Journal of Cereal Research

Volume 15 (2): 157-169

Homepage: http://epubs.icar.org.in/ejournal/index.php/JWR

Review Article

The Potential of Millet Grains: A Comprehensive Review of Nutritional Value, Processing Technologies, and Future Prospects for Food Security and Health Promotion

Preeti Dixit and R. Ravichandran

Department of Humanities Science Education and Research, PSS Central Institute of Vocational Education (NCERT), Shyamla Hills, Bhopal – 462 002, India.

Article history:
Received: 24 Jul., 2023
Revised: 28 Sep., 2023
Accepted: 12 Oct., 2023

Citation:
Dixit P and R Ravichandran. The Potential of Millet Grains: A Comprehensive Review of Nutritional Value, Processing Technologies, and Future Prospects for Food Security and Health Promotion. *Journal of Cereal Research* ***15 (2):*** *157-169. http://doi.org/10.25174/2582-2675/2023/136711*

****Corresponding author:***
E-mail: preetidixit07@yahoo.com

Abstract

Millets, are classified as major and minor/small millets, and considered extremely nutritious when compared to staples such as wheat and rice. Nutri-Cereals, Shree Anna, miracle grains, and superfoods are all names for them. Millets thrive in arid and semi-arid tropics dry land agro-ecologies. They are high in carbohydrates, proteins, dietary fiber, healthy fats, minerals (calcium, potassium, magnesium, iron, manganese, zinc), and B vitamins. Bioactive phytochemicals found in millets include feraxans, lignans, -glucan, inulin, resistant starch, sterols, and phenolic compounds. It is critical to rekindle interest in millets as nutritious foods in order to improve food and nutritional security and reduce malnutrition. Major millet crops include Jowar or Sorghum, bajra or pearl millet, mandua/ragi or finger millet, and many small millets as kangni or foxtail millet, kutki or sama or little millet, kodo millet, jhangora or sawan or barnyard millet, cheena or proso millet, and korale or brown top millet. These millets have historically played an significantly role in the diet of the people across the world. India has the largest area under millet cultivation, followed by Niger. Millets are cultivated on 312.44 lakh hectares globally, with India leading in production, followed by Niger. Uzbekistan has the highest millet yield per hectare, followed by Switzerland. The flexibility of millets to adapt to shorter growing seasons, a wide range of temperatures, moisture regimes, and input conditions makes them valuable. Since they increase the conversion of carbon dioxide into oxygen, they are advantageous as C4 crops. Millets have the ability to support food and nutritional security by offering food and feed to smallholder farmers in drylands. The research scope outlined in the review paper provides valuable recommendations for advancing millet-based agriculture, expanding the range of food options, and achieving comprehensive food and nutritional security in a society devoid of hunger.

Key words: Millet Grains; Nutritional Value; Processing Technologies; Food Security; Health Promotion; Future Prospects.

1. Introduction

Millets, a group of small-seeded grasses, have served as a staple food source for both humans and livestock for thousands of years. They are cultivated extensively in Africa, Asia, and select regions of Europe and America. The various types of millet include pearl millet, finger millet, foxtail millet, sorghum millet, and proso millet. These grains exhibit exceptional nutritional qualities, encompassing high-quality protein, vitamins, minerals, bioactive compounds, and dietary fiber. Additionally, millets are rich in antioxidants, rendering numerous health benefits such as enhanced digestion, reduced risk of cardiovascular ailments, and improved blood sugar management. Furthermore, millets, being gluten-free, represent a commendable alternative to wheat for individuals afflicted with celiac disease or gluten intolerance. The versatility of millet grains allows for their incorporation into diverse culinary preparations, including porridge, roti, bread, cookies, desserts, sweets, snacks, and noodles. Despite their remarkable health advantages and culinary adaptability, millets remain underutilized in various parts of the world. Nevertheless, there is an emerging interest in promoting millets as sustainable and nutritious food sources, particularly in regions affected by climate change and other environmental factors adversely impacting crop productivity.

The objectives of this review paper is to present a comprehensive synthesis of the diverse types of millet grains, elucidating their nutritional composition in terms of macronutrients and micronutrients, and exploring the potential health benefits associated with their consumption. The review also critically assesses various processing techniques employed for the preparation of millet grains, examining their influence on nutrient composition and bioavailability. Moreover, this review delves into the future prospects of millet as a viable food source for enhancing food security and advancing public health, with particular attention to its role in sustainable agriculture and the capacity of millet-based products to cater to the dietary requirements of vulnerable populations.

2. Types of Millets & their Nutritional Value:

Pearl millet (*Bajra*): Pearl millet, a prominent variety of millet extensively cultivated in India, stands out for its notable nutritional composition. It boasts a significant protein content, alongside rich dietary fiber and essential minerals like iron, calcium, and magnesium. Notably, studies have demonstrated that pearl millet exhibits substantial levels of resistant starch, soluble and insoluble dietary fibers, minerals, and antioxidants (Ragaee et al., 2006). Compositional analysis reveals that pearl millet comprises approximately 92.5% dry matter, 2.1% ash, 2.8% crude fiber, 7.8% crude fat, 13.6% crude protein, and 63.2% starch (Ali et al., 2003). This millet variety is commonly employed in the preparation of flatbreads such as roti and bhakri, as well as porridge and khichdi, owing to its culinary versatility and nutritive value.

Finger millet (*Ragi*): Finger millet, a widely consumed millet variant in India, is characterized by its popularity and nutritional significance. It boasts elevated levels of protein, calcium, and dietary fiber, rendering it a valuable dietary component. Finger millet finds common usage in the preparation of porridge, dosa, and idli, showcasing its culinary versatility. In terms of composition, finger millet contains approximately 5-8% protein, 65-75% carbohydrates, 15-20% dietary fiber, and 2.5-3.5% minerals (Chethan and Malleshi, 2007). Notably, among cereals, finger millet displays the highest calcium content, measuring 344 mg/100g. Additionally, finger millet exhibits notable quantities of phytates (0.48g/100g), polyphenols, and tannins (0.61%) (Thompson, 1993). Renowned for its distinctive nutty flavor, finger millet finds application in various traditional Indian sweets and snacks.

