

# Millets in Sustainable Food Systems: Insights into Processing Technologies, Nutritional Benefits, and Value-Added Applications

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## ABSTRACT

Millets are traditionally known for their high nutritional values, climate resilience, and ability to grow even in harsh environment. They have been significantly cultivated as sustainable crops for their need of low water requirement, tolerance to drought like conditions, and adaptability to marginal lands. They significantly help in dealing global problems of food insecurity, climate change, and malnourishment. Further, their rich nutritional value, including dietary fiber, protein content, vitamins, minerals, and different bioactives, makes them a valuable choice for developing functional and nutrition-rich foods. Different technologies and approaches have been developed to enhance and add-on to their nutritional value and avoid any processing damage. Moreover, millets also contribute to several United Nation Sustainable Development Goals (SDGs) making them a critical part of food requirement. Literature search involved extensive collection and analysis of data from different databases like PubMed, Scopus, Google Scholar, World Health Organization (WHO), Food and Agriculture Organization (FAO), USDA FoodData Central and other using keywords including "Millets", "Value-added products", "Fermentation", "Germination", "Extrusion", "Nutritional Improvement", and "Climate resilience" individually and in combination. Review demonstrates significant progress in optimization and development of value-added millet-based products like gluten-free bakery products, fortified products, functional beverages, ready-to-eat snacks, and nutraceuticals. Also, advanced processing techniques like germination, fermentation, malting, extrusion, and thermal treatments have been developed showing improved nutrition, digestibility, sensory characteristics, bioavailability, and overall consumer acceptance. The review discussed the promising and sustainable potential of millets in developing nutritious, consumer-friendly food product contributing to global health and food security.

**Keywords:** Functional food, Millets, Nutrition, Processing technologies, Sustainable system, Value-added products.



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## INTRODUCTION

Historically, millets have been an important food source, especially in Africa and Asia, as a group of small-seeded grasses. However, pearl millet, finger millet, and sorghum are some of the varieties that have been used by several communities as staple foods because of their excellent nutritional quality and adaptability to difficult environments.

<sup>[1]</sup> Millets are rich in dietary fibres, proteins, vitamins and minerals and offer significant health benefits. They have long been part of the diet of many regions of the world, playing an important role during droughts and famines.<sup>[2]</sup> Although millets had their own historical importance, they became less popular as other more lucrative grains became available. However, there has been a renewed interest with the world now appreciating the health benefits and sustainability of millets.<sup>[3]</sup> In recent times, there has been a renewed interest in millets due to the rising awareness of their nutritional advantages and the demand for sustainable food products.<sup>[4]</sup> In recent years, the prevalence of lifestyle diseases, including diabetes and obesity has highlighted the importance of millets, which are low-glycemic and rich in dietary

fibre.<sup>[5]</sup> This revival is not just a rediscovery of an ancient food source, but a recognition of the important role millet can play in addressing some critical challenges in today's global food systems. From the food security perspective, millets have emerged as an important crop everywhere around the world. Millets are also a sustainable and resilient option that could help address the needs of the world, such as food security and water scarcity, as climate change becomes more common in the future.<sup>[6,7]</sup> Millets are important in providing food availability in arid and semi-arid regions of the world, where other staple crops are not able to thrive. Their alleviation of the need for chemical inputs also results in more sustainable farming practices.<sup>[8]</sup> Moreover, the nutritive value of millets is useful for reducing malnutrition particularly in developing countries where micronutrient deficiency is a common problem.<sup>[9]</sup> The advantages of using millets for food security are not just that they can survive in difficult environments, but also that they could diversify the world's food supply. Millets reduce the vulnerability of food systems associated with monoculture by reducing reliance on a few crops.<sup>[10]</sup> The objective of this review is to explore the potential of millets as a future food source, especially by innovations in value-added product development. This

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review aims to shed light on the nutritional benefits, innovations in processing methods, and current market trends for millets. Additionally, it will discuss the challenges and opportunities related to millet-based products, offering insights into their role in fostering sustainable agriculture, enhancing public health, and strengthening global food security.

## METHOD OF LITERATURE SEARCH

All the scientific and common databases including PubMed, Scopus, Web of Science, Google Scholar, ScienceDirect, World Health Organization (WHO), Food and Agriculture Organization (FAO), Food and Agriculture Organization Corporate Statistical Database (FAOSTAT) and other databases were exhaustively searched using millets related keywords individually and in combination. Various literature, reviews, data, and reports published in the last 20 years were critically analysed to develop a basic knowledge about millets, recent development in millet processing technologies, product development involving millets, nutritional benefits of millets, sustainability aspects and relative challenges. The data was analysed and a comprehensive review made based on the data acquired.

