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Review

Maximizing the Nutritional Benefits and Prolonging the Shelf Life of Millets through Effective Processing Techniques: A Review

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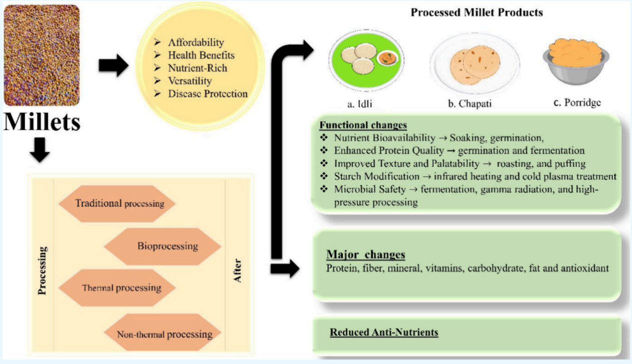
ABSTRACT: Maximizing the nutritional benefits and extending the shelf life of millets is essential due to their ancient significance, rich nutrient content, and potential health benefits, but challenges such as rapid rancidity in millet-based products underscore the need for effective processing techniques to enhance their preservation and global accessibility. In this comprehensive review, the impact of diverse processes and treatments such as mechanical processing, fermentation, germination, soaking, thermal treatments like microwave processing, infrared heating, radio frequency, nonthermal treatments like ultrasound processing, cold plasma, gamma irradiation, pulsed light processing, and high-pressure processing, on the nutritional value and the stability during storage of various millets has been examined. The review encompasses an exploration of their underlying principles, advantages, and disadvantages. The technologies highlighted in this review have demonstrated their effectiveness in maximizing and extending the shelf life of millet-based products. While traditional processes bring about alterations in nutritional and functional properties, prompting the search for alternatives, novel thermal and nonthermal techniques were identified for microbial decontamination and enzyme inactivation. Advancements in millet processing face challenges including nutrient loss, quality changes, resource intensiveness, consumer perception, environmental impact, standardization issues, regulatory compliance, and limited research on combined methods.



1. INTRODUCTION

Cereal grains, serving as the primary source of calories for the majority of the global population, play a pivotal role in sustaining human nutrition. Notably, developing nations heavily rely on cereal grains for nourishment, with approximately 60% of their caloric intake derived from cereal.[1] Within this context, millets, categorized within the Poaceae family, emerge as small-seeded grains cultivated extensively in arid and tropical regions of Africa and Eurasia. With roots dating back to the ancient Indus Valley civilization (3000 BC), millets are now recognized as the world's fifth most crucial cereal grain crop.[2] Their historical significance notwithstanding, millets are gaining renewed attention as indispensable food sources for future generations, particularly in the face of climate change's adverse effects on sensitive ecosystems.[3] Beyond their historical prominence, millets stand out for their exceptional nutritional composition. They rank favorably in both micro and macronutrients, showcasing superior mineral content and essential amino acid profiles compared to mainstream cereals like wheat and rice.[4,5] As billions globally rely on staples like rice, wheat, and maize for sustenance, millets offer a promising alternative due to their resilience in semiarid and dry environments, thriving where water supply is limited and soil conditions are challenging.[1] This unique adaptability positions millets as vital crops in ensuring food security amid varying agroclimatic conditions. Recognizing the nutritional richness of millets, there is a growing emphasis on their processing to maximize benefits and address hidden hunger on a global scale. The surge in research and innovation in millet processing is evidenced by the significant increase in both scientific publications and patents over the past two decades (Figure 1). Analyzing the trends from 2004 to 2023, as illustrated in the graph, reveals a marked growth in academic and commercial interest. Initially, the number of publications and patents remained relatively low with minimal fluctuations. However, starting around 2010, there has been a noticeable rise, peaking in 2023 with an impressive 47 publications. This trend highlights the intensified focus on developing efficient processing methods to harness the full potential of millet. Concurrently, the number of patents has shown steady growth,

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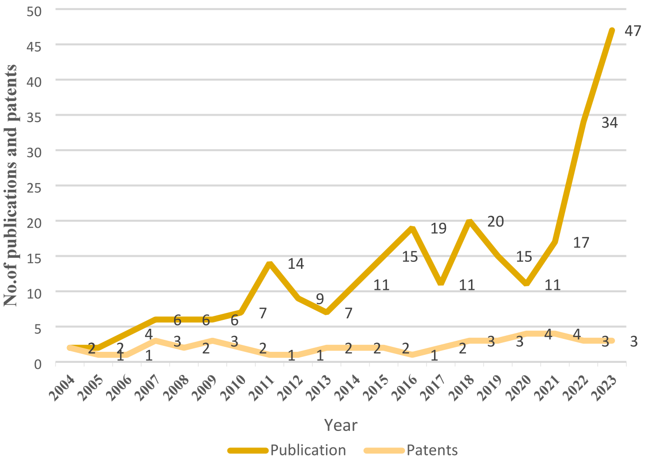

Figure 1. Trends in publications and patents in millet processing (2004–2023).[141,142]

peaking at 4 patents annually from 2019 to 2021, reflecting ongoing technological advancements and innovation in millet processing methods.

Millets are commonly processed before consumption to remove any unpalatable components, extend their shelf life, and improve their nutritional and sensory qualities.[6] Millets contain significant concentrations of phenolic phytochemicals, specifically flavonoids and phenolics.[5] Phenolics and tannins make up most of the polyphenols, and flavonoids are present in small amounts. While millets have a good nutritional profile, their tannin and phenolic content may hinder the absorption of important nutrients. These compounds form complexes with minerals like iron and zinc, reducing the bioavailability of nutrients and impeding their absorption.[3] Another antinutrient in millets is phytic acid, which binds to proteins and minerals, further inhibiting absorption. Different processing techniques can lower the amounts of these antinutritional substances despite these challenges. This involves primary processing methods such as dehulling, soaking, germination, roasting, drying, polishing, and milling.[7] Additionally, millet-based processed food items are made using secondary processing techniques including flaking, extrusion, frying, puffing, popping, fermenting, parboiling, and baking.[5] These methods help to mitigate the effects of antinutrients and improve the nutritional benefits of millets. Millets have a much longer shelf life when they are kept whole rather than being ground into flour. Traditional storage methods such as mud rhombuses, earthen bins, underground pits, and aerial storage in knotted bundles can keep whole millets for 4–5 years by minimizing bug infestations and moisture accumulation.[6] However, once millets are milled into flour, the seed structure disintegrates, significantly reducing their shelf life and making them more susceptible to biological activity and environmental factors. The main factors impacting the shelf life of millet flour are the activity of the enzyme lipase and microbiological contamination. Environmental influences and inappropriate storage conditions can lead to microbial contamination, which can cause food spoilage.[6] When lipase activity breaks down the lipids in flour, it can result in rancidity and off-odors, making the flour harmful for consumption. Studies have shown that pearl millet flour, which has a higher fat content, begins to deteriorate after 10 to 15 days under typical storage conditions.[7] To increase the shelf life of millet flour, various processing methods such as preservatives, heat treatments, and mechanical processing are used to inhibit enzymes and prevent microbial growth. Additionally, conventional processing techniques like fermentation, soaking, and malting are used to improve the bioavailability and storage stability of millet-based products.[4] Millet processing aims to enhance the bioavailability of nutrients, improve organoleptic properties, and reduce antinutritional factors. However, it is important to note that these processing methods can lead to a significant loss of nutrients. For example, traditional and modern processing methods like dehulling, milling, extrusion, and thermal treatments can result in significant nutrient losses.[2] Decortication and milling often lead to reduced fiber and micronutrient content, primarily due to the removal of the nutrient-rich bran and germ portions.[5] High-temperature processes, such as roasting, puffing, and popping, can degrade fats, leading to reduced fat content and potential rancidity issues due to lipolysis and oxidation of fatty acids.[6] On the other hand, simple techniques like soaking, germination, and malting can enhance protein digestibility and mineral bioavailability while maintaining a lower fat content.[4] Understanding the impact of various processing methods is crucial for selecting appropriate techniques to maximize the nutritional benefits and shelf life of millet-based products.

This study conducts a thorough investigation of the most recent scientific studies on functional and nutritional alterations that occur during millet processing. Furthermore, it delves into studies investigating the storage stability of millets. The primary objective is to unravel the intricacies of millet processing techniques, which not only enhance nutritional value but also contribute to prolonged shelf life. Beyond the nutritional realm, these techniques address global nutritional challenges, mitigate hidden hunger, prevent food wastage, bolster economic viability in agriculture, foster culinary innovation, and align with environmentally sustainable practices.

2. INTERNATIONAL SCENARIO OF MILLET PRODUCTION

FAOSTAT (2021) estimates that 84.17 million metric tonnes of millet were produced worldwide in 2019–20 from an area of 70.75 million hectares, with 20.50% of the production being in India.[140] Figure 2 indicates that almost 90 million people in Asia and Africa eat millet as part of their diet. Africa contributes more than 55% of global output, while Asia is second with about 40%, and Europe contributes only about 3% of the market.[19] Sorghum is the most widely farmed millet in the world, accounting for 65.8% of overall millet production. Sorghum and pearl millet together contribute to 92.6% of the

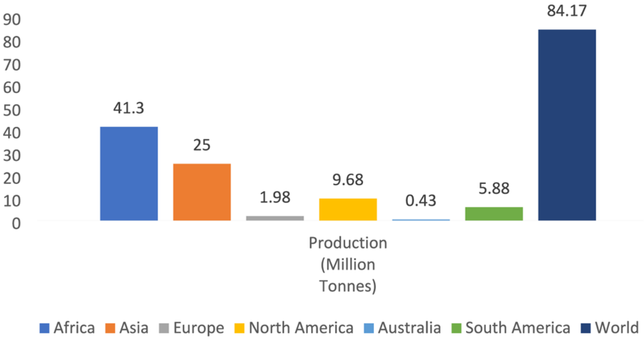

Figure 2. Global scenario of millet production.[140]

worldwide millet production, with the remaining 7.94% divided among proso millet, little millet, foxtail millet, kodo millet, and other varieties.

3. DIETARY ATTRIBUTES AND POTENTIAL WELLNESS GAINS OF MILLETS

Most millets are nutritionally superior to, or preferably equal to, main grains such as wheat and rice.[7] A comparison of the nutritional value of millets and other common cereals is depicted in (Figure 3). In Asian and African nations, millet is a common food source, providing a calorie-dense, nutrient-rich diet associated with numerous health advantages. Millets contain significant concentrations of phenolic phytochemicals, specifically flavonoids and phenolics.[8] Phenolics and tannins make up most of the polyphenols, and flavonoids are present in small amounts. While millets have a good nutritional profile, their tannin and phenolic content may hinder the absorption of important nutrients.[8] These compounds form complexes with minerals like iron and zinc, reducing the bioavailability of nutrients and impeding their absorption. Another antinutrient in millets is phytic acid, which binds to proteins and minerals, further inhibiting absorption. Different processing techniques can lower the amounts of these antinutritional substances despite these challenges.[9] Millets serve as a rich reservoir of both macro (Table 1) and micronutrients (Table 3), surpassing other primary cereals like wheat and rice in terms of their mineral composition and essential amino acid makeup.[10] Several necessary amino acids are also abundant in millet protein.[11]

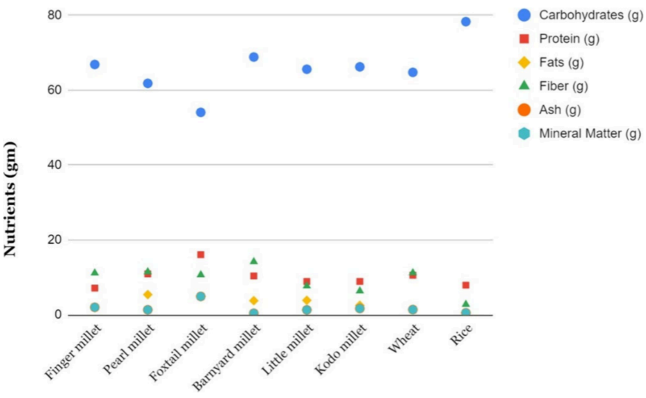

Figure 3. Comparison of the nutritional content of various millets with that of other common grains.

