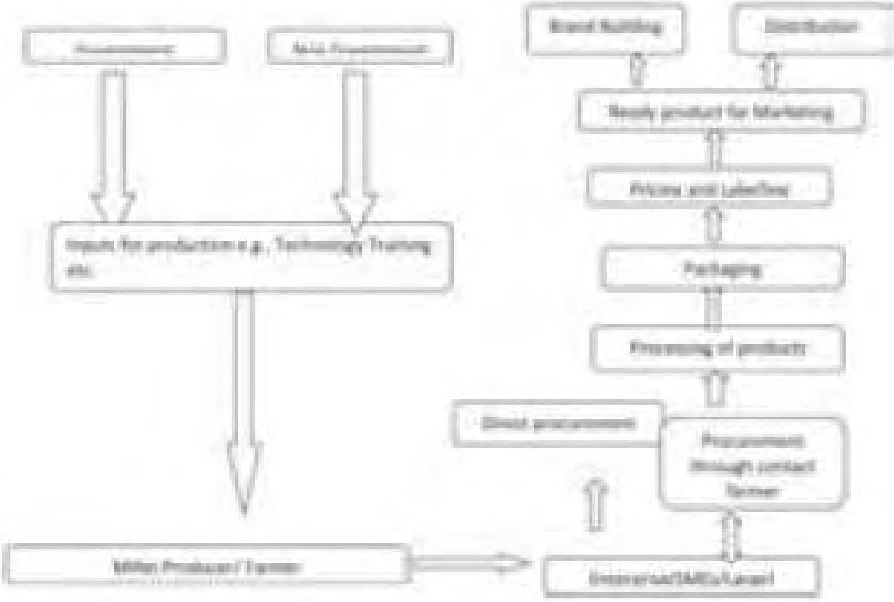
Marketing

Market access can play an important role in promoting millet and millet products in India. Proper marketing strategy including focus on brand management, Pricing, packaging, labelling can play an important role in promoting the millet and millet products. The two models for millets are SHG based model and Model for enterprise's. The promotion of millets should be an integrated effort involving government, non-government organisation, private players as well as community (Kajale and Bharti 2017)

SHG based Model



Enterprise based model



Conclusion

Millets are nutritious but neglected crops with an indefinite shelf life which is grown in both plains and hilly regions. To enhance the utilization of millets in daily diets, it is desirable to develop novel processing techniques, equipment and value-added products from millets. Recent and availability of processing technology made easy to prepare fermented products – dosa, idli, baked – biscuits, cakes, are some of the popular forms in which millets are consumed. Gaining popularity owing to nutritional advantages and providing health benefits. Based on primary, secondary and tertiary processing plant could be set up with 0.8 tons 1 ton capacity per day with minimum investment of Rs. 5 lakh and generate good profit per annum. Establishment of millet processing unit could be viable option to increase the productivity and profitable venture for entrepreneurs and healthy nutritious food for consumers.

References

Adesina, A. (2021). Effect of Packaging Material and Storage Conditions on the Microbial Quality of Pearl Millet Extruded Snack. Journal of Food Processing & Technology. 12:857.

Ambrose, DC., Annamalai, SJK., Naik, R., Dubey, A.K. and Chakraborthy, S. (2017). Performance studies on millet processing machinery for tribal livelihood promotion. Journal of Applied and Natural Science. 9(3), pp.1796-1800.

Chapke RR, Shyam Prasad G, Das IK, Hariprasanna K, Singode A, Kanthi Sri BS and Tonapi VA. (2020). Latest millet production and processing technologies. Booklet, ICAR-Indian Institute of Millets Research, Hyderabad 500 030, India: 82p. (ISBN: 81-89335-90-X).

Kajale, DB., Bharti, N. (2013). Marketing Strategies for Millet and Millet Products in India. Conference: Global Consultation on Millets Promotion for Health & Nutritional SecurityAt: HyderabadVolume: Volumes 18-20

Kotwaliwale, N. (2023). Millet Processing: Innovative Technologies. Agricultural Engineering Today. 47(1), pp.36-40.

Kunkari, DA., Lokhande, M., Gaikwad, ST. (2023). Traditional and Advance Processing Technology ofMillets- A Review. Journal of Emerging Technologies and Innovative Research. 10(4): 386–404.

Tonapi, V. (2023). Processing Machinery Enabling Millet Ecosystem, Branding and Farmgate Processing. Agricultural Engineering Today. 47(1), pp.15-20.

