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REVIEW ARTICLE

Literature Review: From Grain to Functional Food: Physicochemical Properties and Processing Applications of Pearl Millet (*Pennisetum Glaucum*)

Clarinda Djuali*
Master of Food Technology Program, Soegijapranata Catholic University
**Corresponding author, email: djualiclarinda@gmail.com*

ABSTRACT
Pearl millet (*Pennisetum glaucum*) is the sixth most important cereal grain consumed by approximately one-third of the global population and has long served as a staple food for many communities worldwide. However, this cereal remains significantly underutilized despite containing a wide range of nutritional and functional components that are largely underrecognized. This review critically examines the physicochemical characteristics, nutritional and functional components, antinutritional factors, and processing technologies of pearl millet, comparing findings across studies and highlighting key research gaps. The crop's tolerance to drought, low-fertility soils, and extreme temperatures makes pearl millet more resilient that other cereal crops such as wheat and rice, thereby positioning it as a superior option for food security. In West Sulawesi, pearl millet is used in traditional foods such as porridge and cakes, and it can also be processed into various products including couscous, bread, non-alcoholic beverages, and beer. Prior to consumption, pearl millet requires processing due to its bitter taste and susceptibility to rancidity. Processing technologies such as fermentation, malting, and extrusion have been shown to effectively enhance nutritional bioavailability and functional properties, though gaps remain in standardizing processing parameters and establishing safe consumption thresholds.

KEYWORDS: *Nutrition, Pearl millet, Processing, Technology*

Introduction

Millet is a local food grown in Indonesia, particularly in the Nusa Tenggara region. Millet can be used as an alternative carbohydrate source due to its relatively high starch content (Widyastuti, 2021). According to Karim *et al.* (2019), pearl millet has the potential to replace rice as an alternative carbohydrate source in West Sulawesi. Pearl millet is the sixth most important grain, consumed by one-third of the global population and has become a staple food for many populations worldwide (Punia *et al.*, 2020; Karim *et al.*, 2019). Pearl millet (*Pennisetum glaucum*) is an annual crop grown in the summer (Yadav *et al.*, 2019). Pearl millet seeds contain high levels of protein, fiber, minerals, fatty acids, and antioxidant properties (Dias-Martins *et al.*, 2018). Although pearl millet serves as a major staple food for many populations around the globe, its utilization as a food ingredient remain limited, as it is still considered a food for the lower socioeconomic groups and tends to be excluded from the diets of the elite (Nambiar *et al.*, 2011 in Punia *et al.*, 2020). One reason is the lack of public awareness regarding the benefits and functional components of pearl millet, as well as limited processing technology that could increase its attractiveness and value as a food ingredient. In addition to its use as animal feed, pearl millet can be applied in the food sector, such as a thickener, stabilizer, or fat replacer in foods and beverages (Punia *et al.*, 2021). Furthermore, consumption of healthy and functional foods globally opens opportunities for developing pearl millet-based food innovations. As a crop tolerant to extreme environmental conditions, pearl millet also has the potential to be a solution for food diversification, food security, and addressing malnutrition, especially in areas vulnerable to climate change (Yadav *et al.*, 2016). This study critically examines the physicochemical characteristics, nutritional composition, functional components, antinutritional factors, and processing technologies of pearl millet, comparing findings across studies and identifying research gaps to support the development of pearl millet as a high-value functional food ingredient. Furthermore, the discussion covers processing technologies that can be applied to improve the quality and acceptability of pearl millet as a food ingredient, as well as its application in food product innovation. Therefore, this literature review is expected to serve as a reference for further development in utilizing pearl millet as a high-value source of nutrition and functional food.

Material and Method

The method used in writing this article review is a narrative review method. Literature was collected from Google Scholar and other accessible scientific databases. The research covered publications from 2013-2025 using keywords including “pearl millet”, “food innovation”, “food technology”, “characteristics”, “nutrition”, “processing”, both singly and in combination.

