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REVIEW ARTICLE

Millets beyond grains: A review of the value chain and value addition for sustainable crop utilization

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Abstract

Millets often termed as "nutri-cereals" and traditionally viewed as subsistence crops, are now increasingly recognized for their nutritional value, climate resilience and their potential to enhance food and nutrition security, particularly in rainfed and dryland regions like India. Significant advancements have been made in millet processing, resulting in the emergence of value-added products. These innovations are helping in transforming millets from "poor man's food" to "modern health-conscious choices" in both rural and urban markets. This study explores the existing value chain of millets, production, processing, value addition, marketing and consumption. Despite their significance, the millet value chain remains fragmented and underdeveloped when compared to other staple cereals such as rice and wheat. By aligning production, processing, marketing and consumption through policy support, infrastructure development and market innovation, the millet value chain can evolve into a robust, inclusive and sustainable agri-food system.

Keywords: millets; nutritional security; processing technologies; value-addition; value chain

Introduction

Millets have been domesticated for over 10000 years. They are typically grown in degraded and marginal lands (1). Millets consist of sorghum, pearl millet, finger millet and small millets. Small millets include barnyard millet, proso millet, foxtail millet, kodo millet and little millet (2). Consumption and cultivation of millets have several nutritional benefits. Millets offer more health benefits than common staples such as rice and wheat (3). Millets have 3-5 % higher nutritional content compared to staple grains. Food security is satisfied by rice and wheat, whereas millets satisfy food security in addition to nutrition, livelihood, health and animal food security (4).

Due to their beneficial properties, millets have been processed to develop value-added millet products. Despite being nutrient-rich, millets must be processed to improve nutrient bioavailability. Processing millet for human consumption involves various processing techniques such as milling, dehulling, soaking, malting, puffing, germination, fermentation and so on (5). All these operations require specific types of equipment and machinery for processing. The selection of the particular type of machinery/ equipment for processing is based on output (6). The shelf life of processed millet products was extended from less than a month to eight months, providing consumers with a broader and more convenient range of food options, promoting millet consumption and opening opportunities for the commercialization of millet-based foods (7).

Building on processing, the next crucial step is the millet value chain, which links production to market through a series of interconnected activities. Value chain refers to the network of relationships formed between actors, both directly and indirectly influenced by others, to enhance value at each stage of the chain. It improves business efficiency and adds value at the lowest possible cost. The value chain includes connections between producers, distributors, processors, support institutions and traders (8). Millet is an adaptable and multifaceted crop. It provides feed, food, fuel and fodder. It is known as biomass crop as it is utilized entirely (9). Millet value chain refers to a series of interconnected and organized value-adding activities that develop and grow a specific type of millet into processed food products for end consumers (10).

Nutritional value of millets

Millets are vital food crop worldwide, playing an important economic role in developing nations. These grains are valued for their drought tolerance and pest resistance. They are small-sized crops grown extensively across tropical and subtropical (11). Millets are well-suited to drought-prone areas and can thrive under high-temperature conditions. They can grow without irrigation and in regions with very low rainfall, ranging from 200 mm to 500 mm, demonstrating their ability to withstand water scarcity (12).

Millets are rich source of proteins, vitamins, fatty acids, fibres, minerals and other phytonutrients. Nutritional benefit of different millets is considered as an advantage of developing value-added millet products. The development of these high-value, nutrient-rich products will enhance consumers' immunity, health and socioeconomic well-being (13). The nutritional content of 100 g of different millets are shown in Table 1 (12, 14).

Millet for sustainable agriculture

Sustainable agriculture is now a worldwide priority, aiming to harmonize food production with environmental care and social welfare. Millets regarded as a "forgotten crops", possess distinct qualities that make it valuable for promoting sustainable agricultural practices (15). Millets are key component of sustainable agriculture, a farming approach focused on maintaining soil fertility, protecting ecosystems and supporting human health. Millet helps in tackling major challenges like water shortages, malnutrition and the impacts of climate change. Millets also have the capacity to help combat widespread problem of malnutrition in our country. Compared to crops like rice, wheat or sugarcane, millet cultivation requires significantly less water (16).

By incorporating millets into farming systems and dietary habits can help India advance meaningfully toward multiple Sustainable development goals (SDGs), including those related to food security, improved nutrition, sustainable agriculture, climate action and the preservation of biodiversity. The central goal to combat hunger by integrating millets into mainstream practices (17).