Foxtail millet (*Kangni/Kakum*): Foxtail millet, characterized by its small, yellowish grains, represents a nutritional powerhouse abundant in protein, fiber, and essential minerals like iron and zinc. Its versatility in culinary applications is evident as it is commonly utilized in the preparation of porridge, pulao, and upma. The mild, slightly sweet flavor of foxtail millet further contributes to its widespread popularity as a preferred ingredient in a diverse range of dishes.

Little millet (*Kutki*): Little millet, characterized by its small and round grains, is renowned for its notable nutritional profile, encompassing high levels of protein, fiber, and essential minerals like iron, calcium, and potassium. Its culinary versatility is evident as it finds common usage in the preparation of porridge, pulao, and upma. The mild, slightly nutty flavor of little millet further enhances its appeal, making it a versatile ingredient suitable for a variety of dishes.

Kodo millet (*Kodo*): Kodo millet, characterized by its small and red grains, exhibits a rich nutritional composition, including significant levels of protein, fiber, and essential minerals such as iron and calcium. Notably, kodo millet, along with little millet, has been identified as a source of dietary fiber, constituting approximately 37% to 38% of its composition. Previously regarded as an "anti-nutrient," dietary fiber is now recognized as a nutraceutical and stands out as the highest among cereals (Hadimani and Malleshi, 1993; Hegde and Chandra, 2005). In culinary applications, kodo millet finds widespread use in the preparation of porridge, dosa, and idli. Its slightly sweet flavor and chewy texture contribute to its popularity as a favored ingredient in various dishes.

Barnyard millet (*Jhangora/Kuthiravali*): Barnyard millet, characterized by its small and white grains, stands out for its significant nutritional composition, encompassing high levels of protein, fiber, and essential minerals such as iron and phosphorus. Notably, barnyard millet holds the distinction of being the richest source of crude fiber and iron. Moreover, barnyard millet grains possess functional constituents such as γ-amino butyric acid (GABA) and β-glucan, which serve as antioxidants and aid in reducing blood lipid levels (Sathish, 2018). In culinary applications, barnyard millet finds common usage in the preparation of porridge, upma, and khichdi. Its mild, slightly sweet flavor adds to its appeal, making it a preferred rice substitute in various dishes.

Proso millet (*Chena/Panivaragu*): Proso millet, characterized by its small and yellowish grains, boasts a significant nutritional profile, including notable levels of protein, fiber, and essential minerals such as iron and magnesium. In fact, among all millets, proso millet contains the highest amount of proteins, reaching 12.5% (FAO, 1995). It finds common usage in the preparation of dishes such as porridge, pulao, and upma. The mild, slightly nutty flavor of proso millet adds to its versatility, making it a favored ingredient suitable for various culinary creations.

Sorghum (*Jowar/Cholam*): Sorghum, known for its versatility, is a grain with a notable nutritional composition, including high levels of protein, fiber, and essential minerals such as iron and potassium. With a moisture content of 11.9%, sorghum offers approximately 10.4% protein and a lower fat content of 1.9%. The fiber and mineral content of grain sorghum are similar, averaging at 1.6% (Gopalan et al., 1996). Sorghum serves as a good source of energy, providing about 349 Kcal and contributing to 72.6% of carbohydrates. The primary carbohydrate in sorghum is starch, accompanied by simple sugars, cellulose, and hemicellulose. The amylose content of sorghum starch can vary but typically falls within a range of 21.28% (Gopalan et al., 1996).

Additionally, sorghum is rich in dietary fiber, with a content of 14.3%. In terms of minerals, sorghum offers 25 mg of calcium, 222 mg of phosphorus, and 4.1 mg of iron per 100 g of the edible portion (Hosmani and Chittapur, 1997). In culinary applications, sorghum is commonly utilized to create flatbreads like roti and bhakri, as well as porridge and khichdi. Its slightly sweet flavor and chewy texture contribute to its popularity as a versatile ingredient in a variety of dishes.

3. Health Benefits of Millet Consumption:

Millet grains are known for their exceptional nutritional profile and have been associated with various health benefits when incorporated into a well-balanced diet. These grains serve as excellent sources of protein, dietary fiber, vitamins, and minerals, including iron, magnesium, and phosphorus. Epidemiological studies have demonstrated the positive effects of millet consumption on reducing the risk of heart disease, diabetes, and certain types of cancer. Furthermore, millets have been found to support digestive health, promote detoxification, enhance respiratory immunity, increase energy levels, and improve the muscular and neural systems. Evidence suggests that millets possess protective properties against degenerative diseases such as metabolic syndrome and Parkinson's disease (Manach et al., 2005; Scalbert et al., 2005; Chandrasekara and Shahidi, 2012).

Additionally, research has indicated that finger millet and proso millet can significantly reduce serum triglyceride levels in comparison to diets consisting of white rice and sorghum in rats. These findings suggest a potential cardiovascular disease prevention mechanism through the reduction of plasma triglycerides in hyperlipidemic rats (Lee et al., 2010).

Furthermore, millet is characterized by its low glycemic index, meaning it elicits a slower increase in blood sugar levels upon consumption. This attribute makes millet a favorable choice for individuals with diabetes or those aiming to manage their blood sugar levels. Sorghum, in particular, contains notable amounts of slow digestible starch (SDS), which prolongs the digestion and absorption of carbohydrates in the intestines. This functional property of SDS is beneficial for dietary management and may have implications for metabolic disorders such as diabetes and hyperlipidemia (Asp, 1994; Wursch, 1997). The dietary fiber, magnesium, vitamin E, phenolic compounds, and tannins found in sorghum contribute to reducing the risk of diabetes by moderating the sudden surge of blood glucose and insulin levels (Montonen et al., 2003).