In millets, carbohydrates are primarily composed of starch (60−75%), nonstarchy polysaccharides (15−20%), and free sugars (2−3%), with variation depending on variety and climate.[12] Furthermore, millets' varied dietary fiber composition contributes to antioxidant activity and may help prevent degenerative diseases.[13] Millets' protein content varies by genetic and agro-geographical characteristics. In addition, proso and little millet have a range of protein contents between ten and 15 percent, making them attractive for use in value-added food products.[14] Millets, such as finger millet and kodo millet, stand out for their notable amino acid compositions, particularly lysine, which ranges from 2.2 to 5.5 g per 100 g of protein. In comparison, pearl millet exhibits a significantly higher lysine content of up to 6.5 g per 100 g of protein.[15,16] When comparing these millets to other common cereals, the lysine content of millets generally varies, with finger millet containing 2.83 g, kodo millet 1.42 g, and little millet 2.42 g per 100 g protein. In contrast, rice and wheat have lysine contents of 3.70 and 2.42 g per 100 g protein, respectively. This makes pearl millet's lysine content particularly notable among the cereals considered. Additionally, millets offer a rich profile of other essential amino acids, such as histidine, leucine, isoleucine, methionine, phenylalanine, threonine, tryptophan, and valine, further emphasizing their nutritional value compared to traditional cereals like rice and wheat. For a detailed comparison of the essential amino acid distribution in millets and other grains, refer to Table 2. Generally, pearl millet has a higher lipid content compared to sorghum and most other popular grains. Pearl millet has a total lipid content of 5.06%, with 77.22% mono- or polyunsaturated fats. The extracted oil has a high concentration of linoleic acid (47.5%) but low quantities of linolenic acid (2.15%). In comparison, finger millet differs, with oleic acid accounting for 47.5% of total lipids. Millets' nonpolar lipids, which account for over 80% of total fat, are primarily triacylglycerols.[17] Polar lipids in pearl millet include phospholipids (∼12%) and glycolipids (∼3%) encompassing various components such as phosphatidylglycerol, phosphatidylcholine, acyl-monogalactosyldiacylglycerol, lysophosphatidylcholine, cerebroside, sterol glycoside, among others.[13] The research findings suggest that millets, including seven varieties such as little, barnyard, kodo, foxtail, finger, pearl, and proso millet, are characterized by an excellent nutrient profile (Figure 3). This profile encompasses high levels of insoluble dietary fiber, lipids, and minerals, coupled with a rich content of unsaturated fatty acids and phenolic acids.[18] The nutrient composition of millet and other cereal grains is given in Table 1. Additionally, these millets exhibit a low glycemic index ranging between 42.7 and 58.3, indicating their potential to be valuable and sustainable functional food ingredients, particularly beneficial for individuals with diabetes.

Minerals and vitamins are classified as micronutrients since they have minimal needs for the human body. Minerals are essential for bone formation, blood coagulation, cardiac

Table 1. Nutritional Content of Different Millets Compared to That of Other Common Grains (per 100 g)[113]

Millet	Moisture (g)	Protein (g)	Ash (g)	Fats (g)	Fiber (g)	Carbohydrates (g)	Energy (kJ)
Finger millet	10.89 ± 0.61	07.16 ± 0.63	2.04 ± 0.34	1.92 ± 0.14	11.18 ± 1.14	66.82 ± 0.73	1342 ± 10
Pearl millet	08.97 ± 0.60	10.96 ± 0.26	1.37 ± 0.17	5.43 ± 0.64	11.49 ± 0.62	61.78 ± 0.85	1456 ± 18
Foxtail millet	9.27 ± 0.10	16.08 ± 0.33	4.94 ± 0.002	4.86 ± 0.05	10.70 ± 0.42	54.04 ± 0.07	1470 ± 10
Barnyard millet	9.8 ± 0.05	10.4 ± 0.02	0.45 ± 0.01	3.8 ± 0.02	14.2 ± 0.28	68.8 ± 0.11	1284 ± 0.08
Little millet	14.23 ± 0.45	08.92 ± 1.09	1.34 ± 0.16	3.89 ± 0.35	7.72 ± 0.92	65.55 ± 1.29	1449 ± 19
Kodo millet	14.23 ± 0.45	08.92 ± 1.09	1.72 ± 0.27	2.55 ± 0.13	6.39 ± 0.60	66.19 ± 1.19	1388 ± 10
Wheat (whole)	10.58 ± 1.11	10.59 ± 0.60	1.42 ± 0.19	1.47 ± 0.05	11.23 ± 0.77	64.72 ± 1.74	1347 ± 23
Rice (raw milled)	09.93 ± 0.75	07.94 ± 0.58	0.56 ± 0.08	0.52 ± 0.05	2.81 ± 0.42	78.24 ± 0.68	1491 ± 15

Table 2. Millet Essential Amino Acid Distribution Compared to That of Other Common Grains (per 100 g)[113]

Millet	Histidine (g)	Leucine (g)	Isoleucine (g)	Lysine (g)	Methionine (g)	Phenylalanine (g)	Threonine (g)	Tryptophan (g)	Valine (g)
Finger millet	2.37 ± 0.46	8.86 ± 0.54	3.70 ± 0.44	2.83 ± 0.34	2.74 ± 0.27	5.70 ± 1.27	3.84 ± 0.45	0.91 ± 0.30	5.65 ± 0.44
Pearl millet	2.15 ± 0.37	8.52 ± 0.86	3.45 ± 0.74	3.19 ± 0.49	2.11 ± 0.50	4.82 ± 1.18	3.55 ± 0.40	1.33 ± 0.30	4.79 ± 1.04
Little millet	2.35 ± 0.18	8.08 ± 0.06	4.14 ± 0.08	2.42 ± 0.10	2.21 ± 0.10	6.14 ± 0.10	4.24 ± 0.12	1.35 ± 0.10	5.31 ± 0.16
Kodo millet	2.14 ± 0.07	11.96 ± 1.65	4.55 ± 0.22	1.42 ± 0.17	2.69 ± 0.16	6.27 ± 0.34	3.89 ± 0.16	1.32 ± 0.19	5.49 ± 0.23
Rice	2.45 ± 0.34	8.09 ± 0.40	4.29 ± 0.23	3.70 ± 0.39	2.60 ± 0.34	5.36 ± 0.43	3.28 ± 0.27	1.27 ± 0.14	6.06 ± 0.02
Wheat	2.56 ± 0.25	6.13 ± 0.48	3.78 ± 0.21	2.42 ± 0.22	1.77 ± 0.08	5.03 ± 0.14	2.58 ± 0.14	0.99 ± 0.16	5.12 ± 0.48

regulation, immunity, and nervous system function.[19] Mineral shortages can lead to a variety of health concerns. Micronutrient deficits, particularly calcium, and iron, are prevalent globally and nationally.[20] Finger millet has the greatest calcium concentration (350 g/100gm) among cereals, surpassing wheat and rice by manyfold. Finger millet has enough calcium to satisfy 50% of the recommended dietary requirement (RDA) for men, women, boys, and girls, as well as 40% for nursing and pregnant women.[21] Thus, ingestion of finger millet can help with calcium shortage and osteoporosis. Barnyard millet, small millet, pearl millet, and foxtail millet are good sources of iron. Little millet has the greatest iron content (9.3 mg/100gm), meeting about one-third of the daily iron requirement for pregnant women (35 mg/d). Long-term exposure to zinc deficiency increases the risk of diarrhea, limited physical growth, and weakened immunological function.[22]

Little millet has the greatest zinc concentration (3.7 mg/100g), followed by pearl millet (3.1 mg/100g), barnyard millet (3.0 mg/100g), and finger millet (2.3 mg/100g). Millets are rich in water-soluble vitamins, including riboflavin, thiamine, and niacin. The millet variety Foxtail has the highest thiamine level (0.59 mg/100gm) among millet varieties. Pearl millet has the greatest riboflavin concentration (0.25 mg/100gm), followed by finger millet (0.19 mg/100gm) and foxtail millet (0.11 mg/100gm). This is significantly higher than basic grains like rice and wheat. Barnyard millet has the greatest Niacin concentration (4.2 mg/100gm) compared to other millet varieties. Millets are considered nutritious grains due to their high nutritional content. Table 3 summarizes the micronutrient content of millet crops. The dietary attributes of millets, encompassing their richness in minerals, vitamins, proteins, fatty acids, and fiber, coupled with potential wellness gains derived from the presence of positive health-contributing phytochemicals, antioxidants, and prebiotic properties, highlight the significance of millets as a valuable and nutritious component in addressing nutritional security and promoting overall health.[7] To maximize the potential of millet as a valuable and nutritious component, efforts should be made to improve its shelf stability and nutrient bioavailability. Addressing concerns about their storage and processing is critical for nutritional security and promoting overall health.

4. PROCESSING TECHNIQUES FOR MILLETS

Millets are nutritionally similar to major cereals, as they contain significant amounts of protein, minerals, and phytochemicals.[5] Various processing methods such as soaking, malting, decortications, and boiling are known to have a significant impact on their antioxidant content and activity.[23] Processing millets with precision is essential for improving their digestibility and nutritional value. One effective processing method that enhances the nutritional value of millet is fermentation.[15] During fermentation, beneficial microorganisms such as bacteria and yeast interact with the grains, altering the biochemistry of millet. This process increases the bioavailability of some nutrients, including vitamins and minerals, by breaking down complex compounds and releasing substances that would otherwise be less accessible.[5] Additionally, fermentation can improve the digestibility of millet and accelerate the body's absorption of it by partially predigesting complex proteins and carbohydrates. According to Taylor and Kruger, including fermentation in the millet processing process can enhance its nutritional value, taste, and overall appeal as a nutritious food choice.[15] To improve nutrient bioavailability and facilitate the absorption of essential minerals, techniques such as soaking, malting, and boiling reduce levels of antinutrients such as tannins and phytates.[23] Using methods like decortications to remove the outer husks or bran layers from millets makes the grain softer and easier to chew, which helps to increase digestibility.[24] Both nonthermal and thermal processing can significantly lower the amount of antinutrients and improve nutrient absorption. Moreover, processing techniques can enhance the flavor and aroma of millet, increasing its market appeal and popularity.[25]

Processing methods that improve millets' absorption of micronutrients are based on lowering antinutritional elements such phytic acid, tannins, and polyphenols. Key minerals become less bioavailable due to the binding of these molecules.[21] By allowing millet grains to soak, you can release bound minerals like iron, zinc, and calcium by activating endogenous enzymes like phytases, which hydrolyze phytic acid into reduced inositol phosphates and inorganic phosphate. Enzymatic activity is increased during germination, further breaking down phytic acid and raising ascorbic acid levels, both of which can aid in the absorption of iron.[6] Lactic acid bacteria-mediated fermentation lowers pH and breaks down phytic acid and tannins more thoroughly, increasing the solubility and bioavailability of minerals. Proteins that might normally form insoluble compounds with minerals are denatured and their tannin levels are lowered during cooking and roasting. In general, these activities alter the antinutritional factors which reduces their capacity to chelate minerals and increases the bioavailability of micronutrients.[25] Processing techniques significantly impact the morphology of millet grains, resulting in various structural changes. Primary processing methods such as dehulling, milling, soaking, germination, fermentation, malting, and roasting alter the physical and anatomical attributes of millets (Table 4 summarizes changes in the nutritional characteristics of millets as a consequence of processing processes). For instance, decortication removes the outer husk, bran, and germ portions, reducing the grain's fiber content and impacting its overall structure. This process can improve the protein digestibility of millets by eliminating antinutrients like phytates and tannins

Table 3. Micronutrient Contents of Millets with Major Cereals Rice and Wheat[113]