Value chain of millets

Millets are vital crops, especially in rainfed and dryland regions, making it important to examine their value chains at both pre- and post-harvest stages. Unlike other agricultural products like wheat, rice, vegetables, fruits and meat whose value chains are well established and efficiently managed millet value chains are still evolving. However, millets are increasingly being used in industries to create a variety of value-added products such as millet flour, flakes, noodles, cookies and puffed snacks (9).

Millets offer a valuable chance to enhance food and nutrition security while also opening avenues for developing new products and boosting the economy through improved production, value addition and marketing in the area under study. However, to fully realize these opportunities, it is essential to focus on increasing millet productivity. More importantly, efforts must be made to change farmers' perception of millets- from being seen as a poor man's grain to being recognized as a nutritious choice for today's health-conscious consumers (18).

Millet value chain from farm to market involves input supply, production, processing, value addition, marketing and distribution and consumption. Input supply involves access to high-yielding and region-specific varieties, fertilizers and bio-inputs and machinery and followed by production. Processing involves cleaning and grading, dehusking, drying and storage, followed by value addition to produce ready to eat / ready to cook products. The products are marketed and distributed to end users. Fig. 1 illustrates the steps involved in the millet value chain (19).

Most of the millet harvested by farmers is used for household consumption, though in some cases, they also serve as a source of income. Around half of the farmers surveyed reported selling a portion of their produce. They estimated that between 20 % to 60 % of their harvest is consumed at home, while the rest is sold to nearby retailers, local markets (shandies), neighbours or farmer producer companies that have recently started promoting millet commercialization and involved in collecting millet grains and selling them in bulk after cleaning and grading. Additionally, various local efforts have focused on producing millet-based value-added products (20). Millets, like other traditional grains, raise considerations regarding nutritional composition, food safety and processing methods. In terms of nutritional content, millets are excellent sources of key nutrients, including proteins, dietary fiber and minerals like iron, zinc, as well as B vitamins (21).

Millet production

Millets are key cereal crops that contribute greatly to food and nutrition security in developing nations. They make up around 10 % of Asia's total coarse grain output, with India leading as the top producer, contributing more than 80 % of the region's production. Despite the use of improved varieties and hybrids, crop yields in India remain relatively low. The utilization of millets varies by country or region to another; in many African countries, they serve mainly as staple food grains, especially for low-income populations (22).

The FAO reported that global millet production was estimated at 28.33 million metric tonnes in 2019 and rose to 30.08 million metric tonnes by 2021. As of 2021, India held the position of the leading millet producer, contributing 41 % to the global output. Data from the Ministry of Agriculture and Farmers Welfare shows that India's millet production grew from 14.52 million tonnes in 2015-2016 to 17.96 million metric tonnes in 2020-2021 (23).

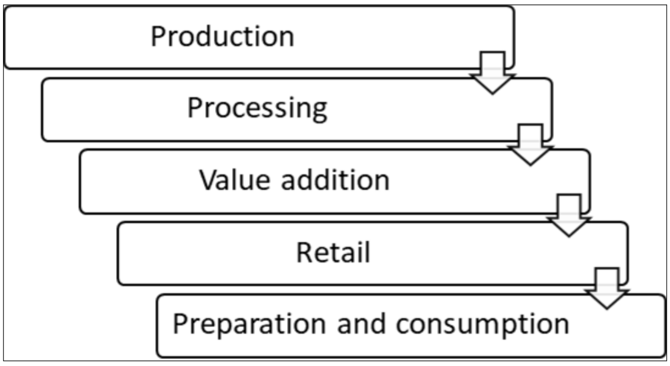

Fig. 1. Value chain of millets (19).

Table 1. Nutritional profile of millet cereals (12, 14)

Millet cereals	Nutritional value (100 g cereal)				
	Proteins (g)	Fiber (g)	Minerals (g)	Iron (mg)	Calcium (mg)
Sorghum	11	6.7	2.7	3.4	13
Pearl millet	10.6-14	1.3-2.5	2-2.3	7.5-16.9	10-38
Finger millet	7.3-10	3.6-4.2	2.7-3	3.9-7.5	240-410
Foxtail millet	12.3-15	4.5-8.0	2-3.3	2.8-19	10-31
Proso millet	10-13	2.2-9	1.9-4	0.8-5.2	14-23
Kodo millet	8.3-10	5-9.0	2.6-5	0.5-3.6	10-31
Little millet	7.7-15	4-7.6	1.5-5	9.3-20	17-30
Barnyard millet	6-13	10.1-14	4-4.4	15.2	11
Rice	6.8	0.2	0.6	0.7	10
Wheat	11.8	1.2	1.5	5.3	41

Millets and its processing

Millet grains offer significant benefits for health and nutrition, while also supporting rural livelihoods, boosting household earnings, strengthening local and national economies and promoting sustainable environmental practices. Millets are packed with micronutrients (vitamins, minerals, antioxidants and phytochemicals) and macronutrients (carbohydrates, protein, fiber, fat and energy). Millets must be processed before cooking and consumption to enhance the nutritional value and palatability (24).