Chapter 19

Opportunities and Challenges for Farmers, Processors, and Consumers in the Millet Value Chain

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Abstract

Globally millets are considered as healthy coarse foods. It has extremely nutrient-dense foods. After India's press on UNO, International Year of Millets is being celebrated; millets production and processing are gaining moment in India in recent years as a result of governmental initiatives. However, the productivity of millets is low and the quantity of usage of millets is clue less. So, the shortcoming of millet production, processing and consumption must be analyzed to achieve desired level of millet consumption. With this background, a value framework for value chain analysis of millets is analyzed in this chapter. This chapter included, mapping of millet value chain, mapping of actors and policies in the value, mapping quality knowledge of the actors in the millets, andmethod to assess the millet value chain is discussed.

Key words : Mapping, Michael Porter Value Chain Analysis, VIRO framework, gap analysis, Benefit cost ratio

Introduction

Value chain analysis is used to examine every step in a process. It is a series of processes required to organize or assess a thing or service, starting from conception to the final consumers. The value chain analysis is applicable to both physical transformation of products or the services [Kaplinsky & Morris, 2000]. The difference between value chain and supply chain is to a set of business processes where utility is added to the products and services the company offers in order to increase consumer value whereas the supply chain describes the coordination of all operations related to sourcing, purchasing, converting, and logistics. Value chain analysis is significant for three key reasons 1. Systemic competitiveness has grown in significance as a result of the expanding division of labor and the globalization of component manufacturing, 2. Production effectiveness is merely a prerequisite for effectively entering international markets, and 3. Making the most of globalization demands entering markets on a sustainable basis, which necessitates a grasp of dynamic dynamics along the entire value chain.

The millet value chain analysis assesses the tasks performed during production, processing, storage and supply chain and consumption of millets. In a value chain analysis, the varieties of millets cultivated, the land used for cultivation, the climate's suitability, the package of practices, seed availability and source, the cost of production of millets and the returns on the production cost, types of processing techniques, the returns the consumers receives, and finally the difficulties encountered by actors in the value are assessed[Tapas Chandra Roy, 2023]. In this chapter, the recent package of practices, primary and secondary processing equipment and technologies, processed foods, quality standards, supply chain process and, and finally the challenges that processors face is all be covered under the heading of processing. The availability of value-added products on the market, their cost, their profit margins, and the strategies employed for distributing and selling these products are only a few of the topics covered in the marketing section.

Present Status of Millet Production and Processing

India is one of the top 5 exporters of millets in the world. Millet exports increased from $400 million in 2020 to $470 million in 2021, according to the ITC trade map. With a value of $75.46 million (up from $62.95 million in 2021–2022), millets were one of India's top exports in 2022–2033. There was an increase in this over the previous year.Millet-based value-added products have a very small market share. The production of millet has increased recently in India. India is one of the countries that produces the most millets, and Indian farmers are increasingly growing millet as a crop that can withstand droughts. The National Food Security Mission of the Indian government includes the promotion of millet cultivation. These elements is likely cause millet production in India to increase throughout the upcoming years. Numerous agronomic, economic, and societal issues have contributed to the fall in minor millets in India. Government encouragement of rice and wheat during the Green Revolution of the 1970s pushed minor millets into ever-more-peripheral locations. Millets have developed the terrible reputation in certain areas of being poor people's crops that should be avoided[Padulosi et al., 2015].

At present, 15 million hectares are used for millet cultivation. due to processing of millets requires more time-consuming, tedious primary processing of millets by farm women's, low yields and a change in land usage. Very little amount of millet is marketed and converted into value-added items. However, over 54 million tonnes of grains were procured for Public Distribution System (PDS), the Integrated Child Development Scheme (ICDS), and school meals in 2019–20. These government agencies by millets about 10.8 million tonnes to replace 20% of the current supply of rice and wheat, then consumption will be increased for Sorghum (jowar), pearl millet (bajra) finger millet (ragi) and other millets. Millets are difficult for customers to buy from traditional and retail markets, because millets are frequently more expensive than conventional cereals. Low-income -Large consumer group findshigh price of millets. Some people avoid eating millets because they think they have a dull or disagreeable flavor. Milletsgive low production and less profitable, not readily accepted in the market, hence farmers deter themselves to produce millets.

The National Millets Mission (NMM) was established in 2007 to encourage the growth of millets as a food source. Farmers are given financial support through the Price Support Scheme (PSS) to cultivate millets. promotes the manufacturing of millet-based products with added value to boost millet demand and consumption. Millets are now available and reasonably priced to the general public thanks to the government's inclusion in the Public Distribution System. To enhance production and consumption of organic millets, the government is encouraging organic millet farming.