## Nutritional Profile

Millets include several types of grains like pearl millet, finger millet, foxtail millet, and sorghum, all of which have a varied and nutrition-rich composition that contributes significantly to the well-being of an individual.<sup>[11]</sup> All these types of millets contain their own unique nutritional benefits; for instance, pearl millet is known for its higher amounts of proteins and energy, while finger millet has higher amounts of calcium, which is essential for maintaining strong bones. Foxtail millet contains a low glycemic index and high amounts of carbohydrates, making it easier to control the blood sugar level, and sorghum has

antioxidant properties that help fight oxidative stress.<sup>[12]</sup> Table 1 shows information regarding nutritional benefits and nutritional contents of various types of millets.

The health benefits of eating millet are plentiful. Their low glycemic index helps to manage chronic diseases such as diabetes and cardiovascular diseases.<sup>[17]</sup> In addition, millet is rich in dietary fibre, which helps to maintain good digestive health by regulating bowel movements and reducing the risk of constipation. It's also helpful for weight loss because it increases satiety and reduces calories. Millets are rich in antioxidants such as phenolic acids and flavonoids which have protective effects against oxidative stress and inflammation, which are linked to ageing and chronic diseases like cancer. The minerals found in millets, including magnesium, potassium, and calcium, play a vital role in a number of bodily functions, such as maintaining bone health and blood pressure regulation.<sup>[18]</sup> In particular, the calcium content in finger millet is particularly beneficial for bone strengthening, and it's a great choice for those who are at risk of osteoporosis. Millet can be incorporated into various diets to enhance people's health and aid in managing diseases to correct nutrient deficiencies. Their wide-ranging nutritional benefits render them a valuable component of contemporary diets, particularly in tackling global health issues and promoting sustainable food practices.<sup>[19]</sup>

## Sustainable Production and Processing of Millets

Millets are sustainable crops with a lot of advantages related to their cultivation and processing.<sup>[20]</sup> They are appropriate to dry and semi dry zones and this would make them a good choice for water scarcity areas. Unlike other crops such as rice and wheat, millets require significantly less water, making them a valuable crop for areas with water constraints. They have a large root system that helps to stabilize soils and protect them from erosion, thereby promoting sustainable agriculture practice over the long term. Additionally, millets can thrive in poor soil conditions

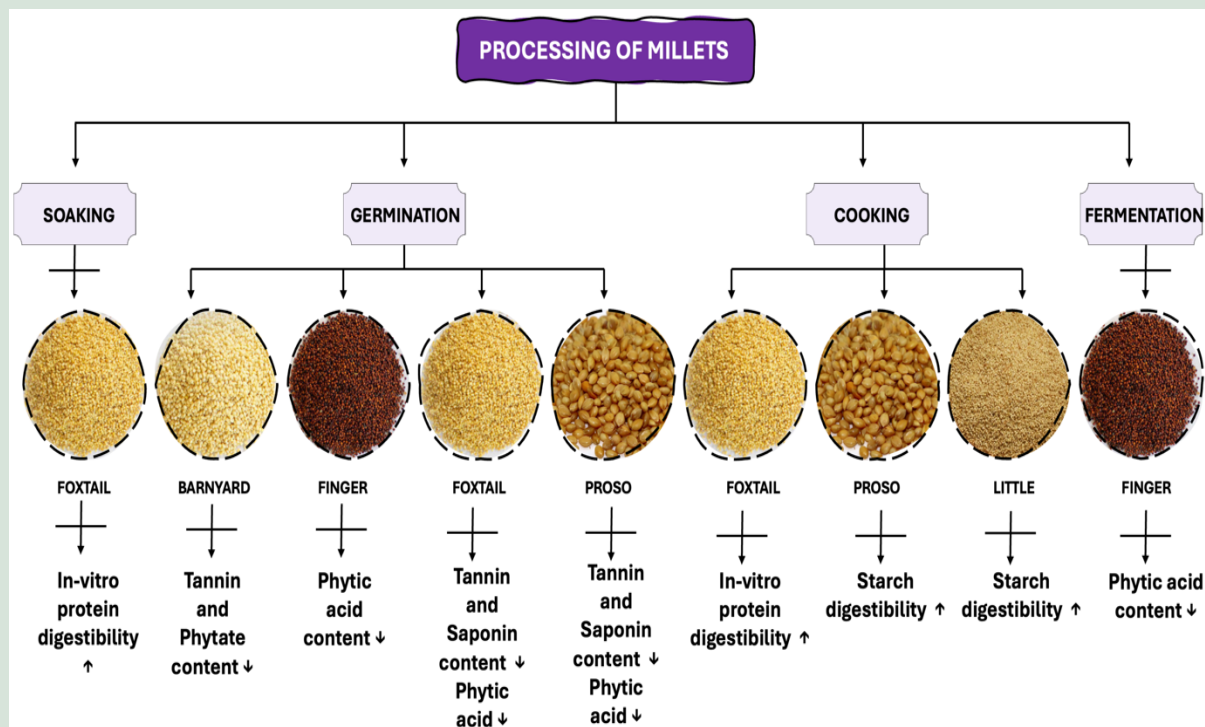


Figure 1: Different Techniques for Millet Processing.