Crops	Fe (mg)	Ca (mg)	K (mg)	Mg (mg)	Zn (mg)	Thiamine (μg)	Riboflavin (μg)	Niacin (μg)	Biotin (B7)	Ref
Finger millet	4.62 ± 0.36	364 ± 58.0	443 ± 59.6	146 ± 10.7	2.53 ± 0.51	0.37 ± 0.041	0.17 ± 0.008	1.34 ± 0.02	0.88 ± 0.05	113
Pearl millet	6.42 ± 1.04	27.35 ± 2.16	365 ± 18.0	124 ± 19. 5	2.76 ± 0.36	0.25 ± 0.044	0.20 ± 0.038	0.86 ± 0.10	0.64 ± 0.05	
Foxtail millet	2.8	31.0	250.0	81.0	2.4	0.59	0.11	3.20	-	
Barnyard millet	5.0–18.6	22	-	82.0	3.0	0.33	0.10	4.2	-	
Little millet	1.26 ± 0.44	16.06 ± 1.54	105 ± 15.7	91. 41 ± 12.6	1.82 ± 0.14	0.26 ± 0.042	0.05 ± 0.008	1.29 ± 0.02	6.03 ± 0.57	
Kodo millet	2.34 ± 0.46	15.27 ± 1.28	94 ± 10.7	122 ± 5.9	1.65 ± 0.18	0.29 ± 0.054	0.20 ± 0.018	1.49 ± 0.08	1.49 ± 0.18	
Wheat(whole)	3.97 ± 0.78	39. 36 ± 5.65	366 ± 59.6	125 ± 14.8	2.85 ± 0.65	0.46 ± 0.067	0.15 ± 0.041	2.68 ± 0.19	1.03 ± 0.58	
Rice (raw milled)	0.65 ± 0.11	7.49 ± 1.26	108 ± 10.9	19.30 ± 6.99	1.21 ± 0.17	0.05 ± 0.019	0.05 ± 0.006	1.69 ± 0.13	0.60 ± 0.12	

concentrated in the outer layers.[10] Milling, another common processing technique, often leads to the reduction of grain size and the transformation of whole grains into flour or semolina. This size reduction process significantly changes the grain's surface area, enhancing its cooking and digestibility properties but also potentially leading to nutrient losses.[22] Advanced processing methods, including extrusion, puffing, and popping, also induce significant morphological changes by applying high temperatures and mechanical forces. These techniques can cause the starch granules within the millet to gelatinize and expand, resulting in a puffed texture. Such transformations not only alter the physical appearance and texture of the grains but also affect their nutritional profiles and shelf life.[6] Understanding these morphological changes is crucial for optimizing processing methods to retain the nutritional benefits while enhancing the sensory properties of millet-based products.

Furthermore, proper processing ensures food safety by reducing the likelihood of infection with harmful or hazardous bacteria. Effective processing methods are necessary to optimize millets' nutritional content, digestibility, safety, and consumer appeal and promote its usage as a healthful staple food.[24] All things considered, adding effective processing methods to millet may enhance its nutritional content, flavor, and general attractiveness as a healthful food option.

5. TRADITIONAL PROCESSING TECHNIQUES

5.1. Decortication. Decortication is a complex process of rubbing the outer layer and carefully removing the internal part of millet seeds. Millet seeds lose 20−22% of their weight when decorticated, yet this treatment enhances their nutritional value and economic viability. Decortication lowers the overall mineral contents but raises calcium, iron, and zinc's bioaccessibility by 15, 26, and 24 g/100 g, accordingly.[26] It increases the digestibility of proteins while markedly reducing polyphenols, total phytic acid, fiber, and tannin content. A 6 min duration of milling provides maximum bioaccessibility of iron and zinc.[26] Decorticated millet has a higher market value because of its increased nutritional profile and adaptability in a variety of food items, including flour, cereals, and snacks. While there are costs involved with the decortication process, these can be mitigated by increasing demand and the opportunity to reduce waste via usage.[27] Overall, the nutritional and economic benefits of decortication outweigh any weight loss, providing decorticated millets an important contribution to the food market.

Proso millet has higher levels of essential amino acids and selecting the right cultivar is important due to variability in methionine levels. Proso millet (Panicum miliaceum L.) samples, comprising 23 whole and 12 dehulled, were analyzed for their amino acid profiles, including methionine. Significant differences in methionine content were observed among the cultivars. Several cultivars have been identified as superior in terms of nutritional content. For instance, the cultivar "30-Sunrise-H" had methionine levels close to the mean of all samples, making it a good choice for nutritional balance. Additionally, the cultivar "Kornberger" was noted for having the highest total amino acid content among the samples tested, indicating its superior overall nutritional profile. These findings[138] suggest that while there is considerable variability in methionine levels among proso millet cultivars, selecting specific cultivars like "Sunrise" and "Kornberger" can enhance the nutritional value of millet-based diets. Removing the outer layer of the grain does not significantly affect the amino acid

Table 4. Changes in the Nutritional Characteristics of Millets as a Consequence of Processing Processes

Processing Methods	Millets	Inference	References
Decortication	Pearl millet	Decreased overall polyphenolic content to 9% and phytic acid in PM by 53%	114, 115
		Decreased ash by 0.8%, fiber by 1.61%, protein by 1.58%	
		Lowered tannins per 100g to 174.4 mg from 343.91 mg	
		Lowers phytic acid per100g to 77.95 mg from 301.10 mg, calcium to 115 mg from 129 mg	
	Finger millet	Decrease in phytate phosphorus up to 39%	116
	Small millet	Decreases phytic phosphorus by 39%	117
	Barnyard millet	Decreased phytic acid to 23%	24
	Little millet	Decreased 67% of vitamin E	118
Germination	Foxtail millet	Germination increased protein content from 10.60 to 13.75. Increased level of antioxidants	119
	Kodo millet	Germinating 38.75 °C millet increased dietary fiber to 38.34g from 35.30 g	120
	Finger millet	Tannins reduced to 0.83% from 1.6%	121
		Protein level increased from 6.3 to 8.8 g per 100 g	41
		Dietary fiber increased from 18.9 to 20.0 g	
	Proso millet	The bioavailability of protein and minerals increased	122,123
	Pearl millet	Resulted in a reduction of polyphenols up to 75% concentration	33
		Increased crude fiber and 50% of protein content	
		24 h of malting increased protein content to 7.87% from 7.52%	
		Increased fiber content to 7.87% from 7.52%	
		Decreased fat content to 5.55% from 6.34%	
Soaking	Finger millet	Phytic acid was significantly reduced by immersing finger millet	53
		250 mg in 12 h of immersion, from 241 mg to 221 mg/100 g when soaking was increased to 24 and 48 h.	
	Pearl millet	12 h of soaking resulted in a decrease of polyphenol to 184.43 from 241.47 GAE mg per 100 g	124
	Kodo millet	By eliminating antinutrients, soaking increased protein digestibility from 62.3 to 76%.	125
Fermentation	Foxtail millet	Increased the content of crude protein, decreased the number of total carbohydrates, and improved nutritional value.	98, 52
		Increased the total phenolic content by 81.11% and the free radical scavenging capacity by 7.02 mg/g.	
	Finger millet	24 h of fermentation resulted in a decrease of phytate by 20% and tannin by 52%	57
		Increased calcium by 20%, zinc by 26%, and iron by 27%	
		Vitamins like riboflavin, niacin, and thiamine also increased	
	Little millet	Protein content increased and fat content decreased	126
	Pearl millet	Protein content increased from 8.7% in the unfermented sample to 20.54%	127, 98
		Lipid content dropped from 10.34 to 0.34 and 0.74, respectively	
		Protein content increased to 13.65% from 10.99 and crude fat increased to 3.71% from 1.83%	
		After 16 h of fermentation protein content increased by 15.32%	
Cooking	Pearl millet	Bioaccessibility of minerals like iron, zinc, and calcium increased in vitro, whereas antinutritional elements such as phytic acid decreased	128, 129
		Increased phenolic content to 3137 from 2394 g GAE/g	
	Proso millet	Reduced starch by 28%	130
		Protein digestibility was shown to be drastically reduced after cooking	
Roasting	Pearl millet	Increased overall polyphenol bioaccessibility from 73.2% in native grains to 78.1% in roasted samples	37
		Increased total ash from 1.68% to 2.21%	33
		Decreased crude fiber from 1.06% to 0.50%	
	Foxtail millet	Reduced antinutrients such as tannins 221.1 to 92.4 mg CAE per100 g and phytic acid from 306 to 180.5 mg per 100 g	131
	Finger millet	Increased minerals such as calcium from 337.31 to 341.24 mg per 100 g and iron from 3.45 to 3.91 mg per 100 g	28
		Increased carbohydrate from 75.94% to 79.32%,	
		Decreased moisture by 2.67%	
		Decreased protein by1.4%	
		Decreased fat by 0.12%	
		Decreased phenolics from 314.24 to 223.31 mg per100 g	
	Proso millet	Increased phenolic content from 295 to 670 mg per100 g	132
Puffing	Finger millet	Decrease in Crude fiber 1.71% and fat content 0.06%	133
		Resulted in a decrease of calcium to 18 mg from 27 mg per 100 g	
		Increased iron content to 5.1 g from 3.7 per 100 g	
		Increased protein content to 7.1 from 6.3 per 100 g	
	Kodo millet	Protein concentration increased to 8.12 from 7.92%	134
	Foxtail millet	Reduced fiber than raw millet	135
	Pearl millet	Resulted in a reduction of crude fiber to 15.8 from 18.9 g/100 g	105
		Reduced 54.78% phytic acid	

compositions.[27] Experiments on little millet, revealed that specific pretreatment methods, such as soaking for 4 h followed by hot air drying at 45 °C, significantly enhance dehulling and milling efficiency. This optimized pretreatment addresses the challenging postharvest operations, thereby contributing to the commercial viability of little millet.[28] The study provides insights into strategies to minimize the loss of essential minerals like calcium, phosphorus, and iron during decortication and storage of millets.[139] It emphasizes the importance of pretreatment methods, such as soaking, drying, tempering, hydrothermal treatment, microwave drying, infrared drying, high-pressure processing, pulsed electric field, cold plasma, and enzyme treatment. These methods help to soften the hull and reduce the loss of nutrients during the decortication process. The use of novel thermal and nonthermal techniques is particularly highlighted for their potential to diminish nutrient loss.[139] The effects of modern and traditional decortication processes on the chemical composition, mineral concentrations, and antinutrients (P, Fe, and Ca) of two pearl millet cultivars (white and green) cultivated in Sudan during storage. The study demonstrates how both decortication processes considerably affect nutritional content, with storage having a progressive effect on numerous components.[29] Modern decortication reduces tannin content, but phytic acid decreases only in green millets. The modern and traditional methods for removing the outer husk from millets have varying impacts on efficiency, cost, nutritional quality, long-term storage, and shelf life. Modern mechanized and automated technologies increase efficiency, homogeneity, and throughput, making them appropriate for large-scale manufacturing despite their high initial and continuing costs.[29] Modern decortication allows for more control over the process, resulting in reduced nutritional loss and improved retention of essential vitamins and minerals. Furthermore, modern methods effectively remove antinutrients such as tannins and phytic acid, improving nutritional quality by enhancing protein digestibility and mineral availability.[30] They also yield millets with lower moisture content and fewer impurities, which increases shelf life and reduces the danger of spoiling and insect infestation.

On the other hand, traditional decortication methods rely on manual labor and simple tools like a wooden mortar and pestle. These methods are less efficient and more labor-intensive but have the advantage of lower initial and operating costs. Traditional methods may result in uneven decortication and higher nutrient loss but tend to preserve more natural fiber, making them valuable in rural or resource-limited settings.[29] While traditional decortication has minimal impact on the protein and fat content of millets, it can reduce crude and dietary fiber and mineral content. Despite their lower efficiency, traditional methods are more accessible and cost-effective for small-scale operations, although they may not achieve the same level of nutritional improvement as modern methods.[30]

In terms of long-term storage and shelf life, modern decortication methods generally offer better preservation by more effectively removing outer layers prone to spoilage. However, both methods show a gradual reduction in protein, oil, and ash content over time during storage, with modern decortication showing a more pronounced decrease. Thus, while modern methods may enhance the immediate nutritional quality of millets, traditional methods provide cost benefits and accessibility, albeit with potentially lower nutritional gains. Ultimately, the choice between modern and traditional decortication methods depends on factors such as economic considerations, production scale, and cultural preferences, as each approach offers unique advantages and challenges. Millet bran contains protein, dietary fiber, minerals, lipids, phenolic compounds, and phytonutrients. Furthermore, the phytonutrients in millet brans increase their antioxidant activity, making them a viable ingredient for producing functional foods.[31] The conclusion is that removing the outer layers of grains increases the availability of minerals and significantly reduces the amount of antinutrients. It is essential to use the process of decortication in the commercial production of edible food items. Additionally, using modern methods of removing the outer layers instead of old ones will save labor, money, and time.