The Indian government had asked the UN to proclaim 2023 the International Year of Millets (IYOM). On March 5, 2021, the United Nations General Assembly (UNGA) formally declared 2023 the International Year of Millets with the support of 72 additional countries, including India. The worldwide year of millet offers a fantastic chance to expand millet's contribution to food security. 2. Increasing millet production on a global scale; 3. Ensuring that millet is efficiently processed, transported, stored, and consumed; and 4. Assuring quality and sustainability of millet production through involving stakeholders.

Methodology of Value Chain Assessment

Value chain assessment for a business model is abstractions of specific organizations that are used to understand, clarify, communicate, develop, and achieve particular goals [Osterwalder et al., 2005]. Customers, value proposition, distribution channels, income flows, client connections, resources, cost structure, key activities, and partner network are the nine elements that make up a company model, according to Osterwalder [Adekunle et al., 2018]. a comprehensive framework to cover the many and various interconnected value chain parts. The framework of value chain assessment highlights the key interventions along the six primary millet value chain segments such as genetic diversity, selection of seeds and cultivation time and practices, harvest method, primary processing and value addition, marketing, and end use[Padulosi et al., 2015]. There are three steps in value chain analysis. 1.Analyse the activities, 2. Analyse the value and cost, and 3. Understand what your consumers value the most. Analyze the activities is a process of analyses the essential activities that are equip to market demand such as quality production, usage of chemicals, supply of millets on time, supply chain, storage, processing and value addition and packing and advertising. Similarly, how the value of the millet to be added in each activity is assessed in analyses the value and cost process. In this step which activity is primary activity where can add value to the millets and why customer value the most are determined. The methods and tools used for value chain analysis for minor millets is provided in the table .1(Adekunle et al., 2018) and the steps involved in value chain analysis is provided in the table 2.

Table 1. Methods, tools used for value chain analysis for minor millets

Methods and tools deployed/developed
Focus Group Discussions on millet varieties, cultivation, processing.
Base line surveys on millet varieties, cultivation, processing.
Mapping of existing cropping pattern, SWOT of existing cropping pattern and compare with millet crops.
Participatory documentation of local varieties and methods of cultivation, storage and processing.
Participatory documentation of millet seeds, seed banks and gene banks, variety selection of high-quality seed varieties.
Improving agronomic practices through introduction machines, cropping patterns, training and demonstration on new methods, tools, operations.
Formation of SHG, FPO, Village Farmers Groups.
Community based cultivation and processing hubs.
Strengthening of famers groups, cooperatives for marketing.
Building platforms and linkages among actors in value chains.

Collection and documentation of traditional recipes.
Training on e-marketing and e- business.
Organising millet expo, millet food festival, recipe competitions.
Persuading the policy makers to procure and use the millets foods.

Table 2. Steps involved in Value chain analysis

Sl.no	Steps	Purpose
	Planning	
	Preparation	Define the goal, objective, actors/customers of the value chain and team/agencies for analysis
	Mapping the various process, actors, inks between the actors, demand and supply data of the value chains	To organise the data to understand the reality and what are the linkages among actors
	Mapping actors/audiences who are not in the value chain	To ensure role of all actors in the value chain.
	Collecting data from all actors through interview, FGD including current poor actors	To collect and provide data from steps 5-8
	Tract the revenue of poor. Estimation of flow of revenues in the value chain, accrued revenues to the poor. Assessing the factors and returns that inhibit the revenues	To determine how return improve the costs and revenues of the poor in the value chain
Scope prioritises and opportunities		
	Which node in the value chain needs change	To focus on priorities on the changes required on each node drawn from step 1 to 5.
	Evaluate the barriers, options and actor in the value chain node to list the required interventions	Rationalaccumulation of various possible interventions
	Prioritisation of interventions on the basis of their impact and feasibility	To list the details of interventions that most likely to results the desired effect.

Feasibility and planning		
	Prioritizing interventions based on their effectiveness and viability	Packaging of selected interventions on funding and deliver

Michael Porter Value Chain Analysis

A value chain is working to enhance the flow of produces from farm materials to customers (Porter, 1985). The greater value is supplied to the client while managing value chain operations, where each action may be changed to reduce cost and raise value. According to Porter, you could get a competitive edge (Fig. 1). A company's profit margin can be increased with the aid of the Porter value chain. Primary value chain activities and support value chain activities are the two different categories of activity.