and with little reliance on synthetic fertilizers and pesticides, reducing the environmental footprint of agriculture. Another advantage of growing millets is the promotion of biodiversity, since they can be used in different cropping technologies and crop rotations, thus contributing to the maintenance of ecological equilibrium and reducing the risk of pest attacks.<sup>[21]</sup> Traditionally, millets have been processed using manual hand-pounding and stone milling methods. The traditional methods are labour intensive but are effective in cleaning millets by removing the husks and other uneaten parts.<sup>[22,23]</sup> In the recent times, however, the processing methods have been modernized, and a number of mechanical machines such as roller mills, de-husking machine, and polishing machines are used for the processing of millets leading to high efficiency and uniformity of processing. The nutritional profile and texture of the millet-based products is further improved with the use of advanced technologies like extrusion and fermentation.<sup>[24]</sup> Increased availability of nutrients can be achieved using fermentation, and the products can have desirable texture characteristics, such as snacks or breakfast cereals from an extrusion process. The nutrient contents and bio-availability of millets are substantially changed after processing. The traditional methods of processing may lead to some loss of nutrients, but advanced processing techniques seek to retain and improve the nutritional qualities

of millets. Anti-nutritional factors such as phytates, which interfere with mineral absorption, can be reduced by hydrothermal treatments.<sup>[25]</sup> Fermentation makes vitamins and minerals more available by promoting the breakdown of complex compounds, and extrusion promotes digestibility and nutrition value of millet product. All of these modern processing methods preserve the nutritional value of millets and make them more palatable and accessible to a broader consumer base, leading to improved health outcomes and sustainable food systems.<sup>[26]</sup> Figure 1 shows different processing methods being used for different kinds of millets and along with the benefits of their application.

### Millet-Based Functional Foods

Functional food products made using millet are becoming popular because of their health benefits as well as flexibility in developing products. There has been a significant increase in the development of products made from millet, driven by increasing demand for healthful, gluten-free and environmentally sustainable foods.<sup>[27,28]</sup> Products made with millet are being developed in wide range of products, from traditional products like porridge and flat breads to modern snack foods, breakfast cereals and ready-to-eat products. Gluten-free nature of millets makes them highly beneficial for individuals suffering from celiac

**Table 1: Nutritional Profile of Various Millets.**

| Millets       | Nutritional Importance                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    | Nutritional Facts                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           | Health Benefits                                                                                                                                                                                                                                                                  | References |
|---------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------|
| Sorghum       | Supports growth and body functions, manages blood sugar, aids digestion, prevents obesity and IBS, lowers cholesterol, enhances bone health and immune function, prevents anemia, reduces oxidative stress and inflammation, and protects against chronic diseases.                                                                                                                                                                                                                                                                                       | Rich in protein (varies by cultivar), contains starch, soluble sugars, fiber, minor lipids (mainly in the germ) with plant sterols, high in B vitamins (except B12), beta-carotene, lutein, zeaxanthin, polyphenols, flavonoids, tannins (antioxidants), and minerals like potassium, magnesium, iron, and zinc.                                                                                                                                                                                                            | In management of celiac disease, obesity, diabetes, coronary heart disease, cancer, and oxidative stress.                                                                                                                                                                        | [13]       |
| Pearl Millet  | Good source of energy due to its high starch and amylose content, supports muscle and tissue repair with a rich amino acid profile, aids in heart health with beneficial fatty acids (linoleic, oleic), and promotes digestive health due to high dietary fiber. It is especially beneficial in managing cholesterol levels and supporting metabolic health, given its unique balance of nutrients and high fiber content.                                                                                                                                | Contains 62.8-70.5% starch, 1.2-2.6% soluble sugar (mainly sucrose), 21.9-28.8% amylose, and 9-13% protein, with variations up to 21% in some varieties. It is rich in essential amino acids like lysine, threonine, methionine, cystine, and tryptophan. Its lipid content varies due to genetic factors, primarily consisting of linoleic, oleic, and palmitic acids.                                                                                                                                                     | Beneficial in treatment of stomach ulcers, heart health, respiratory ailments, bone growth and development, cancer prevention, weight loss, diabetes management, celiac disease, cholesterol reduction, prevention of gall stones, and in preventing allergies.                  | [14]       |
| Finger Millet | Supports bone health due to its high calcium content, aids in weight management with tryptophan that reduces appetite, and promotes digestive health with its high fiber. It has antioxidant properties that protect against aging and metabolic diseases, and it lowers blood glucose and cholesterol levels. It also exhibits anti-ulcerative, antimicrobial, and nephron-protective effects, boosts hemoglobin in infants, and aids in wound healing in diabetes. Its polyphenols have anti-cataractogenic properties and inhibit snake venom enzymes. | Rich in carbohydrates (72-79.5%), mainly starch (59.4-70.2%), with 80-85% amylopectin and 15-20% amylose. It has a high fiber content (18.6%), protein content that varies with variety, and a significant amount of essential amino acids like lysine, threonine, and valine. It is a good source of calcium (344 mg), potassium (408 mg), and antioxidants such as polyphenols and tannins. It also contains small amounts of reducing and non-reducing sugars, and fatty acids like linoleic, oleic, and palmitic acids. | In weight loss, for bone health, for diabetes management, in lowering blood cholesterol, for anemia management, for other health conditions like malnutrition, degenerative diseases, and premature aging, in treating diseases like blood pressure, asthma, and heart weakness. | [15]       |
| Small Millets | Help maintain stable blood sugar levels and lower diabetes risk due to their fiber and phytochemical content. They provide minerals that support migraine relief and energy production. Proso millet, in particular, improves glycemic responses and offers liver protection. Overall, small millets are a nutritious choice supporting metabolic health and providing essential nutrients.                                                                                                                                                               | Rich in dietary fiber, phytates, and phytochemicals like catechins and flavonoids. They provide essential minerals such as copper and iron. Foxtail millet has 12.3% crude protein and 3.3% minerals. Barnyard millet is high in protein and contains beneficial fatty acids like linoleic acid. Proso millet offers protein comparable to wheat, essential amino acids, and B vitamins, including B6 and folic acid.                                                                                                       | Helps in controlling blood sugar and lowers cholesterol, ideal food for patients with diabetes and gastric issues, reduces risk of heart attack, develops body tissues and helps in efficient metabolism, and has antioxidant effects.                                           | [16]       |