Millet is also a good source of antioxidants, such as phenolic acids, avenanthramides, flavonoids, lignans, and phytosterols, which are compounds that protect the body from damage caused by free radicals and oxidative stress thus offers numerous health benefits (Miller et al., 2001; Edge et al., 2005). Kodo millet, finger millet, little millet, foxtail millet, barnyard millet, and sorghum were screened for free radical quenching of 1,1, diphenyl-2-picrylhydrazyl (DPPH) by electron spin resonance (Hegde and Chandra, 2005). Furthermore, finger millet extracts were found to have a potent radical-scavenging activity that is higher than those of wheat, rice, and other species of millet (Dykes and Rooney, 2006). In addition, defatted foxtail millet protein hydrolysates also exhibited antioxidant potency (Mohamed et al., 2012). Thus, millets may serve as a natural source of antioxidants in food applications and as a nutraceuticals and functional food ingredient in health promotion and disease risk reduction

In addition to its nutritional value, millet is a gluten-free grain, making it a suitable alternative for people with gluten intolerance or celiac disease. Sorghum products could not modify the level of anti-transglutaminase antibodies after prolonged consumption (Carolina et al., 2007).

Weight management: Millets possess a favorable nutritional composition characterized by low caloric content and high fiber content, which contribute to promoting weight loss and mitigating the risk of obesity.

Bone health: Millets serve as a noteworthy source of essential minerals such as calcium, magnesium, and phosphorus, which are vital for optimal bone growth and development (Adebayo et al., 2010; Birania et al., 2020). Notably, a randomized controlled trial investigated the impact of biofortified pearl millet, a millet variant enriched with elevated levels of iron and zinc, on the micronutrient status of young children. The study demonstrated that the consumption of biofortified pearl millet significantly improved the iron and zinc status of children compared to standard pearl millet. As adequate intake of these minerals is imperative for maintaining optimal bone health, this research suggests that millets could play a beneficial role in enhancing bone health through their mineral composition (Kodkany et al., 2013). Thus it has been proved that the consumption of millets, with their diverse array of nutritional components, has been associated with numerous health benefits, including cardiovascular protection, diabetes management, and risk reduction for various diseases. These findings highlight the potential of millet-based diets in promoting overall health and well-being.

4. Comparative Analysis of Millet Grains with other Staple Grains:

Millet grains exhibit a distinctive nutritional profile that distinguishes them from other staple grains, including rice, wheat, and corn. Millet stands out as a noteworthy source of protein, dietary fiber, vitamins, and minerals, encompassing iron, zinc, and magnesium.

In comparison to rice, millet showcases elevated levels of protein and dietary fiber, coupled with a lower glycemic index, thereby mitigating the likelihood of blood sugar spikes. Moreover, millet presents commendable antioxidant properties, which contribute to safeguarding against chronic ailments.

Contrasted with wheat, millet possesses the advantage of being gluten-free, rendering it a suitable substitute for individuals with gluten intolerance or celiac disease. Additionally, millet boasts a lower glycemic index than wheat, rendering it a favorable choice for individuals with diabetes or those seeking to regulate blood sugar levels.

In relation to corn, millet exhibits heightened quantities of protein, dietary fiber, and essential amino acids, pivotal for tissue development and repair in the body. Millet also serves as a noteworthy source of antioxidants and minerals, including iron and magnesium.

Millet grains provide a nutrient-dense alternative to conventional staple grains, making them a valuable inclusion in a well-balanced and healthful diet. Epidemiological studies have demonstrated that regular consumption of whole grain cereals and their derivatives offers protection against diabetes mellitus, gastrointestinal disorders, and cardiovascular risks (McKeown, 2002). By consuming millets in their whole grain form, individuals can avail themselves of concentrated essential nutrients, such as dietary fiber, minerals, phenolics, and vitamins found within the outer layer or seed coat of the grain, thereby reaping their nutritional and health benefits (Antony et al., 1996).

5. Processing Technologies for Millet Grains

The initial processing of millet grains is of paramount importance in order to render them suitable for consumption and enhance their quality and desirability among consumers. While sorghum, pearl millet, and finger millet are classified as naked grains due to the natural separation of their glumes during harvesting, certain traditional varieties may still retain glumes that can be gently eliminated using a cereal pearler. Conversely, the processing of Little, Proso, Kodo, Barnyard, Browntop, and Foxtail millets is more intricate due to the presence of inedible husks, necessitating their removal during primary processing, alongside de-branning to the desired degree. The removal of husks for Barnyard, Little, Browntop, and Kodo millets typically entails multiple stages, while Foxtail and Proso millets can usually be dehusked in a single stage. Millet and other coarse grains commonly undergo dehulling and various treatments to improve their sensory and edible quality (Liu et al., 2012).

The primary and secondary processing methods employed for millet grains are as follows:

Cleaning: Millet grains undergo an initial cleaning process to eliminate impurities such as stones, sand, or dust. This can be achieved manually through handpicking or by utilizing a winnowing basket to separate the grains from undesirable debris.

Decortication: Millets are subjected to decortication to enhance their edible and sensory properties and improve the visual appeal of resulting food products. This procedure involves the removal of the outer layer, referred to as the hull or husk. Decortication can be carried out using traditional implements such as a mortar and pestle or a small millstone, which crack the hull and facilitate its separation from the grain. However, the decortication process for certain millet grains, such as finger millet, presents challenges due to their smaller size compared to cereals.

Milling/grinding and sieving: Following decortication, millet grains are milled to eliminate the outer husk and reveal the nutritive inner kernel. This can be accomplished through traditional grinding techniques employing stone or metal grinders, as well as modern machinery such as dehullers and pearlers. The resulting flour can be utilized in the preparation of diverse food products such as porridges, cakes, and breads.

Germination or malting: Germination or malting involves immersing millet grains in water for a specific period, typically lasting 8 to 12 hours. Subsequently, the grains are drained and allowed to sprout for several days, activating enzymes that break down complex carbohydrates into simpler sugars. This process also enhances the bioavailability of vitamins and minerals, thereby augmenting the overall nutritional value of the grains. Once sprouted, the grains are typically dried and roasted to produce malt, which finds application in various food products such as bread, beer, and porridge. The roasting process imparts distinctive flavors and aromas that contribute to the sensory attributes of the final product.