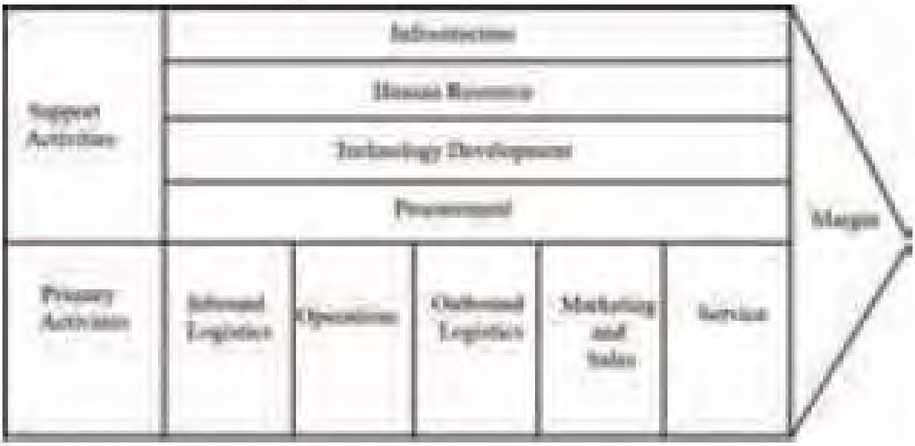

Fig.1. Michael Porter Value Chain Analysis

Primary Activities

Porter's value chain strategy consists of 5 main actions. They are the physical and operational tasks involved in producing commodities. Inbound logistics, operations, outbound logistics, marketing and sales, and service make up the first five categories. Transporting, and receiving raw goods from suppliers, organizing and obtaining supplies are known as inbound logistics. The partnership and transportation agreement between the retailer and the supplier are essential for value creation. The raw ingredients are transformed into finished goods through various operations for creating value to the raw materials. Outbound logistics includes delivering and distributing the finished goods to clients, handling orders, packaging goods, and shipping them. Sales and marketing are procedures used to keep clients informed about the features of the items and to encourage the target market to purchase the products. This entail choosing between many options for price, promotions, and distribution methods. Finally, after-sales services are the actions taken to keep your items' worth high. Service to customers, instruction for installation, maintenance, refunds, and exchanges.

Support Activities

Support activities are management activities and they are meant to support the main value chain operations. There are four types of support activities: procurement, technology development, human resource management, and firm infrastructure. Organizational structure, management, financial planning, everyday operations, and quality control are the infrastructure supporting activity. A company's infrastructure adds value to the business. For instance, the firm's purpose must be achieved through proper preparation. The process of hiring, training, inspiring, rewarding, and keeping a company's personnel is known as human resources management. The values of a firm are totally dependent upon its employees. Managing technological information and developing new technologies are entails of technology development. The firms maintain the technical proficiency to cut down on the expenses, constant eye on research and development, and emerging technologies for successful business. The purchase stage known as procurement of materials for all operations that are required for inbound and outbound operations. This process also includes purchasing marketing supplies for the sales division. The cost of goods and services is decided by procurement, which also has a big impact on the profit margin.

VRIO Framework – Internal Value Chain Analysis

The VRIO methodology is used to evaluate a firm's capabilities and resources. The abbreviation VRIO stands for value, rarity, imitation, and organization. According to Jay Barney, Resources are a company's assets, capacities, organizational procedures, firm characteristics, knowledge, and value chain analysis expertise. The VRIO framework is compatible with strategic analysis such as Porter's five forces analysis and SWOT analysis. Each resource in the internal value chain must be assessed by businesses to identify its value, rarity, uniqueness, and organization and then evaluate each of our strengths to see which one gives us the most competitive advantage. We can identify the assets that have the potential to be core competencies and the assets that are not as important. There are 4 primary criteria or questions in VIRO analysis (Table 3).

Table 3. Four primary criteria or questions in VIRO analysis

Sl. No	Criteria	Question
1	Value	1. Does the business use your resource to put a plan in place to seize opportunities and counter threats? 2. Does it support both revenue growth and expense containment? 3. Does it provide value to customers?
2	Rare	1. Is your resource distinct enough that neither your rivals nor businesses in the same sector own it regularly or could replace it? For instance, no one can have a competitive advantage over the others when everyone in the market uses the same production machinery.
3	Inimitable	1. Can alternative resources be used in its place? Could it be easily acquired or replicated by other businesses? Your resource must cost a lot for others to copy in order to satisfy this requirement.
4	Organize	1. Do you have efficient management structures and methods that enable you to make the most of the resource?

SWOT Analysis

SWOT analysis is used to examine both internal and external elements that have an impact on value chain of the millets. SWOT analysis is can be performed using SWOT Matrix table 4. assists in evaluating the strengths, weaknesses, opportunities, and threats.