Sorghum

Sorghum (*Sorghum bicolor*) ranks as the fifth most significant cereal crop in global production and serves as rich source of vitamins B, including riboflavin, biotin, thiamine, vitamin B6 and niacin (25). The nutritional profile of sorghum is the same as that of rice, wheat and maize. Sorghum is a crucial cop for both food and fodder in the semi-arid tropics globally, serving as a staple food in Africa and Asia (26).

In these regions, the majority of the grain is consumed by humans. Despite its recognized nutritional value, sorghum consumption is declining due to the limited availability of ready-to-eat and ready-to-cook products in the market. Sorghum rice and sorghum flour serve as key ingredients in a variety of products, including instant sorghum rice, instant porridge, diverse cakes and different types of pasta (27). Sorghum processing techniques are listed in Table 2 (28).

Pearl millet

Pearl millet (*Pennisetum glaucum*) is more nutrient-rich than many commonly grown cereal crops. However, its utilization is hindered by the presence of anti-nutritional compounds, such as phytates, tannins and polyphenols, which reduce mineral bioavailability and by its poor shelf life due to high lipase activity (29). Pearl millet is consumed in various processed forms and is also used as an ingredient in diverse foods. Pearl millet consists of mineral, fibre, protein and fatty acids and hence is called “nutri-cereals” (30). Pearl millet is processed using several techniques, which are listed in Table 3 (28).

Finger millet

Finger millet (*Eleusine coracana*) widely known as *Ragi* or *Mandua*, is a significant millet crop cultivated across various regions of India. It boasts exceptional nutritional content including protein, starch, fat, dietary fibre and minerals (31). Finger millet is also recognized for its numerous health benefits, including anti-diabetic, antitumor, anti-atherosclerotic and antioxidant properties, primarily attributed to its high polyphenol and dietary fiber content (32). Finger millet is typically ground into wholemeal flour, which is then used to prepare traditional dishes like roti, kanji and kazhi. Beyond this, finger millet is also processed into popped, malted and fermented products. Non-traditional items such as papads, noodles and soups are also made from finger millet (33). Finger millet involves several processing techniques and are given in Table 4 (34).

Foxtail millet

Foxtail millet (*Setaria italic*) is one of the oldest domesticated crops, widely cultivated in the arid and semi-arid regions of Asia and Africa. It is rich in fiber, protein, minerals and phytochemicals. Its antinutritional components, such as phytic acid and tannins, can be effectively minimized through appropriate processing techniques (35). The processing quality of foxtail millet can be enhanced through modifications without compromising its nutritional value. Currently, various processing techniques are applied to foxtail millet, including heat-moisture treatment, microbial fermentation, enzyme treatment, extrusion, superfine grinding, ultrasonic treatment, microwave treatment and ultra-high pressure treatment. Each of these methods affects the key components of millets in different ways (36). The processing techniques of foxtail millets are listed in the Table 5 (37).

Proso millet

Proso millet (*Panicum miliaceum*) is an annual cereal crop primarily grown in China and India and other Asian countries. It is used as food, animal feed and forage. It is also referred to by other names such as common millet, broomcorn millet, hog millet and red millet. Proso millet contains high levels of sulfur-rich essential amino acids. The nutritional value of

Table 2. Processing techniques of sorghum (28)

Processing techniques	Methodology
Milling	Whole grain is converted to wholemeal flour
Malting	Steeping, germination and drying
Parboiling	Partial boiling to increase nutritional value and hardness
Popping	Expose to high temperature for short time to expand starchy endosperm

Table 3. Processing techniques of pearl millet (28)

Processing techniques	Methodology
Milling	Grinding millets into flour or meal
Malting	Steeping, germinating, drying, grinding and sieving
Blanching	Submerging grains in boiling water at high temperature for a short time
Acid treatment	Soaking the grains in HCl
Dry heat treatment	Led to loss of moisture denaturing the protein
Popping	Exposing to high temperature

Table 4. Processing techniques of finger millet (34)

Processing techniques	Methodology
Soaking and cooking	Soaking in water at a room temperature of 25 °C. Cooking upon boiling water
Fermentation	Converts complex material into simpler form with help of microorganism
Germination/malting	Germinate seeds to activate enzymes that convert starches into sugars
Decortication	Removal of outer layer of seed coat
Parboiling	Soaking, steaming and drying process
Roasting	Cooking the grains in hot air