Fermentation: Fermentation is a traditional processing method employed to enhance the nutritional quality and digestibility of millet products. It involves the enzymatic breakdown of complex carbohydrates by microorganisms or enzymatic hydrolysis. Fermentation can be initiated through the addition of yeast or by employing a sourdough starter derived from previous batches of fermented millet. Enzymatic hydrolysis, on the other hand, employs specific enzymes such as alpha-amylase and beta-glucanase to facilitate the breakdown of complex carbohydrates into simpler sugars. Fermented millet products encompass a range of offerings including porridges, sourdough bread, and alcoholic beverages like beer or wine.

Popping or puffing: The process of popping or puffing involves subjecting millet grains to high temperatures, typically ranging from 180-200°C, for a brief duration. The sudden application of heat causes the moisture contained within the grains to rapidly vaporize, resulting in a rapid expansion of the grain. This expansion causes the grain to puff up, resulting in a light and crispy texture.

Cooking: Millet grains can be cooked using various methods such as steaming, roasting, or frying. The specific cooking time and technique depend on the particular type of millet being utilized. Millet grains can be cooked in a manner similar to rice or boiled to produce porridges. The cooked grains can be consumed as is or combined with other ingredients such as vegetables, spices, or meat.

These traditional processing methods for millet grains have been practiced for centuries and continue to be employed in various regions of the world. However, modern processing technologies such as milling machines, hullers, and extruders have also been developed to enhance efficiency and productivity.

Extrusion: The extrusion process involves blending millet flour or whole grains with water and other ingredients such as salt, sugar, and flavorings. The mixture is then fed into an extruder, a machine that employs high pressure and temperature to cook the mixture and shape it into a specific form. During extrusion, the millet mixture undergoes initial cooking at elevated temperatures (typically ranging from 120-200°C) and high pressure within a barrel-like chamber. This causes the mixture to expand and cook, resulting in a gel-like consistency. Subsequently, the mixture is forced through a die, which imparts the desired shape, such as flakes, shapes, or noodles. Extrusion is a high-temperature, high-pressure process that can be utilized to manufacture millet-based snacks, breakfast cereals, and pasta. The application of extrusion technology enhances the texture, flavor, and shelf-life of millet products.

Fortification: Fortification can be accomplished through various methods, including premix fortification, bio-fortification, point-of-use fortification, and double fortification. These approaches aid in elevating the levels of essential micronutrients such as iron, zinc, and vitamin A in millets, which are often deficient in the diets of individuals reliant on millets as a staple food. The fortification of millets contributes to the improvement of nutritional status among vulnerable populations and the reduction of nutrient deficiencies.

Baking, flaking, expanded millets, instant/convenience foods, and other similar technologies are examples of secondary processing. Through the utilization of these technologies, a range of millet-based ready-to-eat (RTE) foods, such as puffs, flakes, muesli, extruded snacks, cookies, and murukus, as well as ready-to-cook (RTC) foods like vermicelli, pasta, millet semolina (medium, fine & coarse), instant mixes, and millet-plus-milk-based beverages have been developed. These processing technologies have enhanced the taste, convenience, and nutritional quality of millet products.

6. Impact of Processing Techniques on the Nutritional Composition of Millet Grains:

The nutritional value of millet grains can be influenced by processing techniques such as milling, cooking, fermentation, and sprouting.

Milling involves removing the outer layer (bran) of the millet grain. This results in a loss of dietary fiber, vitamins, and minerals. However, milling also improves the digestibility and bioavailability of nutrients, especially the protein and starch.

Germination can increase the digestibility and availability of protein and minerals in millet grains. Germinated or malted millets have been shown to have higher levels of antioxidants, amino acids, and vitamins compared to non-germinated millets. They are also easier to digest, as the germination process breaks down the phytic acid and other anti-nutrients present in the grains. (Oghbaei & Prakash, 2016; Jood & Kapoor, 2016; Ndolo et al., 2012). The malting of pearl millet (24 h soaking, followed by 18 h germination) significantly enhanced the protein (Morah and Etukudo, 2017).

Fermentation helps to improve the nutritional value of millet by increasing the levels of vitamins, minerals, and amino acids. Fermentation can also reduce the levels of anti-nutrients like phytic acid, making the minerals in millet more available for absorption. Sprouting millet grains involves soaking the grains in water until they germinate. This can increase the levels of certain nutrients, including vitamin C and some B vitamins.

Studies have shown that fermentation and enzymatic hydrolyzation can both be effective methods of processing millets to improve their nutritional quality and digestibility. Fermentation of millets using lactic acid bacteria increased the levels of protein, fiber, and vitamins in the grains, while reducing the levels of anti-nutrients such as phytic acid (Kumar et al., 2018). Similarly, enzymatic hydrolyzation of millets using alpha-amylase and beta-glucanase improved the solubility and digestibility of the carbohydrates in the grains (Prakash et. al., 2017).

The puffing or popping of kodo millet increased the protein concentration from 7.92 to 8.12% (Jaybhaye, et. al., 2014)

Cooking millet grains can increase their digestibility and improve their nutritional value. Boiling or steaming can help to break down the starch and reduce the levels of anti-nutrients such as phytic acid, which can reduce the absorption of minerals like iron and zinc.

Processing techniques can have both positive and negative effects on the nutritional composition of millet grains. While certain methods may lead to nutrient loss, others can enhance digestibility and bioavailability. Consequently, it is crucial to consider the specific processing techniques employed and their impact on the nutritional value of millet grains when evaluating their role in a healthy diet.

7. Challenges and Opportunities for Millet Processing Technologies:

Millets have garnered global recognition as an esteemed and sustainable food option, owing to their remarkable nutritional value characterized by high protein, fiber, mineral, and vitamin content. They possess numerous health benefits that contribute to overall well-being. Unfortunately, millet production and consumption have experienced a notable decline over the past few decades. This decline can be attributed to the preference for more commercially viable crops, insufficient investment in millet research and development, and evolving consumer preferences. Furthermore, the millet processing industry confronts a range of challenges that impede the efficiency and quality of millet processing. Some key challenges faced by millet processing technologies include:

Small size of the millets grain: Millet grains are small in size, which can make them difficult to handle during processing and process millets using traditional processing methods, such as milling and polishing, which were developed for larger grains such as rice and wheat. Stone and plate milling have resulted in lower yields and poor quality flour due to the small size and hardness of millet grains. Modern milling techniques, such as pin milling and air classification, have produced higher yields of better quality flour. Chimmad and colleagues (2017) found that roller milling and jet milling were more effective at producing higher yields of pearl millet flour than traditional milling methods. However, further research is required to develop and optimize processing technologies that can efficiently process millets into value-added products.