Table 4. SWOT Matrix of Value Chain Analysis of Millets

Strength	**Weakness**
1. High nutritional, minerals, 2. Dietary fiber 3. Anti-oxidant rich 4. Drought resistance crop	1. Less attractive 2. Low digestibility 3. Low varieties of foods 4. Non-avalability

Opportunity	Threat
1. More convenience product development 2. Niche market	1. Existing food habits 2. Not interested by young and urban consumers

Gap Analysis

The four gaps such as extension gap, technology gapand technology index are calculated using equations 1, 2 and 3 (Samui et al., 2000). Benefit cost ratio (eqn.4) of each technology is required assess how much value that the technology adds to the value chains.

$$\text{Technology Gap} = \text{Potential yield} - \text{Demonstrated yield} \quad \ldots (1)$$

$$\text{Technology index} = \frac{\text{Potential yield} - \text{Demonstrated yield}}{\text{Potential yield}} \times 100 \quad \ldots (2)$$

$$\text{Extension Gap} = \text{Yield in dmeonstration field} - \text{Yield at farmers practices} \quad \ldots (3)$$

$$\text{Benefit Cost Ratio} = \frac{\text{Net income,kg/hr}}{\text{Cost of cultivation,kg/hr}} \quad \ldots (4)$$

The Cobb-Douglas frontier production function was taken to be the defining specification of the production method used by the pearl millet farmers in Kano State, Nigeria. Numerous empirical studies have employed the Cobb-Douglass frontier production function to determine the impact of factors in the value chain especially on agriculture (Ogundari et al., 2006; Tsue et al., 2013)

$$\ln Y_1 = a_0 + a_1 \ln X_{1i} + a_2 \ln X_{2i} + a_3 \ln X_{3i} + a_4 \ln X_{4i} + +a_5 \ln X_{5i} + a_6 \ln X_{6i} + v_1 - u_i \quad \ldots (5)$$

Where: ln = the natural logarithm,

Yi = Quantity of Pearl millet output (kg),

X1 = Farm Size (hectares),

X2 = Fertilizer (kg),

X3 = Manure (kg),

X4 = Labour (man-days),

X5 = Seeds (kg),

X6 = Agrochemicals (litres),

β0 = Intercept to be estimated

β1 - β6 = Parameters to be estimated,

i = number of farms,

Vi = Stochastic component of error term beyond the control of farmers,

Ui=non-negative random variables assumed to account for technical inefficiency in production process.

Mapping of Value Chain Analysis of Millet

In the millet value chain analysis, there are six major channels (Table.4) involved. Millets producing farmers buy the seed from private/govt seed suppliers, and sell their products to collection agent or nearby dealers, wholesalers. Local dealers and wholesaler add little value to the millet such as drying and cleaning or grading and then supply to retails or processor. Then from the retailers' whole millets goes to consumers. Retailers do pack of whole millets whereas processors process the millets such as grinding, product development and then packing and selling in the market. Many values added products are processed from the millets. mapping of millet value chain analysis is given in the figure 2.

Table 4. Various channels of supply chain of millets

Sl. No	Channel	Stages
	Channel 1	Input Suppliers-Farmers-Local Traders-Wholesalers-Processors-Retailers-Consumers
	Channel 2	Input Suppliers-Farmers-Local Traders-Other states
	Channel 3	Input Suppliers-Farmers-Wholesalers-Retailers-Consumers
	Channel 4	Input Suppliers-Farmers-Local Traders-Wholesalers-Other states
	Channel 5	Input Suppliers-Farmers-Processors-Retailers-Consumers
	Channel 6	Input Suppliers-Farmers-Retailers-Consumers

Fig. 2. Mapping of Millet Value chain

Value Chain During Production

Seed varieties, season, tillage, seed rate, sowing/planting, spacing and manuring, fertilizer application, soil moisture management and conservation, weed management are the basic practices followed during millet production. The monsoon season, or the kharif period, is the period millet is grown commonly. The region where the rainfall is more than 800 mm annually, many millets can be grown in the second season, or as a rabi crop and some part of areas with the correct soil and topography, a small number of millets can even be grown in the third season, during the gloomy winter months. The soil moisture is maintained by precipitating dew.

The agricultural practice of preparing soil through various types of mechanical agitation, such as digging, stirring, and overturning, is known as tillage. Shovel, pick, mattock, hoe, and rake work are some instances of human-powered tilling techniques. Generally ploughing and seed bed preparation are made for millet cultivation. No specific machines are required for tillage of soil to cultivate millets.