The inclusion criteria were: (1) original research articles, review articles, and book chapters published between 2013-2025; (2) studies focusing on pearl millet characteristics, nutritional composition, processing technologies, food product development, or food industry applications; and (3) articles with accessible full texts. The exclusion criteria included: (1) duplicate publications; (2) articles not directly related to pearl millet; (3) conference abstracts without full manuscripts; (4) studies lacking sufficient methodological information.

The article selection process consisted of identification, screening, eligibility, assessment, and final inclusion. Initially, relevant articles were identified through keyword searches. Subsequently, titles and abstracts were screened to evaluate relevance to the review objectives. Full-text articles that met the inclusion criteria were then assessed for eligibility. Finally, selected studies were analyzed and grouped according to six main themes: (1) Physicochemical Characteristics of Pearl Millet, (2) Nutritional Value of Pearl Millet, (3) Functional Components of Pearl Millet, (4) Antinutrient Properties of Pearl Millet, (5) Latest Technology and Processed Pearl Millet Products, and (6) Future Trends in Pearl Millet. Information from the selected articles was synthesized narratively to provide a comprehensive overview of current developments and future prospects of pearl millet utilization.

Results and Discussion

Physicochemical Characteristics of Pearl Millet

Pearl millet is very flexible in terms of soil conditions, as it can grow in a variety of soil types, including loam, sandy loam, and clay. For optimal growth, pearl millet requires annual rainfall between 200 and 600 mm, a soil pH between 6.0 and 7.0, and temperatures around 30-34˚C. however, this plant is tough enough to survive extreme temperature up to 46˚C, rainfall of 150-800 mm, and a soil pH up to 8. In addition, pearl millet is also tolerant of high soil salinity levels (up to 11-12dS/m), although optimal yields can only be obtained at salinity up to 8 dS/m (Kumar *et al.*, 2024). This plant’s tolerance to drought, infertile soil, and extreme temperatures makes pearl millet more resistant than other cereal crops such as wheat and rice (Yadav *et al.*, 2016). This is supported by Suherman *et al.*, 2005) in Karim *et al.* (2019) found that pearl millet is easy to cultivate, can grow in dry and infertile soils, and has a short growing season, making it a superior choice for food security. However, this crop is sensitive to waterlogged soil conditions, so waterlogging should be avoided (Lee *et al.*, 2012 in Kumar *et al.*, 2024). The appearance of pearl millet can be seen in Figure 1-2.

(a) (b)

Figure 1. Pearl Millet Plant
(a) Distant View (University of Georgia, USDA-NRCS PLANTS Database); (b) Close View.
Source: Sheahan (2014); Geisen *et al.* (2021)

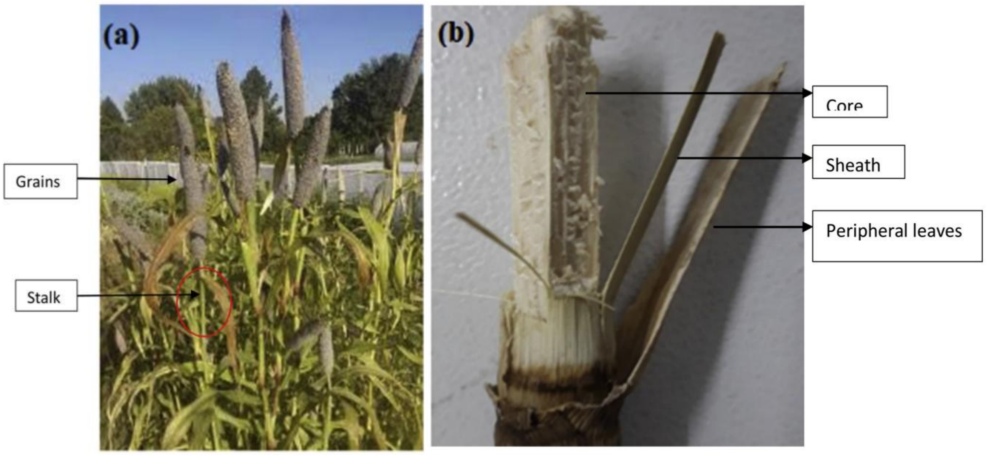

Figure 2. (a) Pearl Millet plant; (b) Part of a pearl millet stem.
Source: Yadav *et al.* (2019)