5.2. Roasting. In roasting, dry heat is used to brown the outermost layer of food and enhance its flavor, whether it comes from an open flame, an oven, or anything else. Roasting may also enhance the range of fragrance molecules in millets and give them a distinct odor.[32] Roasting reduced protein content from 8.38% to 7.34%, increased total ash from 1.68% to 2.21%, and decreased crude fiber from 1.06% to 0.50%.[33] The control sample had the highest protein content, suggesting that roasting can alter the millet's protein structure and lead to the loss of some amino acids due to heat. some amino acids in millets are more prone to breakdown. Specifically, roasting has a major impact on essential amino acids such as lysine and methionine. Lysine is particularly susceptible to heat and degrades significantly, limiting its availability. Methionine also declines, although not as much as lysine.[33] The ash content increased with higher roasting temperatures, with millet roasted at 180 °C for 10 min having the highest ash content, while native millet had the lowest. An increase in roasting temperature resulted in decreased crude fiber content in the pearl millet flour. A study on finger millet found that roasting led to a decrease in moisture content from 10.67% to 8.00%, a rise in total carbohydrate content from 75.94% to 79.32%, an increase in ash content from 3.10% to 4.00%, and a slight increase in crude fiber content from 3.90% to 4.20%.[34] Further, crude fat content decreased from 1.54% to 1.33%, while protein levels decreased from 8.75% to 7.35%. As a result of fat or starch lipid compounds developing that are resistant to lipid extraction and heat exposure, fat and moisture content decreased. Also, roasting increased iron content from 3.45 mg/100g to 3.91 mg/100g, as well as calcium content from 337.31 mg/100g in raw finger millet to 341.24 mg/100g in roasted finger millet.[34] The increase in iron concentration may have resulted from contamination of the iron roasting pan. This should be recognized as a potential limitation of the study rather than an actual outcome of the roasting process.

A more recent study observed that roasting reduced moisture content from 8.53% to 0.81%, fat reduced from 4.29 to 4.13%, protein reduced from 13.01% to 11.46%, crude fiber reduced from 7.92% to 7.13%, and ash reduced by 2.78% to 2.64%. In contrast, carbohydrates increased to 72.28% from 65%.[35] In another study found that roasting significantly increased carbohydrate, ash, fat, fiber, and protein content in white finger millet (WFM) KMR-340 flour, indicating substantial changes in its nutritional composition. Both processing methods also altered amino acid composition, improved functional properties, introduced variations in starch behavior, and reduced the percentage crystallinity in the processed flours, indicating structural changes.[36] The research recommends roasting at temperatures ranging from 120 to 140

°C for 5 to 15 min.[33] This helps to maintain a greater protein and fiber composition. In comparison to higher temperatures, roasting at these temperatures preserves more protein, lysine, and methionine. However, protein content normally declines with increasing roasting temperature due to denaturation and amino acid loss. Furthermore, roasting at moderate temperatures can improve functional properties like water solubility and oil absorption capacity, which are critical for flavor and mouthfeel. After roasting, the moisture level falls dramatically, reducing the danger of microbial development and perhaps extending the flour's shelf life. Higher temperatures (160 to 180 °C) can enhance functional characteristics, but they also significantly reduce phenolic content and other nutrients. The mineral content, notably iron, rises as temperatures rise, most likely owing to leaching from roasting equipment, whereas potassium and phosphorus levels fall. The concentration of crude fiber functional properties, and longer shelf life.[33] These insights suggest that roasting can be strategically employed to enhance the nutritional value of millet. By carefully adjusting roasting temperatures and durations, it may be possible to optimize millet's nutritional composition, influencing protein structures, amino acid content, and overall nutrient bioavailability.

5.3. Milling.

Milling separates the endosperm, bran, and germ in millet flour production. This process can be done manually or by machine and has a significant impact on millet's chemical composition. When preparing chapati, milling removes bran, which reduces polyphenols and phytic acid. The bran portion, which is richer in these compounds, is separated during milling.[37,38] Despite its utility, milling comes with a nutritional trade-off, leading to a substantial loss of essential nutrients, vitamins, and minerals. This phenomenon is especially evident in the bran portion of grains, resulting in decreased levels of vitamin B, vitamin E, protein, fat, dietary fiber, and essential minerals such as iron, zinc, and calcium, as indicated by studies on pearl millet and finger millet.[15,38] The nutritional implications of bran separation during sieving underscore the need for a nuanced approach in millet processing. In the pursuit of maximizing nutritional quality and increasing shelf life, it becomes imperative to address the challenges posed by nutrient loss during milling. Balancing the efficiency of milling with the retention of key nutrients is crucial for optimizing millet product production. Implementing innovative techniques that minimize nutrient loss, such as controlled milling processes or fortification strategies, can help preserve the nutritional integrity of millet-based products.

5.4. Puffing.

Puffing and extrusion processes typically involve short-duration exposure to high temperatures. The expansion process of proso millet grains, known as puffing, can result in an apparent increase in starch content due to a significant loss in water content throughout the process. Before puffing, proso millet grains contain 73.81% ± 4.29% starch. After puffing, the starch concentration dramatically decreases to 72.58% ± 3.19%. This slight drop in starch % might be attributed to the mechanically disordered structure of starch polymers caused by temperature and pressure during puffing. Chilling causes partially broken starch polymers to stretch and gelatinize, resulting in a starch gel.[39] This research study focused on the suitability of puffing as a food processing method for kodo millet varieties, specifically examining the nutritional changes in two varieties, JK48 and JK155. Upon puffing, JK48 demonstrated a decrease in moisture (7.35% to 3.35%), fat (1.44% to 1.41%), crude fiber (9.83 g/100gm to 8.92 g/100gm), and phosphorus (188 mg/100gm to 178 mg/100gm). Simultaneously, protein increased from 7.92% to 8.02%, carbohydrate from 69.48% to 74.38%, and energy value from 322.56 kcal/100gm to 342.56 kcal/100gm.[40] The research study on finger millet, the popping process, applied to Popped Finger Millet Flour, brought about noteworthy changes in its nutritional attributes.[41] The moisture content decreased due to the expulsion of water under the high-temperature conditions during popping. The fat content witnessed a significant decline due to a phenomenon attributed to the denaturation of lipolytic enzymes during the intense heat treatment. Concurrently, there was a significant reduction in calcium, crude fiber, moisture, and fat content from 342 to 338 mg/100 g, 18.9 to 15.8 g/100 g, 13.1 to 12.2 g/100 g, and 1.3−0.63 g/100 g, respectively, and an increase in protein, carbohydrate, and iron content from 6.3 to 7.1 g/100 g, 71.9 to 75.73 g/100 g, and 3.7 to 5.1 mg/100 g, respectively. Moreover, the crude fiber content experienced a notable decrease, declining suggesting alterations in the fibrous composition of the millet.[41] These findings underscore the transformative impact of popping on the nutritional composition of finger millet. In this research study, the focus was on exploring the impact of various parameters, including pearl millet variety, amylose content, pericarp thickness, processing temperature, and chemical composition, on the volume expansion ratio and sensory properties of popped pearl millet. Employing a conventional salt-popping technique at three different temperatures (220 °C, 240 °C, and 260 °C) for five pearl millet varieties, the investigation delved into the relationships between these parameters and the popping characteristics. Results highlighted the positive correlation of amylose content and pericarp thickness with popping qualities, particularly emphasizing the superior properties of the AIMP 92901 variety, which exhibited the highest popping yield and expansion ratio at 260 °C. This conclusion underscores the efficacy of conventional salt popping at 260 °C in producing optimal popping characteristics in pearl millet, with potential implications for enhancing the utilization of this underutilized grain in ready-to-eat snacks.[42]

6. BIOPROCESSING

6.1. Soaking and Germination.

Soaking grains is an established method of food preparation at home. Soaking increases mineral accessibility by reducing antinutrient levels.[43] Millet germination is the process by which millet seeds absorb water and undergo biochemical and physiological modifications that result in the formation of a sprout or seedling. In a comprehensive exploration conducted by Prasad et al.,[43] the transformative effects of soaking and germination on proso and foxtail millet flour were unveiled. Soaking, serving as a pretreatment, expeditiously activated enzymes and initiated sprout development, leading to substantial changes in millet nutritional composition. Notably, overall starch content witnessed significant reductions of fifty-two percent for proso millet, 30 percent for foxtail millet, and twenty-six percent for white quinoa flour. The intriguing observation of reduced fat content, adds another dimension to the nutritional optimization process. While contributing to healthier millet products, this phenomenon may also play a role in extending shelf life through decreased lipid oxidation. Furthermore, soaking and germination revealed noteworthy alterations in millets. Proso millet exhibited a commendable 15% increase in phenolic content and a 4% increase in flavonoid content. Similarly,

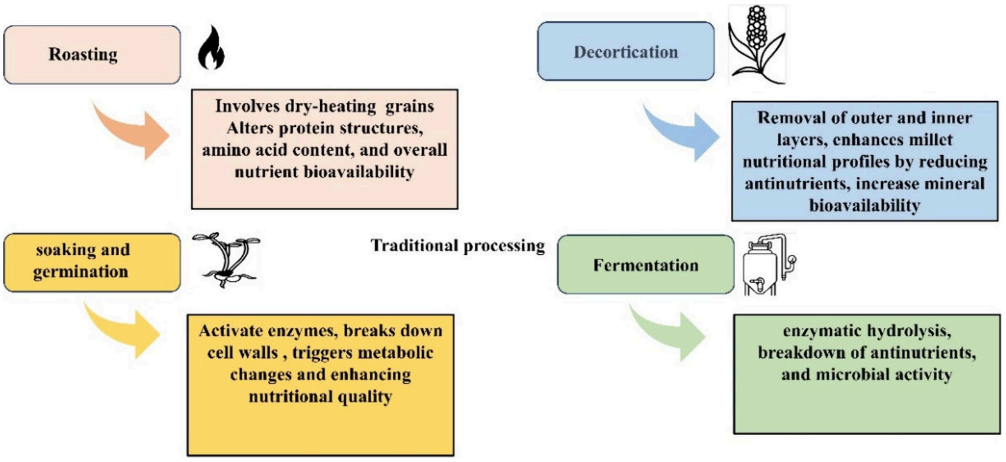

Figure 4. Traditional processing and bioprocessing techniques

foxtail millet displayed remarkable increments in both phenolic content (36%) and flavonoid content (24%). The molecular pathways that cause starch and fat content to decrease while phenolic and flavonoid concentrations increase during soaking and germination are tricky. When seeds absorb water while soaking, it activates a variety of enzymes. Enzymes like α-amylase and β-amylase break down starch into simpler sugars, resulting in lower starch content. This procedure is critical for giving a sprout the vitality it requires to thrive. During germination, these enzymes continue to degrade the starch granules, causing them to expand and finally disintegrate.[43] Similarly, activation of lipase enzymes, which degrade lipids into free fatty acids and glycerol, lowers fat levels. This hydrolysis is part of the seed preparation process, which releases stored energy for the growing plant. The breakdown of complex lipids into simpler ones makes energy more readily available for metabolic processes during germination. The rise in phenolic and flavonoid content is owing to the release of these compounds from the cellular matrix as a result of cell wall breakdown, as well as the formation of new phenolic compounds.[44] Key enzymes such as phenylalanine ammonia-lyase and chalcone isomerase are essential in the phenylpropanoid pathway, which transforms phenylalanine into bioactive compounds. During germination, the activity of these enzymes increases dramatically, resulting in greater quantities of phenolic and flavonoid compounds. Changes in the seed's structure during soaking and germination, such as cell wall loosening and increased enzyme activity, help to release and produce these beneficial compounds.[45] This will maximize the nutritional content but also has the potential to extend shelf life by combating oxidative deterioration.[46] Abioye et al.[47] delved into the malting process, uncovering its significant impact on the protein content of pearl millet flour. The protein content surged from 10.48 ± 0.01% in debranded pearl millet to an impressive 15.39 ± 0.00% in malted pearl millet flour, marking a remarkable 50% increase.