disease or gluten intolerance. Moreover, rich nutrient content of millets that include high amounts of fiber, protein, vitamins and minerals makes millets important in health-promoting foods.<sup>[29]</sup> Table 2 provides information about products prepared from different kinds of millets.

Millets are also used as ingredients in the functional foods for specific nutritional requirements. These foods cater to specific health benefits, like blood sugar control, heart health or gut wellness. For example, millets are used to make low-glycemic-index foods, which are beneficial for people with diabetes or those who are trying to manage their blood sugar levels. Millet is rich in dietary fibre that promotes a healthy digestive system by promoting regular bowel movements and helping with weight management.<sup>[41]</sup> Furthermore, some of these millets, such as sorghum, have antioxidant properties which can be utilized for the development of functional foods and beverages for reducing oxidative stress and inflammation. In the food industry, millet flour is used for making nutritious and healthy baked goods, snacks, and beverages. In the health and wellness industry, food products made with millet flour are becoming popular as healthier alternatives to traditional food items. For instance, fermented millet beverages offer probiotic advantages,

aiding intestinal health and wellbeing. The adaptability of millets allows them to be included in various food and beverage products, making them a crucial ingredient in creating functional foods that address particular dietary needs and health issues. With consumers' growing demand for foods with nutritional and health benefits, millets are poised to play a major role in functional food development in the near future.

### Innovative Approach of Millet Fortification and Enrichment

The improvement of millets' fortification and enrichment is making these traditional cereal grains a useful tool in the fight against malnutrition and improving public health. The addition of nutrients to millet products or products made from millet, known as nutrient fortification, adds important vitamins and minerals to the product to enhance its nutritional value.<sup>[42]</sup> New technologies for the fortification of millets involve extrusion, coating, and blending, which have the advantage of distributing and retaining the nutrients in the product (such as iron, zinc, vitamin A, and B) uniformly. The enriched products are especially beneficial in regions where the nutrient deficiencies are common,