Millets have a high level of pest resistance. When designing a mixed crop farm that uses non-pesticide management strategies, this quality is highly helpful. Farms all around the world frequently follow the technique of separating rows of more vulnerable leguminous crops with a few rows of millets.A seed rate of 10 kg ha-1 and 5 kg ha-1 are found to be ideal for drill sowing. Line sowing is advantageous because it promotes excellent weed control and intercropping, line sow plants in an irrigation system with a spacing of 22.5–30 cm between rows and 7.5–10 cm between plants. Maintaining a plant population of 4-5 lakh plants per hectare.

Crop harvesting at the physiologically mature stage is crucial because unexpected rainfall can contaminate grains with pest insects and diseases like grain molds. A timely harvestisensure good grain quality, minimize grain losses, and maximize milling return. Harvesting too early causes many grains to be immature, thin, and low in test weight, which reduces milling efficiency. Too late for harvest: Shattering generates a large amount of grain loss and causes the grain to dry out, which leads to cracking during threshing and breaking of cracked grains during milling.

Good Agricultural practices, organic certification, recommended seed treatment and fertilizer application, nutritional care, cropping pattern are the important factors for increasing value of millets during production.

Value Chain During Processing

Separating the edible portion from the pericarp, grit, and occasionally the germ is the main value chain processing of millet. In contrast to rice or wheat, millet is restricted by its outer rough seed coat, unique flavor, cultural connotations, and scarcity of processed millet products. These are the primary justifications for why rice and wheat eaters are less likely to choose millet dishes. Farmers are paid substantially less for their raw produce (Rs. 15-20/kg) than they are for their processed commodities (Rs. 80-100/kg). Unfortunately, there isn't a practical commercial process for turning colored small millets into white goods (Chapke et al., 2020].

Millets come in a variety of shapes, sizes, and colors, making them challenging to processing and outer husk of millet must be removed to make the millet for consumption. There are various machines such millet thresher, dryer, cleaner, de-stoner, huller, polisher, size grader, colour sorter, gravity separator, and packing polisher developed by TamilNadu Agricultural University, Coimbatore, *University* of *Agricultural* Sciences, Bangalore, GKVK, Bengaluru, Punjab Agricultural University, ICAR-Vivekananda Parvatiya Krishi AnusandhanSansthan, Almora, and manyresearch institutes. 100 kg of unhulled millet grains could provide 65–70 kg of processed grains.

Assessment of technology index indicates the degree of viability of commercially available technologies. The technology index estimated for finger millet ranged from 24.92 to 28.83% for grain yield whereas barnyard millet exhibited 30.14 to 40.05% [Rawat et al., 2019]. According to Thakur et al. [Thakur et al., 2017], the indices for finger, kodo, and tiny millet were 39.63, 27.17, and 70.97% respectively. According to Jat and Gupta [15], the average technology index for pearl millet fodder output was determined to be 69.30%. The technology index was greatest in village Singwara in 2008, at 110.82 percent, and lowest in villages Aluda and Reta in 2011.

Fig. 4 Mapping of Various Quality Knowledge of Actors

Value Chain During Storage

The millet must be dried, cleaned and store it in a aerated place to prevent moisture accrual, mold development, and insect infestation. The moisture content shouldn't be higher than 10-12% to avoid damage. The quantity of seed stored, temperature and relative humidity of the storage godown, type of package materials, duration of the storage are the important factors to considered in value chain during storage. Value of the millets stored in a scientifically constructed storage godown and normal storage at farmers filed varies due to the quality of the millets. So how the improved storage facilities fetches more value to millets to focused (Venkatesh et al., 2016).

For short-term storage, food grains are widely utilized in sacks in farms, cities, and commercial storage facilities. Jute, sisal, indigenous grass, cotton, and other locally accessible materials are used to weave sacks. All crops can be hermetically sealed and stored very effectively in polyethylene storage bags. To obtain the highest level of airtightness and water resistance, regular storage bags are placed within multi-layer polyethylene storage bags as an additional layer of protection (Mutungi et al., 2015).

Value chain during Marketing

Millet is bought and sold in both the public and private sectors in several states. End users must pay more for the processed items as a result of the extensive supply chain of agents, traders, brokers, wholesalers, and millers, which raises millets' prices without providing any value. This high price can only be decreased if Farmer Producer Organizations (FPOs) are in charge of marketing and purchasing and if FPOs are connected to millet business owners. Ragi is purchased from farmers in Odisha at the Minimum Support Price (MSP), and tiny millet is purchased from farmers in Chhattisgarh by the Forest Development Corporation.