The exploration of finger millet, subjected to soaking and germination, yielded increased protein content proportional to the germination duration. Higher protein values in malt can be attributed to the accumulation of protein reserves, protein synthesis, and the formation of specific amino acids. Notably, antioxidant content increased to 51.13% from 48.30%, and flavonoid content rose to 33.33% from 26.66%. Additionally, reductions were observed in phytate levels (from 51.67 to 43.33 mg/100 g), tannin content (from 53.33% to 43.33%), and trypsin content (from 0.47% to 0.37%). These reductions contributed to a decrease in antinutrients, enhancing mineral bioavailability. The soaking and germination of waxy and nonwaxy proso millet showcased a slight increase in protein content. Extended germination led to increased fiber content due to sprout growth, resulting in the synthesis of new primary cell walls. Remarkably, antioxidant content showed significant increases, particularly for waxy proso millet (from 43.43 to 124.82 U/g) and nonwaxy proso millet (from 3.86 to 101.9 U/g).[48] Flavonoid content also played a pivotal role, with notable increases, especially during a prolonged germination period of 4 days. Furthermore, protein digestibility improved for both nonwaxy and waxy proso millet flours. During germination, sprouted millet shows increased in vitro protein digestibility due to enhanced intrinsic proteases/proteolytic activity, the elimination of protease inhibitors, and improved protein solubility. In another investigation by Sharma S, et al.,[49] the effects of germination on Kodo millet were explored, revealing an impressive overall increase in antioxidant activity from 45.34 to 67.23 mg AAE/g. This heightened antioxidant capacity was attributed to metabolic changes during germination, leading to increased production of phenolic compounds through the activity of hydrolytic enzymes. The metal-chelating activity of Kodo millet also increased significantly from 62.34 to 89.32 mg EDTA/g. The heightened metal-chelating activity further suggests potential benefits in preserving millet products by mitigating oxidative reactions that could compromise shelf life. These studies collectively emphasize that the strategic application of soaking and germination in millet processing serves as a powerful means to maximize nutritional content. Some of the traditional and bioprocessing methods are depicted in Figure 4.

6.2. Fermentation. Fermentation is critical in the lasting preservation of foods worldwide, wherein current preservation technologies must be used to increase flavor and nutrition while lowering antinutrients in food products.[50] Using a starting culture or naturally occurring bacteria, fermentation can happen on its own. One possibility is to inoculate the subsequent fermentation process with a part of the fermented food or an intermediate product, such as dough or yogurt.[51] Some nations, particularly in Africa, ferment millets to make a range of meals, such as bakery goods, alcoholic and nonalcoholic drinks, and thick and thin porridges.

Chu et al.[52] reported that fermenting dietary fiber produced from foxtail millet bran with *Bacillus natto* resulted in a substantial increase of 10.9% in soluble dietary fiber (DF) content, as well as a 16.8% rise in the ratio of dissolved DF to insoluble DF. The changes in DF were linked to cellulose and hemicellulose breakdown, which resulted in increased porosity and a loose structure for polysaccharides after fermentation.

The study on fermenting pearl millet by natural means grains revealed that crude protein content has increased from 10.99% to 13.65%, and the crude fat content has increased from 1.83% to 3.71% signifies a substantial enhancement in the nutritional profile.[53] This rise is attributed to the synthesis of proteins during the fermentation process. Furthermore, the decrease in ash, crude fiber, and carbohydrate content, although seemingly negative, can be viewed positively in the context of shelf life. The reduced ash content (4.37% to 3.45%) due to the leaching of soluble inorganic salts, contributes to improved storage durability. The decline in crude fiber (1.20% to 0.54%) due to the enzymatic breakdown of fiber during fermentation may indicate a softer texture, potentially enhancing the palatability and acceptance of millet-based products. Moreover, the decrease in carbohydrate content (75.75% to 73.76%) suggests a possible reduction in sugars due to the metabolic activity of microbes on sugars, contributing to a more stable product with prolonged shelf life.[53] Similarly the protein content of pearl millet grains increased by 15.32% after 16 hours of natural fermentation. The rise in protein levels is due to the solubility of insoluble amino acids during the fermentation process, suggesting that fermenting pearl millet may be an effective strategy to boost its protein content.[54]

Pearl millet's in vitro starch and protein digestibility improves significantly after 72 h of natural fermentation at temperatures ranging from 20 to 30 °C. The highest significant increase, 110.1%, occurs at 30 °C, due to enzymatic hydrolysis during fermentation.[55] Another study reported the improved protein digestibility of pearl millet flour upon 0, 8, and 16 h of fermentation. However, the value was highest (45.75−64.38%) after 16 h of fermentation. The increment in IVPD of fermented millet flour could be due to antinutrient (phytate) degradation by microorganisms, production of some proteolytic enzymes by the microflora, and partial degradation of complex storage proteins into simple and soluble products during fermentation.[56] Similarly, 24 h of fermenting finger millet flour with endogenous grain microflora decreased phytate and tannin by 20% and 52%, respectively. This fermentation procedure significantly boosted calcium, iron, phosphorus, and zinc mineral availability by 20 percent, twenty-seven percent, twenty-six percent, and twenty-six percent respectively. The breakdown of phytate during fermentation was attributed to the reduction in phytic acid concentration, implying higher mineral availability in fermented finger millet. Furthermore, an increase of particular vitamins and some amino acids (methionine and cysteine) in fermented finger millet, indicates that fermented millet products have the potential to add strongly to dietary diversity and nutritional quality.[57] In the case of finger millet, an overall drop in phenolic compounds of as much as 41% after traditional fermentation.[45] This decrease was attributed to the rearrangement of phenolic compounds caused by self-polymerization under acidic conditions throughout fermentation. However, other studies suggest that fermentation boosts bioactive content. The utilization of *Rhizopus azygosporus* as a starting culture over a 10-day fermentation period significantly increased millet's total phenolic content (TPC) from 6.6 to 21.8 mg GAE/g.[58]

Furthermore, Balli et al.[59] reported that fermenting millet for 72 h with yeast and *Lactobacilli* resulted in a 36% increase in phenolic content and an approximately 30% increase in flavonoids (vitexin 2-O-rhamnoside and Vitexin). Notably, these flavonoids were discovered to partially inhibit the tyrosine phosphatase enzyme, which is higher in type 2 diabetes. Vila-Real et al.[60] showcased the benefits of coculturing *Weissella confusa and Lactiplantibacillus plantarum* in finger millet fermentation. This new approach resulted in a fermented beverage with more beneficial strains and increased levels of threonine, arginine, GABA, and glutamine. The fermentation process significantly increased dextran production, apparent viscosity, and protein digestibility, highlighting the potential of coculturing to improve the nutritional profile of fermented millet beverages. Studies suggest that optimizing processing techniques like fermentation, malting, and coculturing can increase the nutritional value of millet-based products. By doing so, millet can become a nutritious and varied dietary source. Overall, fermentation is a useful technique alone or with other processing methods to manufacture highly nutritious food products.

In traditional processing, germinating and fermenting stand out as the superior treatments due to their ability to significantly enhance protein, vitamins, and antioxidants, which are crucial for health. Puffing also shows benefits, particularly for enhancing dietary fiber and antioxidants, but with more nutritional losses compared to germinating and fermenting. In conclusion, germinating and fermenting millets are highly recommended processing methods to maximize nutritional benefits and potentially extend shelf life, despite some loss in energy content and other minor nutrients. These methods effectively address the challenge of nutrient preservation and enhancement in millet-based products.

7. THERMAL PROCESSING

7.1. Microwave Processing.

Microwaves (MC), operating at 2450 MHz, lack ionizing radiation but interact with ionic and dipole elements in the meal. A standard microwave oven, as depicted in Figure 5, can be used for processing millets. Rao et al.[61] revealed that microwave and hot-air-assisted radio-frequency heating significantly reduced lipase activity (LA) by approximately 40%, decreasing free fatty acids (FFA) during accelerated storage by 30%. However, protein denaturation occurred, impacting purity and foaming properties. The

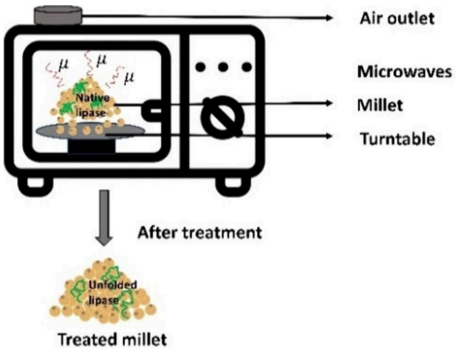

Figure 5. Microwave processing.

Table 5. Changes in the Nutritional Characteristics of Millets as a Consequence of Processing Processes

Processing method	Millets	Inference	References
Microwave processing	Foxtail millet	Increased surface mean temperatures and decreased lipase activity,	61
	white finger millet	Modification on white finger millet (WFM) starch	62
		Increased gel hydration	
		Reduction in oil absorption	
	Little millet	Increased water solubility index (WSI)	62
	Pearl millet	reduced lipase activity by 92.9%	136
Cold plasma	Pearl millet	Reduction in Phytic Acid	76
		Enhanced swelling, water absorption, and pasting characteristics.	78
		Reduced moisture, crude fiber, and protein by starch modification.	
	Kodo millet	Increased water and oil absorption.	77
	Little millet	Reduced amylose concentration	79
		Enhanced the oil absorption capacity, water absorption capacity (WAC), swelling capacity, and solubility index.	
Infrared (IR) heating,	Sorghum	Reduction in free fatty acid (FFA) content with increasing temperature and treatment time.	70
Ultrasound Processing	Finger millet	Reduction in phytates and tannins substantial increase in total phenolic content (TPC) and total flavonoid content (TFC).	85 86 87
Pulsed light processing	Glutinous millet	Reduction in microbial load.	95
High-pressure processing	Foxtail millet	Increases water uptake, starch gelatinization, total phenolic content, and antioxidant activity	98
		Reduction of antinutrients such as phytic acid and tannin	
γ Radiation	Finger millet	Effective starch polymer degradation	68
		Water absorption capacity increased	100
		Increased antioxidant properties	
		Reduced lipoxygenase activity	
	Tunisian millet	Effective in decontamination of millet flour	137
	Pearl, Barnyard, finger, proso and little millet	Reduces the total plate count of microorganisms in millets	67
		Enhances microbial safety and extending the shelf life	

increased surface temperatures suggested efficient conversion of microwave energy into heat, with a rise of approximately 15%. While lipase reduction is beneficial for extending shelf life by decreasing FFA, protein denaturation might pose challenges. Careful optimization is needed to balance these effects to maximize both nutritional content and shelf life.