Pearl millet starch granules (PMS) consist of simple units measuring 3.5-23 μm (Annor *et al.*, 2014 in Punia *et al.*, 2021). PMS vary in size from small to large, are spherical or polygonal, and exhibit pores and deep depressions on their surfaces (Sandhu & S Siroha, 2017; Shaikh *et al.*, 2015). The porous surface of PMS facilitates specific reactions such as structural modification and increased digestibility. Research has shown that PMS exhibits notable physicochemical properties, including swelling power ranging from 14.1 to 17.9 g/g and solubility from 10.4 to 16.2 g/100 g across different cultivars. X-ray diffraction (XRD) analysis reveals an A-type diffraction pattern with peaks at 15˚, 17˚, 18˚, and 23.1˚ (2θ), which is characteristic of cereal starches and indicative of amylopectin-rich composition. This crystalline structure is associated with the high enthalpy of gelatinization (ΔHgel=10.6-12.4 J/g), suggesting greater thermal stability and potential suitability for heat-processed food applications (Sandhu & S Siroha, 2017). The appearance and structure of pearl millet seeds and their components can be seen in Figures 3 and 4.

(a) (b)

Figure 3. (a) Appearance of Whole Pearl Millet Seeds
(b) SEM results with 25x magnification of pearl millet seeds.
Source: Wrigley et al. (2015); Geisen et al. (2021)

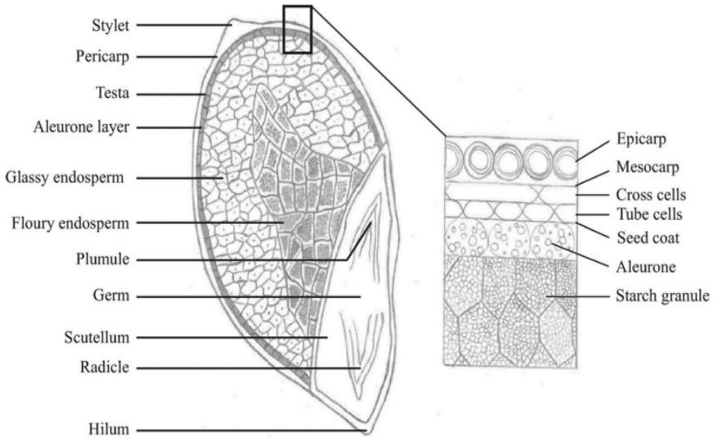

Figure 4. Structure of pearl millet seeds.
Source: Hassan *et al.* (2021)

PMS has a gelatinization temperature ranging from an initial temperature of approximately 63˚C to a final temperature of approximately 73˚C. PMS exhibits a higher water-holding capacity than sorghum, but slightly lower than corn starch (Abd Allah et al., 1987 in Serna-Saldivar & Espinosa-Ramírez, 2019). Swelling power of PMS ranges from 11-17.9 g/g and solubility from 10-16%, which are higher than sorghum starch but lower than commercial starches such as wheat and potato. In terms of viscosity, peak viscosity of PMS range from 1,291-8,303 mPa·s depending on cultivar and starch concentration, which is generally lower than corn starch, attributed to its relatively smaller granule size compared to sorghum and corn starch granules (Sandhu & Siroha, 2017; Punia et al., 2021).