Table 5. Processing techniques of foxtail millet (37)

Processing techniques	Methodology
Boiling	Soaking, steaming and drying
Germination	Germinate seeds to activate enzymes that convert starches into sugars
Pressure cooking	High temperature steaming for preserving nutritional content
Roasting	Heating of grains

proso millet is comparable to that of other major cereals such as oats, rice and wheat (38). The nutritional value of proso millet is higher compared to staple cereals. Processed proso millet has a low glycaemic content on comparison with cereal products. The glycaemic index (GI) of proso millet is lesser than maize and wheat products. The essential amino acid content of proso millet is almost 51 % (39). The processing techniques of proso millet are given in Table 6 (40).

Kodo millet

Kodo millet (*Paspalum scrobiculatum* L.) is believed to have originated in India and is considered as minor cereal crop. Kodo millet thrives best in tropical and subtropical climates. Typically grown in poor soil conditions and is commonly found in arid and semi-arid zones of both India and African nations. It is a rich source of vitamins, minerals and sulfur-based phytochemicals and so called nutria-cereal (41). Processing of kodo millet offers a range of health benefits. Grain extracts show strong antioxidant activity. The higher content of phytochemical and phytates contributes to its anti-cancer properties and is considered to be best source of dietary fibre (42). Processing of kodo millet is given in Table 7 (43).

Little millet

Little millet (*Panicum sumatrense*) serves as a staple food in several regions of Asia and Africa due to its rich vitamin and mineral content and its resilience in challenging growing environments. Improving this crop through natural means and innovative breeding approaches is a promising strategy to strengthen nutrition and food security (44). Little millet is highly nutritious and provides essential macro and micronutrients. Processing methods such as germination, fermentation and milling can alter the levels of these nutrients and bioactive components. It plays an important role in promoting health and supporting various physiological functions (45). Processing of little millet is given in Table 8 (46).

Barnyard millet

Barnyard millet (*Echinochloa frumentacea*) is grown and used as food and fodder by tribal and hill communities across parts of Asia. It is known for its adaptability and is recognized as a promising option for climate-resilient farming. It is traditionally served as an alternative to rice in the Indian Himalayan areas (47). Barnyard millet is rich in protein, carbohydrates and fiber and stands out for its higher levels of micronutrients like iron and zinc compared to other common cereals. Its rich nutritional profile and strong antioxidant properties have led to it being regarded as a functional food crop (48). Processing of barnyard millet is given in Table 9 (49).

Table 6. Processing of proso millet (40)

Processing techniques	Methodology
Fermentation	Soaked and fermented
Roasting	Dry roasted in pan/oven
Germination	Soaking and sprouting
Extrusion	Subject to heat and pressure to create different shapes and textures

Table 7. Processing techniques of kodo millet (43)

Processing techniques	Methodology
Decortication	Removal of outer husk to make grain edible
Roasting	Dry heating of grains
Germination	Sprouting the grains
Fermentation	Natural microbial action

Table 8. Processing techniques of little millet (46)

Processing techniques	Methodology
Milling	Grinding grains into flour
Roasting	Dry heating of grains
Decortication	Removing the tough outer husk of grains
Germination	Sprouting grains

Table 9. Processing techniques of barnyard millet (49)

Processing techniques	Methodology
Flaking	Pressing cooked grains into thin, flat pieces as breakfast-cereals
Puffing and popping	Rapid heating of grains
Malting	Soaking and germinating and drying
Dehulling	Removal of outer, inedible husk from grains

Value-added products

Millets are more nutritious than many cereals because they are rich in dietary fiber, high-quality protein, essential amino acids and micronutrients such as iron, calcium, magnesium, zinc and vitamins B. They also have a low glycemic index, making them beneficial for managing blood sugar levels. Additionally, their antioxidant content contributes to better overall health and disease prevention. They also serve as a viable alternative to commonly consumed grains like rice and wheat. The products prepared by the value addition of millet are given in Table 10 (50).

Retailing and consumption of millets

Urbanization has led to changes in consumer attitudes and eating habits, becoming a major driving force behind current trends. Today's consumers are more focused on fitness and overall well-being. However, it is essential to offer them nutritious options like millet in convenient product forms like ready-to-eat (RTE) and ready-to-cook (RTC), which fit seamlessly into their daily routines. Millets has gained popularity among consumers for its taste. Its rich nutritional value and health benefits are attracting growing interest and this trend is expected to drive even greater demand in the future (51).