Microwave processing can affect the nutritional components such as vitamins, minerals, and antioxidants in different ways. The heat generated during microwave processing can destroy heat-sensitive vitamins like vitamin C and several B vitamins.[63] However, shorter cooking times in microwave processing can help retain more vitamins compared to traditional techniques. Vitamins such as niacin and riboflavin generally remain stable during microwave processing. Minerals are typically stable during microwave processing and are less affected by heat than vitamins.[65] Furthermore, microwave processing can enhance the bioavailability of some minerals by reducing antinutritional substances such as phytates, which bind minerals. It is important to note that microwave processing can both increase and decrease antioxidant levels. For example, microwave popping of pearl millet raised steryl ferulates content by more than 50%, owing to the breaking of the pericarp during the process.[65] However, certain antioxidants may deteriorate when exposed to high temperatures over a lengthy period of time. Nonetheless, regulated microwave processing can reduce this loss and sometimes even improve antioxidant capabilities by inactivating degradative enzymes such as lipase and lipoxygenase. The hydrothermal and microwave modifications of white finger millet (WFM) starch resulted in enhanced gel properties.[62] Hydrothermal treatment led to protein denaturation, primarily due to heat-induced unfolding of protein molecules. This unfolding increases the exposure of polar side chains, enhancing the interaction between starch and protein. Consequently, this process improves water absorption capacity (WAC) and impacts the starch's hydration properties and texture. On the other hand, microwave treatment showed a nonsignificant reduction in oil absorption capacity (OAC). Both treatments increased peak viscosity by 20%, affecting retrogradation and gel formation. While starch modifications can improve product texture, they may also alter nutritional content.[62] To extend the shelf life of a product, it is important to understand the balance between structural changes and nutritional benefits. Kumar et al. found that microwave heating affected the water absorption index and water solubility index in tiny millet flour. Pan heating boosted the protein content of proso millet flour by almost 15%. The observed alterations in carbohydrate content (10%) and calorific value indicated cooking-induced modifications.[63] Cooking methods influence functional properties and nutritional composition. Balancing these alterations is essential for creating products with enhanced nutritional content and extended shelf life. Microwave treatments, especially popping of pearl millet, significantly increased steryl ferulates content by over 50%. This was attributed to the breakdown of the pericarp during microwave popping. Microwave heating techniques, like popping, offer a functional method for enhancing specific nutritional components, contributing to both improved nutritional content and potential shelf- life extension. A comparative analysis between microwave (MC) and ultrasound (UC) modification of millet starch showed that MC had a more pronounced influence, impacting various properties. This included reducing peak viscosity (−25%) and relative crystallinity (−15%) and increasing in vitro enzymatic digestibility by approximately 30%.[64] Understanding the superior impact of microwave modification on starch properties provides insights into optimizing both nutritional quality and shelf life. Microwave pretreatment of wholegrain sorghum kernels improved flour stability by reducing lipase activity by 25%, resulting in decreased porridge rancidity and pasting peak viscosity. Changes in sensory properties emphasized the importance of consumer acceptability evaluation.[65] Research findings indicated enhanced inactivation kinetics of lipase (LA) and lipoxygenase (LOX) with increasing system temperature in both microwave irradiation and conventional heating.[65] Microwave roasting of sorghum resulted in significant alterations, including improved antioxidant properties. Managing enzyme inactivation through controlled microwave processing can contribute to enhanced antioxidant properties, positively impacting both nutritional content and shelf life. Microwave treatment of pearl millet grains at 18% moisture level for 80 s significantly reduced lipase activity by 92.9%, resulting in lower free fatty acid content (20.80−22.25% oleic acid) during a 30-day ambient storage period. This sustained overall acceptability, emphasizing the potential for shelf life extension. The reduction in lipase activity demonstrates the practical application of microwave treatment in extending shelf life while maintaining overall product acceptability. Microwave processing reduces antinutritional components and induces starch gelatinization by rapidly heating the starch granules, causing them to swell and burst, thus making them more digestible and offers promising avenues for maximizing nutritional content and extending shelf life, but it involves a delicate balance.[65] Table 5 summarizes the impact of various processing methods on the thermal and nonthermal properties of millets.

7.2. Infrared. Infrared (IR) energy falls between visible light and millimeter wave wavelengths. It is categorized into far-IR, mid-IR, and near-IR. When IR light enters water molecules, it makes them vibrate and generate heat. IR technology offers advantages such as consistent heating, reduced heating times, lower energy usage, high heat transfer rates, and improved product quality.[66] The thermal energy from IR radiation can lead to the disintegration of mesosomes, disruption of cytoplasmic membranes, damage to microbial cells, and deactivation of lipase, thereby reducing the formation of free fatty acids. This thermal processing induces moisture loss in grains, which can lead to an increase in starch digestibility due to gelatinization. The pearl millet, proso millet, and finger millet treated with a 2.5 kGy radiation dose showed good phenolic content and a DPPH concentration ranging from 42.77% to 72.65%. This indicates that irradiation has a positive effect on the antioxidant content and shelf life of millet.[67]

An investigation conducted on finger millet slurry found that an IR dosage of less than 10 kGy reduces antinutrients, bulk density, and swelling index, while increasing nutrient contents, color, WAC, and OAC.[68] In a recent study on storage stability, three different dehulled and whole millets (foxtail millet, sorghum, and pearl millet) were examined over 90 days using infrared (IR) methods. The study revealed no significant reduction in fungal count at 0.50 kGy, while γ-irradiation dosages at 0.75 kGy and higher inhibited the proliferation of fungal microorganisms. Therefore, the study suggested using IR as a safe postharvesting approach in the whole and dehulled millet region.[69] One study looked at the impact of infrared heating on sorghum flour quality. They observed that increasing the temperature and treatment period reduced free fatty acid (FFA) levels. Notably, after 10 min of exposure to 120 °C, lipase activity decreased by 88.8%. An optimization experiment showed that processing at a temperature of 120 °C for 8.5 min was ideal for reducing both lipase activity and FFA thus enhancing storage stability. Reductions in lipase activity and FFA content inhibit processes leading to rancidity, preserving desirable nutritional attributes. This drop in LA and consequent reduction in FFA have been related to water desorption processes, as evidenced by a positive relationship between enzyme activity with water activity. Although IR treatment did not cause irreversible lipase and lipoxygenase (LOX) loss, both enzymes recovered following water adsorption during storage.[70] In the research by Rousta et al.,[71] found that infrared irradiation reduced moisture content in sorghum samples. Water contributes to lipid oxidation and previous research showed that infrared light does not cause irreversible breakdown of lipase or LOX (Figure 6). It is also an assumption that a water monolayer is necessary to cover the lipid surface in some food, shielding it from direct oxygen exposure.[72] A significant reduction in phytic acids and tannins, coupled with an increase in total phenols, was reported in sorghum samples. The authors explained this outcome, indicating changes in cellular components during high temperatures or the breakdown of certain insoluble phenolic molecules.[71] In the study,[70] the application of Infrared (IR) heating on sorghum starch revealed a reduction in the ordered structure, implying decreased crystallinity and double helix structure. While this alteration could potentially enhance starch digestibility, the combination of IR treatment with enzymatic treatment resulted in improved starch alignment, higher crystallinity, and a reduced double helix structure, contributing to a decrease in starch digestibility. The starch modification is crucial for optimizing processing techniques to achieve desired nutritional outcomes in millet-based products. Radiation therapy improved millet flour's quality without significantly altering its nutritional makeup.[73] However, the impact of IR heating on microbial stability in millet flour requires further research.

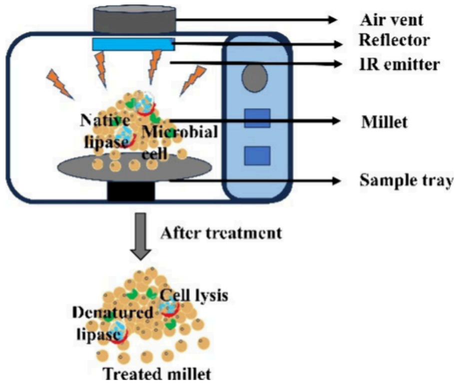

Figure 6. Infrared heating.

7.3. Radiofrequency. Radiofrequency (RF) waves (1−300 MHz), create heat in dielectric materials via ionic polarization or dipole rotation. RF treatment is used for insect/microbial control, enzymatic/protein inactivation, and drying/roasting grains like wheat, corn, rice, and maize. However, it is received less attention in millet.[73] The hot air-assisted radio frequency (HARF) treatment significantly reduced lipase activity in pearl millet grains by 97.30%, limiting the lipolytic breakdown of triglycerides that cause fast rancidity. The remarkable 97.30% reduction in lipase activity achieved by HARF treatment not only inhibits the lipolytic hydrolysis of triglycerides but also demonstrates the efficacy of RF treatment in preserving the quality of millet grains, contributing to increased nutritional content and shelf life.[74]

8. NONTHERMAL PROCESSING

8.1. Cold Plasma. Cold plasma is a nonthermal technology that ionizes gas to produce energetic reactive species. This approach enhances food safety and quality by modifying the surface of treated materials and creating an oxidative atmosphere. It is highly effective for microbial decontamination.[75] This nonthermal process depolymerizes starch molecules, lowering their crystallinity. As a result, the starch becomes more amorphous, which promotes water absorption capacity and increases enzyme accessibility, thereby boosting starch digestibility.[75] Lokeswari et al., treated pearl millet with plasma-processed air bubbles at 180 V for 1 and 2 h, resulting in a considerable reduction in phytic acid concentration of 60.66% and 39.27%, respectively.[76] Additionally, they investigated the reduction of phytic acid by combining traditional soaking (12 h) with cold plasma therapy. They found that 21.6% of the phytic acid was decreased compared to the control sample. The total iron level decreased from 39.9 to 29.8 mg per 100g. These findings demonstrate the possibility of plasma-processed air pretreatment as a strategy for decreasing antinutrients and increasing mineral availability while also adjusting pasting and techno-functional qualities. The reduction in phytic acid concentration improves mineral availability in pearl millet, potentially boosting nutrient absorption.[76] Sonkar et al.,[77] explored various treatment conditions on kodo millet starch, cold plasma treatment resulted in heightened water absorption (1.43 to 1.55 g/g) and oil absorption capacities (1.01 to 1.34 g/g). The reduction in pH (7.5 to 6.9) is attributed to the breakdown of amylose and amylopectin, causing bond disruptions and a substantial decrease in amylose content (31.06 to 25.94 g/hg). The generation of acidic compounds during starch hydrolysis lowers the pH. When amylose and amylopectin degrade, they provide not just simple sugars but also trace quantities of organic acids and other substances. Plasma treatment, which is prevalent in these hydrolysis procedures, can incorporate functional groups into starch molecules such as carbonyl and carboxyl groups.[76] These groups acidify the fluid, resulting in a pH decrease. Additionally, plasma therapy can cause starch oxidation, which results in the creation of carboxylic acids. Even though simple carbohydrates are not acidic, these acids lead to a lower pH. As a result, the observed pH reduction most likely owing to the combined effect of these processes, in which starch breakdown by plasma treatment produces acidic byproducts, resulting in a lower pH. Structural analyses revealed changes in infrared spectra and decreased relative crystallinity (23.06 to 21.63%). The increased water and oil absorption capacities suggest improved functionality, making the millet starch more versatile in food applications. The breakdown of amylose and amylopectin contributes to textural enhancements and potential improvements in digestibility, thus influencing the shelf life positively.[76] Kaur and Annapure et al.,[78] examined atmospheric pressure nonthermal pin-to-plate plasma on under-utilized pearl millet starch, significant changes included a 38.97% reduction in turbidity, a decrease in pH from 6.49 to 4.05, enhanced ζ potential, and observed cross-linking effects at lower voltages and shorter durations. The reduction in turbidity and observed cross-linking effects indicate modified starch properties, potentially leading to improved stability and texture in millet-based products. Increased acidity, measured by a lower pH, hence improves microbial stability. Jaddu et al.[79] found that cold plasma treatment of little millet flour improved its oil absorption capacity, water absorption capacity (WAC), solubility index, and swelling capacity while decreasing dispersibility and viscosity. The increase in WAC might result from starch granule damage after plasma treatment, while the rise in oil retention capacity could be attributed to the presence of nonpolar amino acids and other protein structures.[79] The interconnected relationship between starch granule breakdown and functional property improvements suggests potential benefits for shelf life by enhancing stability and texture.