Value chain in Consumption

Various tactics are used to boost millets' consumption. Both urban and rural communities participate in large-scale awareness efforts. According to reports, social media platforms are crucial for raising public awareness. To enhance consumption, we must introduce more novel millet products, improve their flavor, and make sure they are reasonably priced. Mapping of Various stakeholders/actors/policies and institutions in the millet value chain (Fig.3).

Fig. 3 Mapping of Various stakeholders/actors/policies and institutions in the

millet value chain

Gap Assessment

The differences between prospective yield and demonstrated yield is explained using technological gap. The average technological gap for grain yield in finger millet and barnyard millet ranged from 5.63 to 7.81 q/ha;and 6.63 to 8.81 qtl/ha over the five years (Rawat et al., 2019). Thakur et al., 2017 found that the average technology gap for finger millet is 9.91 qtl/ha and revealed that the average technological gap in the improved technology of millet cultivation was found to be 9.91 q ha-1, 5.43 q ha-1, and 4.15 q ha-1 in finger, kodo, and tiny millet, respectively. Highest gross returns, net returns and B:C ratio of 44651.30 Rs./ha, 24,300.22 Rs./ha, and 1.30 were observed for barnyard millet under farmers' practices across the years (Rawat et al., 2019). Better package of practices resulted more net return and B: C ratio of Rs. 14153.00 and 1.67 for finger millet, 20449 and 3.15 for kodo millet, and 3766 and 0.67 for tiny millet (Thakur et al., 2017). This might be attributed to increased yields achieved from improved technology vs farmer practices.

Benefits of value chain analysis

Recognizes that the target beneficiaries have fewer economic options than stronger firms, which makes it difficult for them to have the same influence over the "rules of the game" in the value chain. Because of its focus on the market, it has both economic viability and commercial sustainability at its foundation. It is a powerful diagnostic tool that can pinpoint important problems and hurdles for particular target groups and offers a plan of action to improve the situation of the resource-poor.The key rents and entry barriers that determine who in the value chain profits from production are identified. Logic behind a value chain development exercise can be applied to a group of companies, a region, or an entire country even if the original focus is on a single producer group or firm. Beyond a concern for chain efficiency and competitiveness, it is relatively value-free in comparison to the baggage and presumptions one must accept when adopting some other theoretical stance. Value chain analysis can be used as a tool for policy and restructuring to deal with market and governmental failures.

Limitations and Strengths of Millet Value Chain

The following points are emphasized in order to strengthen the millet value chain. Encouraging small and marginal farmers to use sustainable farming techniques such as adaptation of new improved package of practices, more intercropping practices, use of organic fertilizers to increase millets' yield and quality. Ensuring the access to improved seeds, tools, and machinery will help farmers to raise millets' productivity and quality. Value addition to millets and create a variety of millet-based goods, including flour, flakes, and snacks, establish regional processing facilities. Assemble a network of farmers, buyers, and sellers to ensure that millet-based products reach consumers quickly and effectively. Raise consumer awareness of millets' health benefits by promoting their use through a variety of projects and campaigns.Support new millet product development, millet variety enhancement, and the growth of the millet value chain by encouraging research and development.Provide small farmers and other members of the millet value chain, such as millet entrepreneurs, with financial assistance so they can overcome challenges and raise their level of living. The millet value chain can be improved by promote sustainable farming, and raise the income and food security of small farmers by putting these measures into practice.

There are limitations in millet value chains analysis while raising crops, farmers run across a number of difficulties. The majority of the time, these issues prevent farmers from implementing the improved agricultural practices advised by research institutes or organizations; some of these issues are addressed in this section and have also been noted by numerous researchers throughout India in their studies like lack of credit availability, lack of irrigation facilities, labor management, low Availability of improved varieties, high cost of fertilizers, unreliable power Supply, inadequacy of labor at low cost, low availability of improved varieties, high cost of fertilizers. The most significant problem for farmers is wild animal damage (86.67%), which causes significant crop losses. This is followed by a lack of high yielding varieties (81.17%), prompt availability of high-quality seeds (78.33%), marketing (76.33%), a lack of technical knowledge (74.78%), and the use of higher seed rates (71.50%) (Rawat et al., 2019). Farmers also highlighted diseases such grain smut in barnyard millet and Cercospora leaf spot in finger millet as a major constraint on grain output (41.67%), followed by insects (21.17%).