Growing awareness of the nutritional and health benefits of millets has brought them back into focus. Their promotion is also seen to reduce the impact of climate change on food production, increasing their importance. To improve the millet value chain, it is essential to boost both supply and demand by raising awareness and implementing supportive policy measures (52). The primary motive for consuming millet-based products includes their taste, health advantages, support in weight management and other factors like curiosity to try something new. Millets are also viewed as more affordable alternatives to traditional cereals (53).

Table 10. Value added millet products (50)

Conventional food products	
***Roti* (unleavened pan cake)**	Millet flour mixed with hot water which forms dough and flattened into thin sheets and baked to *roti*
Multigrain flour	Blended flours of millets and pulses
Fermented foods	Blackgram and millet (1:3) ground wet and fermented overnight
Parboiling of millets	Precooked ready to eat
Papad	Mix of millet flour, spice, rice and blackgram
Non- conventional food products	
Millet flakes	Grains cooked at high pressure
Puffing or popping	High temperature short time treatment
Weaning/malting food	Soaking and germinating millets
Noodles-vermicelli	Grounded grains cooked, extruded and dried
Bakery products	Pigeon pea and millet flour blend

Challenges in the millet value chain

Farmers encountered several obstacles, including restricted access to input markets and extension services, unavailability of preferred crop varieties and insufficient processing technologies. Seed companies pointed out the absence of reliable markets and limited demand for improved seeds as major challenges in the sorghum and millet sectors. Low purchase volumes from buyers, late payments by farmers and intense competition among sellers are major challenges in the millet value chain (54). It is evident that the most critical issue affecting input dealers, farmers, processors and sellers of millet and sorghum is insufficient capital. Farmers also faced challenges like fertilizer shortages and drought. Processors and marketers were impacted by issues such as unpaid debts and fluctuating prices (55). Millet supply chain is struggling with irregular supply and demand, which affects its potential for commercial success. Low productivity due to limited availability of high-yielding seed varieties and a lack of awareness about millet's nutritional value have led to their limited use as a convenient cooking option (23).

Opportunities for value chain enhancement

The enhancement of the millet value chain presents a range of opportunities across different stages, from production to marketing. At the production level, millets are inherently climate -resilient, thriving in arid and semi-arid conditions with minimal inputs, making them well-suited for climate change adaptation. Post-harvest handling and processing are another critical area with vast potential. Establishing infrastructure for dehulling, grading, drying and storage will minimize losses and maintain product quality. Setting up primary processing units in rural areas can foster employment and reduce transportation costs, while the introduction of small-scale processing technology can boost efficiency and product uniformity.

Improving market linkages and aggregation mechanisms is vital to enhancing farmer incomes. The rising urban demand for healthy food options has led to the emergence of millet-based RTE and RTC products, such as dosa mixes, snacks and cereals. The global celebration of the international year of millets in 2023 offers a platform for brand building and increasing export visibility. With growing international demand for gluten-free and nutrient-dense foods, Indian millets hold strong export potential, particularly in North America, Europe and the Middle-East.

Policy and institutional support are essential to sustain and scale the millet value chain. Including millets in the public distribution system (PDS) can ensure access to nutritious grains for low-income groups. Institutional demand can also be bolstered by integrating millets into school mid-day meals, hospital diets and military rations. Government incentives such as subsidies for inputs and processing units, along with goods and services tax (GST) exemptions on millet products, will further boost the sector's growth and sustainability.

Conclusion

Millets often termed as "nutri-cereals", offer an untapped potential. Due to their rich nutritional profiles, resilience to climate stress and adaptability to marginal environments, millets are uniquely positioned to contribute to food security, nutrition, rural livelihoods and environmental sustainability. To strengthen the value chain, must address challenges like inadequate processing technologies, market linkages and capital constraints. To fully realize the economic and nutritional potential of millets, a coordinated effort involving policy support, investment in value chain infrastructure, research in varietal improvement and consumer awareness campaigns is essential. Hence, it is concluded that millets must be viewed not just as grains, but as a pathway for sustainable agricultural growth, enhanced nutrition and climate resilient food system.

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Authors' contributions

NSS identified the topic, collected data, analysed the data and drafted the manuscript. RA assisted in data collection and analysis as part of the research study. DN assisted in developing ideas and reviewing the manuscript. SS helped in summarizing and revising the manuscript. SKA provided additional support and contributions to the research study. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: The Authors do not have any conflict of interests to declare.

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Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used Grammarly in order to assist in language refinement and grammar correction. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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