The effects of ultrahigh pressure in conjunction with CP treatment on the physical, chemical, and digestive aspects of proso millet starch. The study discovered slight surface modifications on the starch granule as a result of non-penetrative plasma etching damage. The treated samples' fluorescence intensity dropped as the length of the CP treatment increased. This suggests that the CP treatment led to poor birefringence by causing a loss of radial orientation and an increase in double helical mobility. Furthermore, compared to native samples, those treated with CP had lower relative crystallinity. By depolymerizing starch molecules, reactive oxygen species might be to blame for this.[80]

8.2. Ultrasound Processing. Ultrasound (US), defined as sound waves with frequencies higher than the human ear's audible range (roughly >20 kHz), (Figure 7) offers several benefits, including simplicity, cost-effectiveness, energy efficiency, and environmental friendliness.[81] Energy, temperature, velocity, intensity, and pressure all have an impact on how powerful ultrasound is. Ultrasound can be defined as high or low energy based on its frequency range.[82] The use of high-energy ultrasound in millet processing, with frequencies

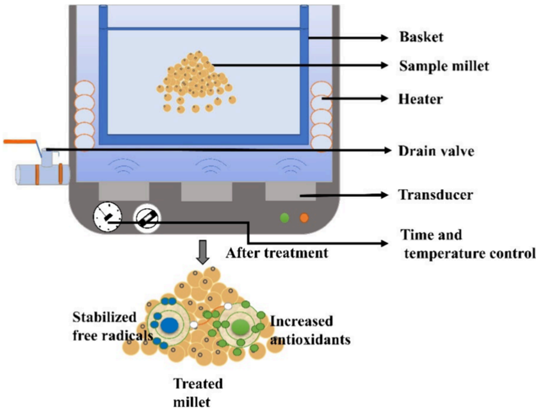

Figure 7. Ultrasound processing.

ranging from 20 to 100 kHz and high intensity (10−1000 W/cm2), causes significant modifications in the chemical, mechanical, and physical properties of proteins via the cavitation phenomenon, potentially increasing millet nutritional content by improving protein function and bioavailability.[82] Low-energy ultrasound, which operates at frequencies ranging from 5 to 10 MHz with low intensity (1 W/cm2), is used to preserve the safety and quality of millet-based food applications, implying a balance between nutritional integrity and food safety.[81] Nazari et al.[83] explored the impact of high-power ultrasound on millet protein concentrate (MPC) solubility, finding that increasing ultrasound duration at 18.4 W/cm2 did not significantly enhance MPC solubility. Conversely, at 73.95 W/cm2 intensity, solubility decreased with longer ultrasound durations. The observed changes were linked to the accessibility of amino acid hydrophilic groups, causing disruptions in internal associations and structural alterations in MPC. The study highlighted the importance of cavitation-induced bond breakdown, influencing molecular weights and interactions. The subsequent rise in MPC solubility is attributed to various mechanisms, such as the exposure of inner hydrophilic groups to water, resulting in ruptured internal connections and structural changes. This increased solubility has the potential to maximize the nutritional content of millet by facilitating amino acid release and enhancing protein functionality.[83] Unlike high-intensity US treatments, low-intensity US treatments notably decreased the foaming capacity of the original millet protein concentrate.

Their study, emphasized the impact of cavitation, highlighting its role in disrupting hydrogen and hydrophobic bonds. This disruption leads to a reduction in protein molecular weight and a subsequent increase in the interaction between the protein and water molecules. As a consequence, a larger surface area of the protein becomes covered by water molecules. This maximizes the nutritional content of millet by enhancing the protein's overall accessibility and interaction with water, potentially improving its functionality and bioavailability.[84] In their investigation, Dubey et al.[85] revealed that ultrasound-mediated hydration (USH) during the processing of finger millet resulted in a significant reduction of 73% in phytates and 71% in tannins. The study, utilizing artificial neural network (ANN) modeling, explored the optimal conditions, indicating that increased ultrasound amplitude, prolonged treatment time, and an optimal water-to-grain ratio collectively contribute to this substantial reduction in phytate and tannin content. This reduction, attributed to the acoustic cavitation and localized thermal effects of USH, signifies a promising approach to enhance the nutritional quality of finger millet by facilitating the leaching and breakdown of antinutritional components.[85] Aligning with the previous study's findings, the current research by S. Yadav et al.[86] affirms a noteworthy decrease in phytate and tannin contents of finger millet, notably by 66.98% and 62.83%, respectively, under optimized ultrasound-assisted hydration conditions. This reduction is ascribed to acoustic cavitation and localized thermal effects, underscoring the effectiveness of ultrasound-mediated hydration (USH) of finger millet through heat-induced chemical conversion of inositol phosphate from phytate. In the study by Meena et al.,[88] the optimization of ultrasound treatment parameters for white finger millet-based probiotic beverages (WFMPB) resulted in a significant increase in total phenolic content (TPC) and total flavonoid content (TFC). Specifically, the TPC was notably higher in the ultrasound-treated sample before inoculation (11.22 ± 0.43 mg GAE/100 g) compared to after inoculation (5.76 ± 0.86 mg GAE/100 g) and the control (10.65 ± 2.72 mg GAE/100 g). Additionally, the TFC for the ultrasound-treated sample before inoculation was substantially higher (9.08 ± 2.17 mg QE/100 g) than the after-inoculation sample (9.74 ± 1.58 mg QE/100 g) and the control (3.64 ± 0.32 mg QE/100 g). The elevated levels of both TPC and TFC observed in the ultrasound-treated samples were attributed to the mechanical effects of acoustic cavitation and shear forces generated during ultrasonication. These mechanisms, known for their ability to disrupt cell walls and vacuoles, played a pivotal role in facilitating the liberation of phenolic compounds, contributing to the improved nutritional content of millet-based beverages.[88]

8.3. Pulsed Light (PL) Processing. Pulsed light (PL) processing, an innovative method in food preservation, employs high-intensity light pulses within the 200 to 1100 nm wavelength range to achieve microbial inactivation (Figure 8). The primary goal is to neutralize microorganisms effectively while preserving the quality and nutritional characteristics of treated food products. This approach minimizes the impact on sensory attributes and nutritional composition, making it a promising technique for ensuring food safety.[89] The studies have delved into the structural impact of PL on proteins, shedding light on its effects on food enzymes. Investigations reveal notable changes, including a decrease in polyphenol oxidase activity linked to structural modifications like unfolding, aggregation, and protein backbone alterations.[90] Lipoxygenase activity also exhibited a reduction due to fragmentation, with distinct patterns observed in high-performance liquid chromatography analyses[91,92] These modifications are attributed to protein absorption of light at 280 nm, involving chromophores like aromatic amino acids, particularly tryptophan, and peptide bonds in the 180−220 nm region.[93] Notably, PL filtration at UV wavelengths induced enzyme deactivation but did not affect microorganism deactivation.[94] Hwang et al.[95] integrated insights from a study examining the bactericidal effects of pulsed light treatment on granular foods, specifically glutinous millet and cassia seeds. In the case of glutinous millet, a reduction of 0.66 log/g in microbial load was observed at a total fluence of 54.43 J/cm2. The study emphasized the importance of microorganism localization in food surface characteristics, highlighting that a rough surface could act as a shield against radiation. Additionally, the design of the treatment compart-

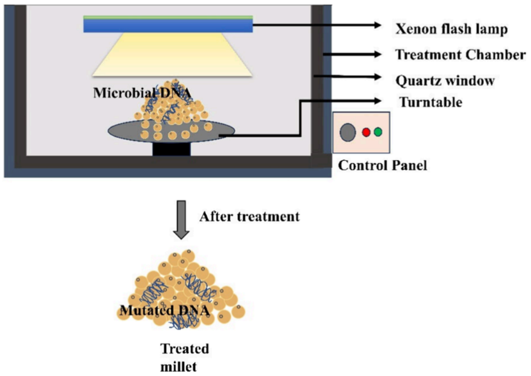

Figure 8. Pulsed light processing.

ment and initial bacterial populations emerged as critical factors influencing bactericidal efficacy. Samples with higher initial microbial loads exhibited elevated effects due to increased microorganism exposure to pulsed light. Simultaneously, the investigation into the effects of intense pulsed light (IPL)devices on cassia seeds underscored the importance of selecting an appropriate device based on sample characteristics. The belt-type IPL device demonstrated superior bactericidal efficacy, attributed in part to the larger particle size of cassia seeds. The study's outcomes, including the stability of properties such as water activity, moisture content, and color under total fluences up to 54.33 J/cm2, showcased IPL's potential as a nonthermal processing alternative in industrial applications.

These results emphasize various factors to consider when using pulsed light to kill bacteria in granular foods, suggesting the need for more exploration in future studies. The intricate interplay between factors such as surface characteristics, initial microbial loads, and the selection of appropriate devices highlights the complexity of implementing PL processing effectively in the food industry.

8.4. High-Pressure Processing. High-pressure processing (HPP),(Figure 9) involving pressures from 100 to 600 MPa, has been extensively studied for its ability to prevent spoilage microbes and pathogens in both packaged and unpackaged foods.[96] Notably, Gulati et al.,[97] found that HPP improves the digestibility of proso millet flour via mechanisms such as the formation of smaller network pathways between starch granules, denaturation of proteins, and internal water transport. Concurrently, N. Sharma et al.,[98] show that high-pressure soaking of germinated foxtail millet grains improves not only total phenolic content, starch gelatinization, water uptake, and antioxidant activity, but also reduces antinutrient levels, implying that it has the potential to improve the quality and Antinutritional profile of foxtail millet grains and flour.

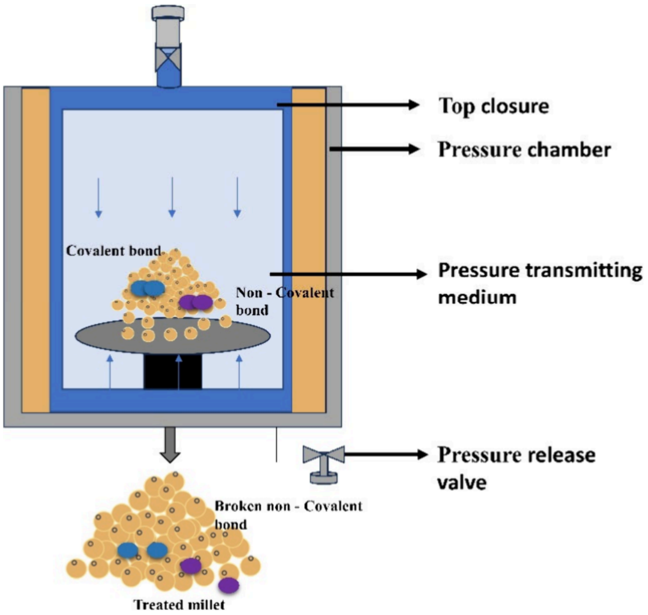

Figure 9. High-pressure processing.

Building on this, their research shows that the improved functional properties of high-pressure processed and germinated foxtail millet flours are due to improved moisture sorption characteristics, providing important insights into the thermodynamic behavior and potential applications of these processed millet flours. The potential of HPP to advance both food quality and nutritional security lies in its ability to maximize millet's nutritional content through improved digestibility and reduction of antinutrients, while also potentially contributing to prolonged shelf life.