**Table 2: Millet-Based Traditional Processed Food and Beverages.**

| Product    | Region                        | Microorganisms                                                                                                                       | Form     | Preparation/ Usage                                                                                                         | References |
|------------|-------------------------------|--------------------------------------------------------------------------------------------------------------------------------------|----------|----------------------------------------------------------------------------------------------------------------------------|------------|
| Malt       | Africa                        | Enzymes produced during germination                                                                                                  | Grains   | Soaking, germination, and drying of millet grains; used in lactic acid and alcoholic-fermented beverages and infant foods. | [30]       |
| Koko       | West Africa                   | <i>Weissella confusa</i> , <i>Lactobacillus fermentum</i> , <i>Lactobacillus salivarius</i>                                          | Porridge | Steeping, milling with spices, fermenting, and boiling; consumed as a daily meal or snack.                                 | [31]       |
| Fura       | Sahel region, Africa          | <i>Enterobacter</i> , <i>Bacillus</i> , <i>Staphylococcus</i> , <i>Aspergillus spp.</i> , <i>Mucor racemosus</i>                     | Porridge | Millet flour mixed with spices and water, molded into balls, and cooked; staple food in semi-arid regions.                 | [32]       |
| Mangisi    | Zimbabwe, Uganda              | Lactic acid bacteria                                                                                                                 | Beer     | Made from naturally fermented millet mash; consumed as a sweet-sour beverage.                                              | [33]       |
| Jandh      | Nepal                         | Lactic acid bacteria, yeast, mold                                                                                                    | Beer     | Fermented finger millet seeds; consumed as a traditional alcoholic drink.                                                  | [28]       |
| Uji        | East Africa (Kenya, Uganda)   | <i>Lactobacillus plantarum</i> , <i>Pediococcus pentosaceus</i> , <i>Weissella confusa</i>                                           | Porridge | Lactic acid-fermented cereal porridge; consumed as a weaning food and refreshment.                                         |            |
| Burukutu   | Sub-Saharan Africa            | <i>Saccharomyces cerevisiae</i> , <i>Candida spp.</i> , <i>Leuconostoc mesenteroides</i> , <i>Acetobacter</i>                        | Beer     | Fermented millet or sorghum grains; popular traditional alcoholic beverage.                                                | [34,35]    |
| Pito       | Sub-Saharan Africa            | Lactic acid bacteria, yeast                                                                                                          | Beer     | Brewed from malted or germinated millet or sorghum grains; similar to Burukutu, consumed as an alcoholic drink.            | [36]       |
| Kunu-zaki  | Sahel region (Nigeria, Niger) | Lactic acid bacteria, yeast                                                                                                          | Paste    | Non-alcoholic cereal-based beverage; fermented with millet, wheat, or malted rice.                                         | [31]       |
| Ogi        | West Africa                   | <i>Lactobacillus plantarum</i> , <i>Lactobacillus fermentum</i> , <i>Leuconostoc mesenteroides</i> , <i>Saccharomyces cerevisiae</i> | Paste    | Fermented millet or maize paste used as a weaning food or breakfast meal.                                                  | [37]       |
| Ben-saalga | Burkina Faso                  | Lactic acid bacteria                                                                                                                 | Gruel    | Made from fermented millet with spices; used as a complementary food for infants.                                          | [38]       |
| Bushera    | Uganda                        | <i>Lactococcus</i> , <i>Leuconostoc</i> , <i>Enterococcus</i> , <i>Streptococcus</i> , <i>Lactobacillus brevis</i>                   | Gruel    | Fermented from sorghum or millet flour; consumed by children and adults as a beverage.                                     | [39]       |
| Togwa      | Tanzania                      | <i>Lactobacillus plantarum</i> , <i>Lactobacillus brevis</i> , <i>Weissella confusa</i>                                              | Gruel    | Lactic acid-fermented from maize flour and millet malt; used as a weaning food and refreshment.                            | [40]       |

helping to combat anemia, stunted growth,<sup>[43-45]</sup> and other public health problems. Another innovative approach to elevating micronutrient content of millets at the farm level is Biofortification. The approach is to develop millet varieties that contain a higher natural content of essential nutrients.<sup>[43,46]</sup> For example, some studies have reported the production of biofortified varieties of pearl millet with increased iron and zinc levels, and these have been promoted in areas with prevalent micronutrient deficiencies. Biofortification is an enduring solution since the nutrient is built into the grain before processing, and the benefits are present in the grain without any additional cost. Table 3 highlights the details of a broad spectrum of innovative products with millets as an ingredient.

It is evident that the health impact of fortification is enormous, as fortified and bio-fortified millets could help reduce micronutrient deficiencies and other health complications associated with it like cognitive development impairment and weak immune system. However, the success of such programs is contingent upon the acceptance of fortified products by consumers.<sup>[59]</sup> Some important parameters, which include taste and texture preferences among others, have an important bearing on the successful use of fortified products by consumers. Scientific research and development currently underway seek to improve the nutrition profile of millets and develop fortified products according to the taste preferences of consumers. Through satisfying dietary needs and consumer preferences, it is apparent that millet fortification and enrichment initiatives hold great promise for health benefits worldwide.

<sup>[60]</sup>

## Technological Innovations In Millet Processing

New technologies for processing of millets are revolutionizing the way in which these traditional grains are being transformed to modern food items. Modern technologies for millet milling and flour making have improved the efficiency of the process. State-of-the-art technologies like roller milling and micronization make it possible to develop refined and consistent millet flours with higher retention of nutritional qualities. This has made it possible to reduce wastage and increase the performance of millet flours in different food preparations, thus making them competitive to other traditional grains like wheat and rice.<sup>[61]</sup> Figure 2 illustrates the processing of millets from the raw form to market-ready forms.

In addition to milling, processes such as fermentation, extrusion, and other processing techniques are becoming increasingly common in the production of foods made from millet. Fermentation is an age-old technique which is now being refined using modern technology, and it makes the products made from millet more nutritious, more flavorful, and of better quality. Fermentation makes the nutrients more available and adds probiotics that improve the health of the digestive system.<sup>[62]</sup> The extrusion method is one in which high temperature and short time are used to make ready-to-eat snacks and breakfast cereals from millets.<sup>[27,63]</sup> Extrusion improves the quality and flavor of the millet products and reduces the number of anti-nutritional compounds in them, thereby making the nutrients easier to assimilate.<sup>[64]</sup> There are