Hard seed coat: Millet grains have a hard seed coat that can be difficult to remove. This can make it challenging to produce high-quality millet flour and other processed products. The hardness of the seed coat can also vary depending on the millet variety. Finger millet is known to have the hardest seed coat. Abrasion-based milling methods, such as stone milling and abrasive decortication, are effective in removing the seed coat but have lower milling yields compared to roller milling. In this scenario further research is needed to optimize millet processing methods and reduce the impact of the hard seed coat on milling efficiency.

Low starch content: Millet grains have a relatively low starch content compared to other grains like wheat and rice. This can make it challenging as it affects the processing characteristics and functional properties of the millets such as gelatinization, viscosity, and texture of millet-based products. Millets with low starch content include finger millet, pearl millet, and foxtail millet, while proso millet and sorghum have comparatively higher starch content. To overcome this challenge, blending of millets with other cereals or legumes that have higher starch content, using modified starches, and utilizing processing methods that improve the gelatinization and digestibility of the starch present in millets can be done. These methods include roasting, popping, and extrusion, which can increase the starch digestibility and improve the overall quality of millet-based products.

Lack of processing equipment and machinery and low yields: One of the main challenges in millet processing is the lack of appropriate infrastructure and equipment. Traditional processing methods may be labor-intensive, time-consuming, and less efficient. There is a need for modern processing technologies that can handle large volumes of millet grains efficiently and effectively. Considering the current situation, it can be said that the effectiveness of the machinery now in use is minimal; only 70–80% of the grain is retrieved, and the remainder is broken or unhulled grain. Due to variations in size, shape, and husk content, one type of dehuller unit is not suitable for all millet types. Husk separation is time-consuming and results in spillage and mixing with the final hulled product. The efficiency of millet dehulling is significantly dependent on impeller speed, necessitating equipment with variable speeds. While gelatinization of starch via hydrothermal treatment, extrusion, and other methods is employed to diversify value addition, creating 100% millet products such as bread remains difficult due to the lack of gluten.

Quality control and standardization: Ensuring consistent quality and standardization of millet products is another challenge. Variability in grain quality, contamination, and inconsistent processing methods can affect the nutritional value, taste, and safety of millet products. Implementing quality control measures, setting standards for millet processing, and establishing certification systems can help ensure the production of high-quality millet products. This includes regular testing, monitoring, and adherence to food safety regulations.

Limited knowledge and awareness: Despite their nutritional benefits, millets are often underutilized and underappreciated. Limited awareness and knowledge about millet grains, their health benefits, and culinary versatility pose a challenge in promoting their consumption and market growth. Conducting awareness campaigns, educational programs, and marketing initiatives to highlight the nutritional value, sustainability, and versatility of millets can help create consumer demand and drive market growth. Collaboration with government agencies, nutritionists, chefs, and food industry stakeholders can play a vital role in promoting millet consumption.

Limited access to credit and markets: Small-scale farmers who grow millets often have limited access to credit and markets, making it difficult for them to invest in production and improve their livelihoods. Millets face stiff competition from other crops, particularly those that are more commercially viable. Cereals such as rice and wheat are available at incentivized prices through public-funded feeding and nutritional programs, making them more accessible than millets. Research efforts to improve millet cultivation have also been inadequate compared to fine cereals. Lower profitability and lack of commercialization, due to lower yields and declining prices, have further affected the growth of millets. The slow pace of outreach to promote millets through various institutions and government programs in past years has led to a lack of awareness about the importance of millets.

Addressing these challenges will require a coordinated effort by governments, the private sector, and civil society organizations to promote millets as a viable crop and increase their availability and consumption

Opportunities:

After reviewing the major challenges faced by the millet processing sector, it is important to also explore the numerous opportunities that the millet processing sector has witnessed in recent years. Millets, with their remarkable nutritional value, sustainable cultivation practices, and versatile applications, have gained recognition as a promising food option globally. In current scenario, several opportunities have emerged that can contribute to the growth and expansion of the millet processing industry. The following are some of the potential areas for growth and development:

Increasing demand for healthy and sustainable food: There is a growing consumer demand for healthy, sustainable, and plant-based food options. Millets, with their high protein, fiber, mineral, and vitamin content, perfectly align with these preferences. This presents an opportunity for the millet processing sector to develop a wide range of innovative and value-added products that cater to health-conscious consumers.

Nutritional value and product diversification: Millet intake has typically been limited to basic forms such as whole grains or flour. However, there is an intriguing opportunity to investigate value addition and product diversification in response to changing consumer tastes and expectations. Innovative millet-based products, such as ready-to-eat snacks, breakfast cereals, bakery products, pasta, and beverages, can expand the market for millets and increase their consumption by harnessing the millet's inherent nutritional richness, gluten-free nature, and diverse array of bioactive components. This opens the door to the development and commercialization of innovative functional meals that explicitly address health issues such as malnutrition, celiac disease, diabetes, cardiovascular disease, and others. Notably, the global demand for gluten-free food options is increasing, and millets, with their gluten-free properties and great nutritional profile, present an exceptional opportunity to address this demand effectively. Products that are convenient, appealing, and match consumer expectations in terms of flavour, texture, and nutritional content should be the focus of research and development activities.

Export potential: Millets have significant export potential, particularly to regions with a growing demand for gluten-free and nutritious food products. This presents an opportunity for Indian millet processors to tap into the global market and expand their reach. Developing effective distribution channels, ensuring quality control, and complying with international food regulations are key factors that can enable successful market penetration. Millets have a considerable export potential, particularly in areas where there is a rising demand for food products that are both nutrient-dense and gluten-free. This offers a chance for millet processors across the globe to enter the international market and broaden their clientele. Developing effective distribution channels, guaranteeing quality control, and adhering to international food rules are critical considerations in achieving market penetration.