8.5. γ Radiation. In the study on Tunisian pearl millet flour by Mustapha et al.,[99] γ radiation proved effective in enhancing the overall quality of millet flour. Despite a consistent fatty acid composition, induced lipid peroxidation led to an increased peroxide value postirradiation. The significant 88.6% loss in vitamin A content emphasizes its radiosensitivity, while subsequent increases may be linked to radioinduced β-carotene degradation. γ Radiation, particularly at 5 kGy, demonstrated dose-dependent efficacy in reducing Total Aerobic Plate Count, suggesting its preservative impact during storage. Additionally, fungal populations were significantly curtailed, emphasizing the method's effectiveness in suppressing both bacteria and fungi, thereby extending the shelf life of the millet flour.The irradiation-induced changes observed by Gowthamraj et al.[68] in finger millet slurry suggest potential benefits in terms of increased nutritional content and extended shelf life in millet-based food products. The reduction in bulk density, particularly at 2.5 kGy, signifies effective starch polymer degradation, potentially leading to improved digestibility and nutrient release. The increase in water absorption capacity, especially in CO15 samples, suggests enhanced hydration properties, contributing to better texture and palatability in food formulations. Decreases in the swelling index at higher doses indicate reduced water uptake, which may contribute to a firmer texture and longer shelf life by hindering microbial activity. The increased solubility index, coupled with stability in moisture content, suggests improved water dispersibility, potentially aiding in the rehydration of millet-based products during cooking or processing. Moreover, the breakdown of complex macromolecules and protein degradation into simpler soluble amino acids could enhance nutrient bioavailability. The slight increase in carbohydrate content and a significant increase in ash content suggest the release of bound carbohydrates and minerals, contributing to the overall nutritional profile. The decrease in total phenolic and tannin content may result in improved color stability and reduced bitterness, enhancing the sensory appeal of millet-based products. The slight increase in total flavonoid content indicates a potential preservation of bioactive compounds, contributing to the nutritional value of irradiated millet. Overall, the observed changes in physicochemical and proximate characteristics postirradiation suggest that the treatment has the potential to enhance nutritional content, improve functional properties, and contribute to the extension of shelf life in millet-based food products.By effectively reducing fungal contamination, gamma irradiation may play a role in prolonging the shelf life of millet flour, ultimately improving its overall quality and safety for consumers. Gamma irradiation at 2.5 and 5.0 kGy significantly reduces the total plate count (TPC) of microorganisms in millet flours, showcasing its efficacy in enhancing microbial safety and extending the shelf life of the flours.[67] In a recent investigation, the application of γ-irradiation to finger millet led to a substantial reduction in moisture content, attributed to the drying effect of the treatment. The study further revealed an enhancement in radical scavenging activity, catalase, and superoxide dismutase activities, indicative of improved antioxidant properties. Concurrently, a decrease in lipoxygenase activity and malondialdehyde content was observed, suggesting a mitigation of lipid oxidation and oxidative stress. The reduced lipoxygenase activity may be due to protein degradation, damage, or conformational changes, possibly influenced by mutations in the active site domain of the lipoxygenase protein.[100] This collective impact on physicochemical properties aligns with the notion that γ-irradiation could be beneficial for shelf life extension and the formulation of tailored food products. Gamma irradiation improves the safety and quality of millet-based products by enhancing microbial safety. It also reduces antinutrients, enhances protein digestibility, and preserves bioactive compounds. These findings highlight gamma irradiation as a valuable postharvest treatment for millet grains, offering multifaceted benefits for quality enhancement and safety improvement.

8.6. Supercritical-Assisted CO_2. To increase food quality, safety, and shelf life, supercritical carbon dioxide (SC−CO2) technology is a cutting-edge nonthermal processing technique that is being used more and more in millet processing.[101] Under operating circumstances, SC−CO2 functions as a gas when CO2 is below its critical temperature of 31.1 °C and pressure of 7.38 MPa. Because of this condition, SC−CO2 may effectively permeate millet grains, extracting bioactive chemicals and inactivating microbes without compromising the grain's nutritional or sensory properties. To keep millet safe and fresh, the method efficiently deactivates spoiling enzymes and lowers the microbial burden. The structural integrity and advantageous components of millet, such as antioxidants, are maintained by SC−CO2 processing but are frequently destroyed by traditional heat treatments.[102] Nevertheless, there are obstacles to the widespread use of SC−CO2 technology in commercial millet processing, chief among them being the high cost of the required machinery and running costs.

High-Pressure Processing (HPP) and Ultrasound Processing are superior thermal and nonthermal treatments, respectively, for millets, as they significantly enhance nutritional value, increase antioxidant content, reduce antinutrients, and extend shelf life.

9. APPLICATIONS OF DIFFERENT PROCESSING METHODS IN THE FOOD INDUSTRY

Puffed, boiled, fermented, roasted, and malted millet products are just a few examples of culinary items that can be produced using various processing techniques. One popular culinary item in Nigeria is tuwo, which is made from dehulled and ground millet flour. This flour is mixed with cold water to form a slurry, which is then cooked by adding hot water until it reaches the desired thickness. Another millet product is gruel, made from millet grains that have been fermented for 72 h. After fermenting, the millet grains are washed, wet-milled, and filtered using muslin fabric. This slurry or gruel can be further cooked to make pap, ogi, and other dishes after allowing it to settle with water.[103] Indian breakfasts that include fermented foods, such as dosa and idli, are quite popular. In these dishes, millet can completely replace rice.[104] Currently, it is common to use millet as a main component, along with other necessary ingredients, in creating different nutrient-dense food items. A study developed a ready-to-eat, nutritious morning cereal by combining popped pearl millet in a standardized quantity with puffed wheat, popped amaranth, flax and sunflower seeds, honey, sugar, oil, and water. This breakfast cereal's sensory qualities are quite satisfactory.[105] In another study, it was found that Nutri-flakes made from finger millet flour were produced by combining 60% millet flour, 30% tapioca flour, and 10% other ingredients. These additional components consisted of 2% rice bran, 3% chocolate powder, and 5% defatted soy flour. To produce Nutri-flakes, the resulting dough was first steamed, baked, chopped, dried, and finally puffed.[106] These types of food products are currently widely available in the market.

10. EMERGING TECHNOLOGIES IN MILLET PROCESSING AND CULTIVATION

Engineered nanoparticles (ENPs) offer a viable approach for alleviating both biotic and abiotic stressors in millets, hence improving their development and production under unfavorable conditions. Recent research has shown that ENPs, because of their unique features and compact size, may successfully relieve stressors such as drought, salt, heat produced, and heavy metal toxicity by increasing water and nutrient usage effectiveness.[107] For example, zinc oxide nanoparticles increase tolerance to drought by controlling gene expression and ion homeostasis, whereas silver nanoparticles can improve salt tolerance by modulating protein synthesis.[108] Furthermore, ENPs protect from biotic stressors such as pests and diseases. Nanoparticles like titanium dioxide, gold, and silver have shown great promise in minimizing fungus and insecticide damage. The incorporation of these nanotechnological innovations into millet farming not only improves stress resilience but also complements traditional processing procedures targeted at maximizing nutritional advantages and increasing shelf life.[107] However, it is critical to employ ENPs with prudence and conduct extensive safety and phytotoxicity studies to prevent possible negative impacts on the surroundings and human well-being.

Online monitoring technologies are essential for improving the quality and efficiency of millet processing. By implementing advanced methods like online monitoring of cutter wear in micromilling processes, intelligent Internet of Things systems for real-time monitoring of milling conditions, and online devices for detecting wear in mill lining plates using electromagnetic ultrasonic sensors, millet processing can be optimized.[109] These technologies support predictive maintenance, continuous data collection, and informed decision-making, resulting in enhanced machining efficiency, better quality control, and energy savings.[110] Furthermore, applying online monitoring technologies in the initial processing stages of agricultural products, including millets, ensures consistent quality inspection and boosts market competitiveness. Utilizing these cutting-edge monitoring technologies in millet processing not only meets the needs for sustainable practices and efficient value chains but also increases market recognition, benefiting both producers and consumers.

11. FUTURE PERSPECTIVES AND CHALLENGES

The millet processing startup industry has demonstrated remarkable growth, as evidenced by the consistent increase in both investment and turnover over the past two decades (Figure 10). For instance, in 2004, the startup required an investment of INR 25,00,000, generating a turnover of INR 40,00,000. By 2023, investment had surged to INR 1,20,00,000, resulting in a turnover of INR 1,45,00,000. This

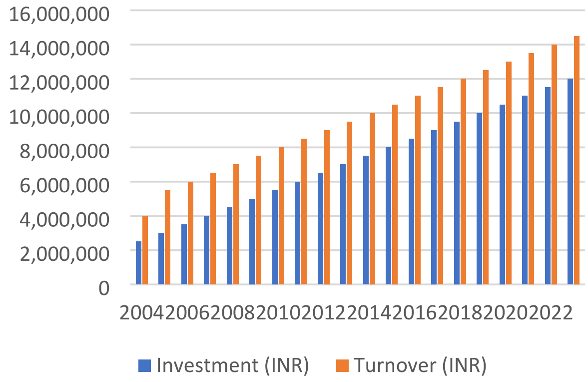

Figure 10. Growth in investment and turnover of the millet processing startup industry (2004–2023)

upward trajectory underscores the robust and expanding market for millet-based products. The effective processing of millets encounters various challenges, notably, the substantial capital investments required for advanced techniques like high-pressure processing and ultrasonication. These methods often demand modifications to existing processing lines, hindering their widespread adoption in the industry. The carbon footprint and sustainability of various processing methods vary significantly. The sustainability of food processing systems is increasingly important for their evaluation and advancement.[111] In comparison to energy-intensive thermal treatments such as microwave processing, infrared heating, and radiofrequency, traditional procedures like mechanical processing, fermentation, germination, and soaking often have a lower carbon impact. On the other hand, advancements in nonthermal processing methods such as cold plasma, ultrasonic treatment, high-pressure processing, and pulsed electric fields offer promising ways to reduce energy usage and emissions. Future research should focus on refining these innovative techniques to reduce their ecological footprint further. These processes could also have a much lower carbon footprint if they utilized renewable energy sources.[112] The research gaps identified in the review highlight the need for further investigation in two critical areas: innovative product development, consumer acceptance and marketability, and technological and economic feasibility. First, while the manuscript discusses various processing methods, it lacks detailed consumer studies exploring preferences and acceptance of processed millet products. Research on the development of innovative millet-based products that cater to modern consumer demands and strategies to increase their marketability is limited. Second, there is a gap in discussing the economic feasibility and technological accessibility of advanced processing methods, particularly in developing regions. Studies addressing the cost-effectiveness and scalability of these methods for smallholder farmers and local processors are necessary. Addressing these gaps can significantly enhance the practical utility of millet processing research for stakeholders, including farmers, processors, and policymakers. The challenge lies in finding a balance between cost, environmental sustainability, and efficiency while adopting these sustainable methods to meet the growing demand for food production. The slow acceptance of these innovative techniques is compounded by the industry's preference for traditional, cost-effective methods, limiting the exploration of potentially superior processing approaches. Additionally, minor millets, despite their nutritional superiority, remain understudied, impeding the development of tailored processing solutions. To address these challenges, future efforts should bridge the gap between traditional and innovative methods, incentivize industries to adopt advanced techniques and prioritize in-depth studies on minor millets. Streamlining postharvest processing and developing sustainable solutions aligned with global demand for healthier options are crucial. Collaborative global initiatives are essential to driving these advancements, ensuring millets fulfill their potential as a staple food source and contribute to global food security.

12. CONCLUSIONS

Millets exhibit remarkable versatility and nutritional richness, showcasing adaptability and resilience with minimal irrigation requirements. To improve nutrients and produce novel functional food items, it is necessary to decrease antinutrients, increase nutrient bioavailability, and extend shelf life, as millet flour's low shelf life is due to increased lipids and enzyme activities. The comprehensive review discussed a variety of traditional and bioprocessing methods, such as mechanical processing, fermentation, germination, soaking, thermal treatments like microwave processing, infrared heating, and radio frequency, as well as nonthermal processing methods, including novel techniques like pulsed electric field, microwave, radiofrequency, infrared, cold plasma, ultrasonic treatment, and high-pressure processing. Most millets exhibit improvements in their nutritional mineral, fiber, and vitamin contents after germination and fermentation. Basic processing methods such as soaking, germination, and fermentation can enhance the absorption of minerals and improve protein digestibility, addressing issues related to protein-energy deficiency. However, milling, dehulling, and decortication processes can reduce the levels of micronutrients, total proteins, and dietary fiber. Excessive dehulling can diminish fiber content and result in the loss of micronutrients by removing the nutrient-rich bran and germ section. Therefore, caution should be exercised when decorticating millets. Thermal and nonthermal processing results in lipase inhibition, ensuring microbial stability and improved storage durability. These methods show promise in enhancing millet properties while minimizing nutrient loss and energy consumption during processing. Regular consumption of items derived from millet might contribute to a healthy lifestyle, as it is an affordable and easily accessible dietary source. The research on millets is extensive, but few studies focus on large-scale production. In conclusion, this study offers detailed insights into millet processing technologies and highlights the potential of millet in the global food industry.

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Notes

This article does not contain any studies with human or animal subjects.
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