**Table 3: Newly Developed Innovative Millet-Based Products.**

| Type                     | Name                                      | Brand            | Nutritional Facts                                     | Health Benefits                                           | Economic Stats                                          | References |
|--------------------------|-------------------------------------------|------------------|-------------------------------------------------------|-----------------------------------------------------------|---------------------------------------------------------|------------|
| Snacks                   | Millet Bhujia Sev                         | Nutraahaar Foods | Contains sorghum flour and gram flour, nutrient-dense | Addresses malnutrition for all age groups                 | The market projected to reach \$3.7 billion by 2031     | [48]       |
| Snacks                   | Millet Snacks                             | Various          | High in fiber, low in calories                        | Satisfies in-between meal cravings                        | Fast-growing segment due to health trends               | [49]       |
| Breakfast Cereals        | Puffed Millet Cereal                      | Arrowhead Mills  | No added sugar or salt, high in fiber and protein     | Gluten-free, supports digestive health                    | High nutritional value with strong market appeal        | [50]       |
| Breakfast Cereals        | Millet Flakes                             | Yummy Valley     | Packed with vitamins and minerals, low in sugar       | Promotes healthy digestion                                | Increasing demand among health-conscious consumers      | [51]       |
| Beverages                | Millet Milk                               | Various          | Dairy-free, rich in calcium and magnesium             | Supports bone health                                      | Emerging segment in plant-based alternatives            | [52]       |
| Infant and Weaning Foods | Holle Organic Millet Porridge (5+ Months) | Holle            | Fortified with calcium, iron, and vitamin B1          | Easy to digest and nutrient-rich for infants              | Market demand increasing                                | [53]       |
| Ready-to-Eat Meals       | Instant Millet Noodles                    | Various          | High in dietary fiber, organic ingredients            | Convenient, healthy meal options for busy consumers       | Strong growth expected as convenience food demand rises | [54]       |
| Ready-to-Eat Meals       | Jowar Idli Instant Mix                    | BeMillety        | Nutrient-rich, easy preparation                       | Quick, nutritious meals that suit various tastes          | Expanding in busy urban markets                         | [55]       |
| Ready-to-Eat Meals       | Bajra Rava                                | BeMillety        | High in fiber and protein, gluten-free                | Great for weight management and energy                    | Increasing popularity in ready-to-eat segments          | [14]       |
| Infant and Weaning Foods | Millet Health Mix                         | Nature's Soul    | USDA Organic, no chemicals, rich in nutrients         | Specifically designed for babies, promotes healthy growth | Growth in organic baby food market                      | [56]       |
| Pasta                    | Millet Pasta                              | Various          | Rich in fiber, lower glycemic index                   | Sustains energy levels, excellent for diabetics           | Rising demand for gluten-free pasta                     | [57]       |
| Crackers                 | Millet Crackers                           | Various          | High in fiber, low in fat                             | Aids in weight management                                 | Trending among health-conscious consumers               | [58]       |