Conclusion

Milletsisonly be grown by small farmers in hilly areas and dryland plains. They are among the poorest farm holds in rural India. A large portion of the population may potentially benefit from improved nutrition like millet foods. So, in this chapter, various methods used to assess the value chain of millets was discussed. Technology gap, extension gap, storage gap are few important gaps found in the millet production and processing. Purchase of millets through PDS system must encouraged to consume more millet food by large group of consumers. Through education and promotion, the lack of knowledge about millets and their health benefits can be overcome. Millets' improved accessibility to consumers and increased market availability can promote consumption. Consumption can be increased by addressing affordability through government subsidies or market actions. Indian millet exports are opening doors for businesspeople.Because they are a nutritious alternative, small millets can profit from having more purchasing power. Unfortunately, because of value chain stagnation, the market is unable to take advantage of this business opportunity. The Millets value chain mapping is helpful for identifying the product and information flows, locating key players, and displaying the various roles and links between participating parties. Smallholders, associations, bigger businesses, and governmental organizations must collaborate to create a viable value chain.

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References

Adekunle, A., Lyew, D., Orsat, V., Raghavan, V. (2018). Helping Agribusinesses—Small Millets Value Chain—To Grow in India. Agriculture. 8:3.

Bhat, BV., Ratnavathi, CV., Rao, BD., Chapke, R., Swarna, R., Padmaja, PG., Prasad, GS., Das, IK., Aruna, C., Venkateswarlu, R., Kannababu, N., Sooganna, Rao, SS., Singode, A., Talwar, HS., Babu, KS., Tonapi, VA. (2016). Manual on Good Agricultural Practices in Millets. ICAR-Indian Institute of Millets Research (IIMR) Rajendranagar, Hyderabad - 500 030, India.

Chapke RR, Shyam Prasad G, Das IK, Hariprasanna K, Singode A, Kanthi Sri BS and Tonapi VA. (2020). Latest millet production and processing technologies. Booklet, ICAR-Indian Institute of Millets Research, Hyderabad 500 030, India: 82p. (ISBN: 81-89335-90-X).

Jat, BL., Gupta, JK. (2014). Pearl millet demonstration for fodder yield gap analysis in dausa district of Rajasthan.Forage Research. 40 (1) : 44-48.

Kaplinsky, R., Morris, M. (2000). A handbook for value chain research. University of Sussex, Institute of Development Studies Brighton.113.

Mutungi, C., Affognon, HD., Njoroge, AW., Manono, J., Baributsa, D., Murdock, LL. (2015). Triple-layer plastic bags protect dry common beans (Phaseolus vulgaris) against damage by Acanthoscelides obtectus (Coleoptera: Chrysomelidae) during storage. Journal of Economic Entomology. 108(5), 2479–2488.

Ogundari, K., Ojo, S. O., & Brümmer, B. (2006). Productivity potential and technical efficiency of aquaculture production in alleviating poverty: Empirical evidence from Nigeria.

Osterwalder, A., Pigneur, Y., Tucci, CL. (2005). Clarifying business models: Origins, present, and future of the concept. Communications of the Association for Information Systems. 16(1), 1.

Padulosi, S., Mal, B., King, OI., Gotor, E. (2015). Minor Millets as a Central Element for Sustainably Enhanced Incomes, Empowerment, and Nutrition in Rural India. Sustainability. 7:7, 8904–8933.

Porter, M. E. (1985). Competitive advantage: creating and sustaining superior performance. New York: FreePress, 43, 214.

Rawat, L., Prasad, S., Bisht, T. S., Naithani, DC., Tiwari, A. (2019). An impact assessment of front line demonstrations on yield and economics of finger millet and barnyard millet under rainfed conditions of Uttarakhand. International Journal of Pure and Applied Bioscience. 7(2), 408–414.

Samui, SK., Maitra, S., Roy, DK., Mandal, AK., Saha, D. (2000). Evaluation of front line demonstration on groundnut. Journal of the Indian Society Costal Agricultural Research, 18(2), 180–183.

Tapas Chandra Roy. (2023). No Millet Value Chain Analysis for the Millet Entrepreneurs. Millet Advisor. https://milletadvisor.com/millet-value-chain-analysis/

Thakur, AK., Kumar, P., Yadav, SC. (2017). Impact of Front Line Demostration on the yield and economics of small millet on Bastar district of Chhattisgarh, India. International Journal of Current Microbiology and Applied Science. 6(9), 1489–1497.

Tsue, PT., Lawal, WL., Ayuba, VO. (2013). Productivity and technical efficiency of catfish farmers in Benue State, Nigeria.Advanced Journal of Agricultural Research.1(002), pp. 020-025.

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