Drought resistance: Millet is a highly drought-resistant crop and require less water and fertilizer compared to other cereal crops such as wheat and rice. As a result, millet cultivation can help conserve water resources and reduce greenhouse gas emissions. The cost of cultivating millets is comparatively lower that the rice and wheat which makes it a valuable crop for farmers in arid and semi-arid regions. Thus, millet processing technologies have the potential to support sustainable agriculture and food security.

Innovation: Millet processing technologies are constantly evolving, with new procedures and equipment being produced on a continuous basis. For the identification of novel processing technologies and the development of novel products that adapt to changing consumer preferences and expectations, research and development activities are required. This will aid in increasing the efficiency and potential of the millet processing sector. This gives a unique opportunity for businesses and entrepreneurs to create new products and processes that will add value to the millet value chain.

Collaboration and exchange of best practices: Collaboration among different stakeholders, including as farmers, researchers, government agencies, and industry professionals, can greatly contribute to the expansion of the millet processing sector. Sharing best practises, collaborating on research projects, and exchanging knowledge can encourage creativity, help solve problems, and hasten the creation of new goods and processing methods.

Policy Support and Investment: Government assistance and policies are critical in promoting the expansion of the millet processing business. Encouragement of infrastructure investment, financial incentives, and the implementation of favourable rules can help firms prosper. Policy efforts that support millet cultivation, processing, and consumption can help farmers' livelihoods and the sector's overall development.

In upcoming years, the millet processing industry is anticipated to expand and grow. With increased consumer demand for healthy, sustainable foods, opportunities for product diversification, access to global markets, technological advancements, collaboration, and governmental support, the industry may reach its full long-term potential. With further investment and innovation, the millet processing industry can contribute to diversifying and strengthening the food security system by delivering healthy and sustainable food options to consumers globally.

8. International Year of Millets-2023 for Advancing Millet Cultivation, Consumption, and Economic Value:

The International Year of Millets (IYM) has been launched by the Food and Agriculture Organization (FAO) of the United Nations with the aim of raising awareness about the importance of millets as a nutrient-rich food crop. By promoting their cultivation, consumption, and marketing, the IYM seeks to address various global challenges, including food security, nutrition, and sustainable agriculture. For India, a country with a strong millet farming heritage, the IYM holds significant value.

Objectives: The IYM sets forth several key objectives to be achieved on a global scale. These objectives include increasing global production and consumption of millets, highlighting their nutritional and health benefits, improving research and development efforts, and enhancing the economic value of millets for smallholder farmers and rural communities. By emphasizing these goals, the IYM aims to foster a more sustainable, healthy, and equitable food system worldwide.

Significance for India: India, being the largest producer of millets globally, stands to gain significantly from the IYM. The initiative is poised to create new opportunities for farmers, processors, and traders, thereby promoting rural development and generating employment and income. Through the IYM, India can also promote sustainable agriculture practices, enhance food security and nutrition, and revitalize traditional millet-based recipes, enriching the country's food culture. Additionally, India has the potential to capture a larger share of the global market by focusing on value addition, product diversification, and strategic marketing campaigns. By leveraging its millet production capabilities, India can strengthen its economy while promoting healthier dietary choices and improving public health outcomes.

Current millet production in India: India's dominance in millet production is evident through its diverse range of millet varieties, including Pearl Millet (Bajra), Sorghum

(Jowar), Finger Millet (Ragi), Foxtail, Kodo, Barnyard, Proso, Little Millet, and Pseudo Millets such as Buckwheat and Amaranths. Among these, Pearl Millet, Sorghum, and Finger Millet account for the majority of millets produced in India. The states of Rajasthan, Karnataka, Maharashtra, Uttar Pradesh, Haryana, and Gujarat contribute significantly to the country's millet production, collectively accounting for over 83 percent. Rajasthan alone accounts for 28.61 percent of India's total millet production. These states possess the potential to further enhance millet production and consolidate India's position as a global leader.

Export potential and opportunities: India's millet exports have experienced steady growth, reaching $470 million in 2021 (ITC trade map). However, there is a considerable opportunity for India to expand its share in the global market through the promotion of millet-based value-added products. Currently, the share of such products remains minimal. By focusing on value addition, product diversification, and effective marketing strategies, India can tap into the growing demand for nutritious and sustainable food options. This approach not only has the potential to boost the country's economy but also presents an opportunity to showcase India's culinary heritage and traditional millet-based recipes on a global scale. As one of the top five millet exporters, India can leverage the International Year of Millets to further strengthen its position and enhance the value of its millet industry.

Cultivation, consumption and future prospects of millets: Millet grains have gained widespread cultivation and consumption across the globe, particularly in Africa and Asia, supporting the dietary requirements of over 90 million individuals in these regions. In contrast, staple foods like wheat, rice, and maize cater to the needs of approximately 4 billion people (Kumar et al., 2022). Millets are not only gaining popularity in developed countries due to heightened consumer awareness about their health benefits but also due to the rising demand for plant-based and gluten-free diets. Their utilization in processed food items, such as breakfast cereals and snack bars, further contributes to their growing demand. Consequently, global millet trade has witnessed a significant upsurge, with India emerging as the largest exporter of millet grains. However, the majority of millet production is consumed domestically, leading to a production deficit in relation to increasing demand, particularly in India where the demand has escalated by 140% (Kumar et al., 2022). According to the Food and Agriculture Organization (FAO), global millet production experienced a notable rise from 28.6 million metric tons in 2000 to 33.6 million metric tons in 2019, driven by the expanding demand for millets as a food and feed crop. Governments of several developing nations are actively promoting millet production and consumption to enhance food security and bolster rural economies, thereby fostering increased investments and research in this area.

The future outlook for millet grains appears promising, supported by escalating demand, advancements in technology, and government initiatives. Millets are poised to play a vital role in improving food security, nutrition, and sustainable agriculture in numerous regions worldwide.