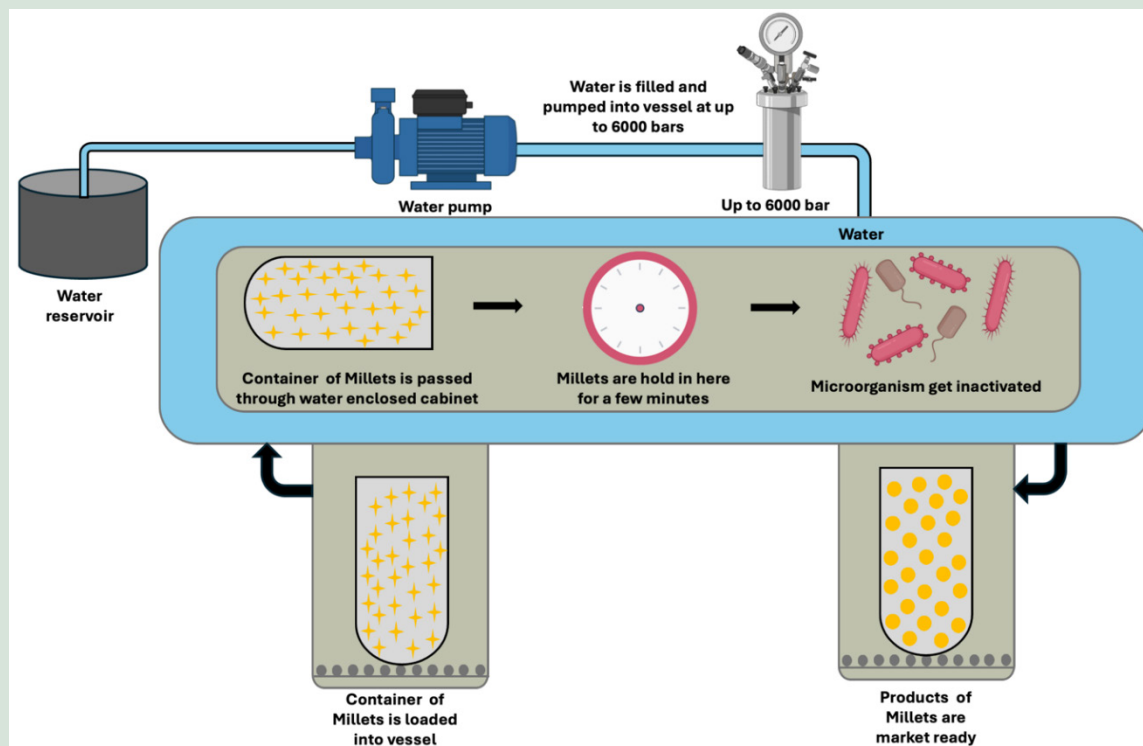


**Figure 2:** Processing of Millets.

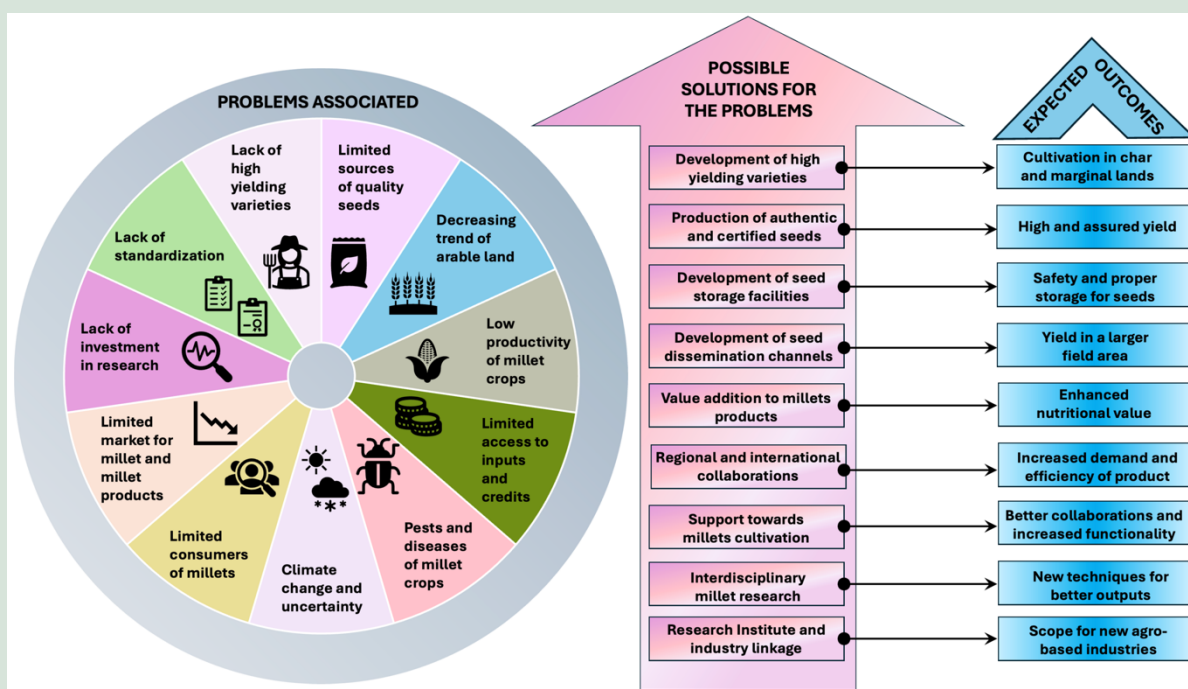


**Figure 3:** Problems, Solution and Expected Outcomes in Production of Millets.

many impacts brought about by the development of these innovations in terms of product quality and nutrition. Through these innovative ways of processing, there could be a preservation of the nutrients already available in the millets or even an improvement on these nutrients. This means that the end products not only will be convenient to the consumers but also will contain nutritional value. These innovations have opened doors for the production of millet products that satisfy the demands of consumers in terms of health and convenience among others, while contributing towards achieving other larger objectives of sustainable and nutritious foods.<sup>[65]</sup>

## Challenges And Opportunities In Millet-Based Food Innovation

Food innovation using millets presents its own set of challenges and opportunities that are integral to incorporating these millets in the modern diet. A major technical challenge posed in millets processing and development is due to the nature of the millets themselves.<sup>[66]</sup> While different from wheat and rice, millets have a more tough seed coat and smaller size grain, thus making milling and de-husking difficult, leading to inefficiencies and inconsistency in flour production and yield. Also, millets have higher levels of anti-nutritional factors such as phytate content that could hamper the absorption of nutrients like iron and calcium. In order to address these technical challenges, further research and development need to be conducted in order to improve processing techniques that ensure maximum retention of nutrients while maintaining consistency in the products developed.<sup>[67]</sup> Figure 3 shows an illustration of the technical problems in producing millets, the probable solutions to these problems and the outcome of these solutions.

The other notable problem is the lack of awareness and acceptance of millet-based foods by consumers. Even though there is an emerging trend towards healthy and gluten-free food products, consumers do not know much about millets and this could limit the demand. It is essential to come up with food products that align with current tastes and preferences of the consumers, as well as the benefits of millets to enhance their consumption.<sup>[68]</sup> Even though there are these challenges, there are opportunities in the expansion of innovations related to millet-based foods. Due to food security, climate change, and health issues on a global scale, millets could be instrumental in developing sustainable food systems.<sup>[69]</sup> There is a growing demand for foods that are healthy, gluten-free, and environmentally friendly; therefore, creating a big opportunity for millet-based products. Innovations in food processing technologies like milling, fermentation, and extrusion have opened up new possibilities in the production of millet-based foods.<sup>[69]</sup> Furthermore, the promotion of millets by international agencies, government institutions, and health campaigners to solve problems related to nutrition and environment is improving their popularity and acceptability.<sup>[70]</sup> Through exploiting such opportunities, food manufacturers can take advantage and develop millet products further to increase their presence in both domestic and global marketplaces. Through collaboration between scientists, industries, and policy makers, it will become possible to overcome any technological constraints and boost the consumer interest towards millets.

## CONCLUSION

Millets are proving to be vital components in the quest for sustainability in food production on the international stage due to their benefits in environmental, nutritional, and health aspects. In the study on food innovations based on millets, it is evident that the old grains have the capability of providing solutions to important problems in agriculture and public health sectors. The environmental benefits of growing millets

in the form of their drought tolerance and low water requirements qualify them to be a viable crop choice in the face of climatic changes and resource scarcity.

Nonetheless, the introduction of millets into the modern diet presents several challenges. Technical barriers in processing and product development and unawareness of consumers pose significant problems. Nevertheless, the possibilities of introducing innovations in millet-based foods are immense. Developments in processing technologies in the form of improved milling, fermentation, and extrusion make it possible to produce a variety of nutritious and attractive products from millets. These developments are important in making sure that millets become more available in the form of nutritious foods.

Millet as a nutritious alternative to other types of crops is gaining importance due to the efforts of the government, international organizations, and food producers. By solving the problems that are associated with the cultivation of millet and by using the current trend towards sustainable and healthy nutrition, it will be possible to use millet as an important component of food systems of the future. The introduction of millet into the mainstream food production is important not only for food security but also for nutrition of people. Millet can serve as one of the components of sustainable agriculture. It is essential to give priority to research on the development of millets and the allocation of necessary funds for this activity. In general, it is possible to state that there are good prospects for millets.

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## ABBREVIATIONS

**FAO:** Food and Agriculture Organization; **FAOSTAT:** Food and Agriculture Organization Corporate Statistical Database; **IBS:** Irritable Bowel Syndrome; **IYoM:** International Year of Millets; **spp.:** species pluralis; **SDGs:** Sustainable Development Goals; **LLM:** Large Language Model; **USDA:** United States Department of Agriculture; **USFDA:** United States Food and Drug Administration; **WHO:** World Health Organization.

## CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

## AUTHORS' CONTRIBUTIONS

**AG:** Conceptualization, Data Curation, Writing- original draft, Writing-review and editing. **HS:** Writing- review and editing. **DR:** Writing-review and editing, Formal analysis. **UKP:** Supervision, Formal analysis.

**AI-ASSISTED:** Authors also declare use of some Large Language Model (LLM) tools to assist solely in improving the language and grammatical flow of the manuscript. No AI tools were used for generation or analyses of the presented data. Authors take full responsibility for the accuracy and originality of the final manuscript.

## SUMMARY

Millets are proving to be vital components in the quest for sustainability in food production on the international stage due to their benefits in environmental, nutritional, and health aspects. In the study on food innovations based on millets, it is evident that the old grains have the capability of providing solutions to important problems in agriculture

and public health sectors. The environmental benefits of growing millets in the form of their drought tolerance and low water requirements qualify them to be a viable crop choice in the face of climatic changes and resource scarcity.

Nonetheless, the inclusion of millets into the modern diet presents several challenges. Technical barriers in processing and product development and unawareness of consumers pose significant problems. Nevertheless, the possibilities of introducing innovations in millet-based foods are immense. Developments in processing technologies in the form of improved milling, fermentation, and extrusion make it possible to produce a variety of nutritious and attractive products from millets. These developments are important in making sure that millets become more available in the form of nutritious foods.

Millet as a nutritious alternative to other types of crops is gaining importance due to the efforts of the government, international organizations, and food producers. By solving the problems that are associated with the cultivation of millet and by using the current trend towards sustainable and healthy nutrition, it will be possible to use millet as an important component of food systems of the future. The introduction of millet into the mainstream food production is important not only for food security but also for nutrition of people. Millet can serve as one of the components of sustainable agriculture.

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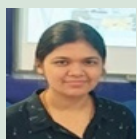
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## GRAPHICAL ABSTRACT



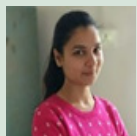
## ABOUT AUTHORS



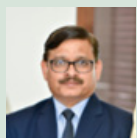
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