9. Potential for Millet Grains to Contribute to Sustainable Food Systems:

The potential for millet grains to contribute to sustainable food systems is increasingly being recognized and embraced by experts and policymakers worldwide. Millets offer numerous advantages that make them an ideal candidate for sustainable agriculture and food production. One of the key advantages of millets is their resilience to environmental stressors such as drought and heat, making them a valuable crop in areas with unpredictable weather patterns. In addition, millets have a short growing cycle and require less water and fewer inputs such as fertilizers and pesticides compared to other cereal crops such as wheat and rice, making them a more sustainable option.

The agricultural sector is confronted with widespread environmental changes including escalating temperatures, uncertain rainfall patterns, elevated levels of carbon dioxide (CO_2) and greenhouse gases, and a heightened frequency of natural calamities. In light of these conditions, the adoption of climate-resilient agricultural practices becomes imperative, wherein the cultivation of climate-smart crops, particularly millets, assumes a central role (Bandyopadhyay et al., 2017) Millets possess a diverse range of efficient traits at the morphological, physiological, molecular, and biochemical levels that confer upon them the ability to withstand abiotic stresses. Notably, their short-duration growth cycle enables them to evade potential stress conditions arising from early or late sowing. Furthermore, millets exhibit reduced leaf area, fortified cell walls, and a compact fibrous root system, thereby enhancing their capacity to tolerate adverse abiotic conditions (Li & Brutnell, 2011). Being C_4 plants, millets demonstrate a heightened capacity to exploit atmospheric CO_2 through photosynthesis, resulting in enhanced assimilate production even under elevated CO_2 levels (Aubry et al., 2011). Additionally, millets demonstrate superior water use efficiency when compared to major cereal crops, rendering them a favorable choice in mitigating water scarcity concerns. Moreover, millets exhibit a lower carbon footprint compared to other cereals, further underscoring their environmental friendliness (Saxena etal., 2018). In terms of soil salinity, specific millet varieties, such as pearl and finger millet, exhibit resilience to salinity levels as high as 11-12 dS/m, surpassing the tolerance threshold of rice, which struggles to thrive in soils with salinity exceeding 3 dS/m (Rathinapriya et al., 2020).

Millet grains are also highly nutritious, containing high levels of protein, fiber, and micronutrients such as iron and zinc. This makes them a valuable addition to diets, especially in regions where malnutrition is a concern. Furthermore, the versatility of millets means they can be used in a variety of food products, from breakfast cereals to baked goods, and even in beer production. As consumers become more interested in diverse and sustainable food options, the demand for millet products is likely to increase.

Given these attributes, millets present substantial opportunities for cultivation in developing nations, serving as an invaluable dietary resource for populations facing resource constraints. With the right support and investment, millets could become a key component of sustainable agriculture and food systems in the future.

Challenges in Millet Processing Technologies

Issue	Impact	Potential Solutions
1. Small Size of Millet Grains	• Handling Difficulties during Processing • Inadequacy of Traditional Processing Methods	• Modern Milling Technique • Pin Milling • Air Classification
2. Hard Seed Coat	• Difficulty in Removing the Seed Coat • Impact on Flour Quality and Processing • Variability Across Millet Varieties	• Abrasion-based Milling Methods, • Stone Milling, • Abrasive Decortication • Roller Milling
3. Low Starch Content	• Challenges in Processing Characteristics and Functional Properties • Impact on Gelatinization, Viscosity, and Texture • Millet Types with Low Starch Content	• Blending with High-Starch Cereals or Legumes, Modified Starches, Roasting, Popping, Extrusion
4. Lack of Processing Equipment, Machinery and Low Yields	• Labor-intensive and Inefficient Traditional Methods • Challenges in Dehulling and Husk Separation • Impact on Gelatinization and Commercialization	• Modern Processing Technologies, • Variable Speed Equipment
5. Quality Control and Standardization	• Variability in Grain Quality and Contamination • Inconsistent Processing Methods • Impact on Nutritional Value, Taste, and Safety	• Implementation of Quality Control Measures, • Setting Standards • Approved Certification Systems
6. Limited Knowledge and Awareness	• Underutilization and Undervaluation of Millets • Limited awareness of Health Benefits and Culinary Versatility	• Awareness Campaigns • Educational Programs • Marketing Initiatives • Collaboration with Stakeholders
7. Limited Access to Credit and Markets	• Challenges Faced by Small-scale Millet Farmers • Preference for More Commercially Viable Crops • Lack of Investment and Research Efforts	• Increased Support, Market Promotion, Government Programs

Conclusion

Millet grains have the potential to contribute to sustainable food systems due to their resilience to environmental stressors and lower resource requirements compared to other cereal crops. Millet grains are highly nutritious and versatile, making them valuable for improving diets and food diversity. However, there are several challenges that need to be addressed to fully realize the potential of millet grains, including increasing awareness and demand, improving accessibility for small-scale farmers, and increasing investment in research and development. More research is needed to understand the potential benefits of millet grains for improving nutrition and health outcomes. Policy interventions are needed to increase the accessibility and affordability of millet grains, particularly for small-scale farmers who may face barriers to accessing markets and resources. Investment in research and development is needed to improve the yield potential of millet varieties and promote their adoption by farmers. Millet grains have the potential to contribute to sustainable food systems and improve food security and health outcomes, particularly in regions where malnutrition is a concern. However, realizing this potential will require concerted efforts by governments, policymakers, researchers, and the private sector to overcome existing barriers and promote the adoption of millet grains by farmers and consumers.

Author Contributions

PD prepared the manuscript and RR helped in preparing the final version of the manuscript and correspond to the journal.

Ethical Approval

This article does not contain any studies involving human or animal participants performed by any of the authors.

Conflicts of Interest:

The authors declare no conflict of interest.

References

1. Adebayo GB, GA Otunola and TA Ajao. 2010. Physicochemical, microbiological and sensory characteristics of kunu prepared from millet, maize and guinea corn and stored at selected temperatures. *Adv J Food Sci Technol* 2(1):41–6.)
2. Ali MAM, AH El Tinay and AH Abdalla. 2003. Effect of fermentation on the in vitro protein digestibility of pearl millet. *Food Chem* 80(1):51–4.
3. Antony U, G Sripriya and TS Chandra. 1996. Effect of fermentation on the primary nutrients in finger millet (Eleusine coracana). Journal of Agricultural and Food Chemistry. 44: 2616-2618.
4. Aubry S, N J Brown and J M Hibberd. 2011. The role of proteins in C3 plants prior to their recruitment into the C4 pathway. *Journal of Experimental Botany*, 62(9), 3049-3059.
5. Bandyopadhyay T, M Muthamilarasan and M Prasad. 2017. Millets for next generation climate-smart agriculture. *Frontiers in Plant Science*, 8, 1266.
6. Birania S, P Rohilla, R Kumar and N Kumar. Post harvest processing of millets: A review on value added products. *Int. J. Chem. Stud.* 2020, 8, 1824–1829.
7. Chandrasekara A and F Shahidi. 2012. Bioaccessibility and antioxidant potential of millet grain phenolics as affected by simulated in vitro digestion and microbial fermentation. *Journal of Functional Foods.* 4: 226-237.
8. Chethan S and NG Malleshi. 2007. Finger millet polyphenols: optimization of extraction and the effect of pH on their stability. Food Chemistry. 105:862-870.
9. Chimmad BV, HV Batra and SS Deshpande. "Milling characteristics of pearl millet as affected by abrasive decortication and roller milling." *Journal of Food Science and Technology.* 54, no. 7 (2017): 1847-1855.
10. Edge MS, JM Jones and L Marquart. 2005. A new life for whole grains. *Journal of American Dietetic Association.* 105(12): 1856-1860.
11. Gopalan C, BV Ramasastri and SC Balasubramanian. 1996. Nutritive Value of Indian Foods. National Institute of Nutrition, Indian Council of Medical Research, Hyderabad, India.
12. Hegde PS and TS Chandra. 2005. ESR spectroscopic study reveals higher free radical quenching potential in kodo millet (*Paspalum scrobiculatum*) compared to other millets. *Food Chemistry.* 92: 177-182.

13. MM Hosmani and BM Chittapur. 1997. Sorghum Production Technology, published by Sarasijakshi M.H., Dharwad, India and 5910, Wood Ridge Hill, San Antanio, Texas 78249, USA.

14. Jaybhaye RV, IL Pardeshi, PC Vengaiah, PP Srivastav. 2014. Processing and technology for millet based food products: A review nutrient composition of millets. *J. Ready Eat Food.* 1, 32–48.

15. Jood S and AC Kapoor. 2009. Antinutritional factors in millets and their removal by processing. *Journal of Food Science and Technology*, 46(4), 327-331.

16. Kodkany BS, RM Bellad, NS Mahantshetti, JE Westcott, NF Krebs and JF Kemp. 2013. Biofortification of pearl millet with iron and zinc in a randomized controlled trial increases absorption of these minerals above physiologic requirements in young children. *The Journal of Nutrition*, 143(9), 1489–1493.

17. Kumar L, RK Naresh, H Tiwari, SK Kataria, S Saharan, BR Reddy, O Singh, S Qidwai and RP Singh. 2022. Millets for Food and Nutritional Security in the Context of Climate Resilient Agriculture: A Review. *International Journal of Plant & Soil Science*. 34(23), 939–953.

18. Kumar S, OP Malav and SS Arya. 2018. Nutritional, textural and sensory characteristics of fermented cereal-based products: a review. *Journal of Food Science and Technology*. 55(10), 3613-3624.

19. Li P and TP Brutnell. 2011. Setaria viridis and Setaria italica, model genetic systems for the Panicoid grasses. *Journal of Experimental Botany*, 62(9), 3031-3037.

20. Liu RH. 2007. Whole grain phytochemicals and health. *J Cereal Sciences.* 46:207–19.

21. Manach C, A Mazur and A Scalbert. 2005. Polyphenols and prevention of cardiovascular diseases. *Current Opinion Lipidology*. 16: 77-84.

22. McKeown NM, JB Meigs, S Liu, PW Wilson and PF Jacques. 2002. Whole-grain intake is favorably associated with metabolic risk factors for type 2 diabetes and cardiovascular disease in the Framingham Offspring Study. *American Journal of Clinical Nutrition.* 376(2): 390-398.

23. Miller G. 2001. Whole grain, fiber and antioxidants. In: Spiller, G.A. (ed). Handbook of dietary fiber in Human Nutrition. Boca Raton, FL: CRC Press. pp: 453-460.

24. Morah FNI, UP Etukudo. 2017. Effect of sprouting on nutritional value of panicium miliaceum (Proso Millet). Edorium. *J. Nutr. Diet*, 4, 1–4.

25. Ndolo VU, T Beta and SP Mccormick. 2012. Effects of germination and fermentation on the phytase activity, phytic acid, total and in vitro soluble zinc in Ethiopian durum wheat varieties. *Journal of Food Science and Technology*, 49(3), 382-389.)

26. Oghbaei M and J Prakash. 2016. Effect of malting on antioxidant activity, phenolics and flavonoids in millet grains. *Food Chemistry*, 197, 858-864.

27. Prakash V, G Narsing Rao and T Jyothirmayi. 2017. Enzymatic hydrolysis of millets: a review. *Journal of Food Science and Technology*, 54(14), 4231-4241.

28. Ragaee S, EM Abdel-Aal, M Noaman. 2006. Antioxidant activity and nutrient composition of selected cereals for food use. *Food Chem.* 98(1):32–8.

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

30. Sathish G. 2018. The Story of Millets.

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

32. Scalbert A, C Manach, C Morand, C Remesy and L Jimenez. 2005. Dietary polyphenols and the prevention of diseases. *Critical Reviews in Food Science and Nutrition*. 45: 287-306.

33. Thompson LU. 1993. Potential health benefits and problems associated with anti-nutrients in foods. *Food Research International Journal.* 26: 131-149.