Nutritional Value of Pearl Millet

Pearl millet plants have the potential to be a source of starch, with a content up to 70%, depending on the specific variety (Punia *et al.*, 2021). Pearl millet contains 67-67.5% carbohydrates; 11.6-11.8% protein; 4.8-5% fat; and 11.3% dietary fiber. Pearl millet seeds contain carbohydrates consisting of starch, dietary fiber, and soluble sugars. Starch is the main component of pearl millet endosperm, consisting of glucose in the form of amylose and amylopectin. Various pearl millet seed genotypes show differences in starch composition. Based on research by Hassan *et al.* (2021), the starch composition in pearl millet ranges from 62.8 to 70.5%, and approximately 71.82 - 81.02%. The soluble sugar content in pearl millet also varies between 1.2 to 2.6%, while the amylose content ranges from 21.9 - 28.8% (Hassan *et al.*, 2021). Pearl millet has an ash content of around 1.8%, which is lower than barley (2.2%) and oats (2.5%), higher than rice (0.9%) and corn (1.3%), and comparable to wheat, which reaches 1.9% (Dias-Martins *et al.*, 2018). The proximate content of pearl millet can be seen in Table 1.

Table 1. Nutritional content of pearl millet.

No	Proximate content	Pearl millet (g/100g)
1	Water Content	12.4
2	Carbohydrate	67-67.5
3	Protein	11.6-11.8
4	Fat	4.8-5
5	Dietary fiber	11.3
6	Mineral (mg/100g)	
	Phosphorus	296
	Potassium	307
	Magnesium	137
	Calcium	42
	Sodium	10.9
	Zinc	3.1
	Iron	8
	Manganese	1.15
	Copper	1.06

Source: Amadou *et al.* (2013) in Hassan *et al.* (2021)

Pearl millet has a low glycemic index (GI) of 55 (Punia et al., 2020). This value is related to the slower-digesting characteristics of its starch, influenced by its amylose content, high fiber content, polygonal and porous starch granule structure, starch-protein-lipid interactions, and the formation of starch complexes with fatty acids such as oleic acid (Annor et al., 2017). These characteristics support a more stable glycemic response.

The total dietary fiber content of pearl millet ranges from 6.9-12.1% (average ±9%), with insoluble fiber accounting for approximately 6.3-7.6% and soluble fiber accounting for 0.6-4.5% (Serna-Saldivar & Espinosa-Ramírez, 2019). Comparatively, its fiber content is higher than rice (3.5%), similar to corn (8.1%), but lower than rye (16.8%), barley (14.5%), and oats (11.8%). Its high fiber content plays a role in supporting digestive health, helping control blood glucose and cholesterol, and reducing the risk of chronic diseases such as diabetes and cardiovascular disease (Dias-Martins *et al.*, 2018).

Pearl millet seeds contain more energy and protein than other cereals and foods, particularly corn and sorghum (Karim *et al.*, 2019). This type of millet is tannin-free and contains around 5-7% oil. Furthermore, pearl millet has a more balanced amino acid profile than both cereals (Rai *et al.*, 2008 in Pattanashetti *et al.*, 2016). Protein is the second most important component of millet. Pearl millet has a higher protein content than rice (7.2%); barley (11.5%); corn (11.1%); and sorghum (10.4%). Compared to corn, pearl millet contains higher crude protein, ranging from 8-60% by weight (Jha *et al.*, 2013 in Hassan *et al.*, 2021). The amino acid profile of pearl millet can be seen in Table 2.

Table 2. Amino acid profile of pearl millet.

No	Essential	Pearl Millet	Non-Essential	Pearl Millet
1	Isoleucine	5.1	Alanine	8.1
2	Leucine	14.1	Arginine	0.9
3	Lysine	0.5	Aspartic acid	6.2

4	Methionine	1.0	Cysteine	0.8
5	Phenylalanine	7.6	Glutamic acid	22.8
6	Threonine	3.3	Glysine	0.7
7	Valine	4.2	Serine	5.4
8	Histidine	1.7	Tyrosine	2.7
9	Tryptophan	1.2	Proline	8.2

Source: Amadou *et al.* (2013) in Hassan *et al.* (2021)

Functional Components of Pearl Millet

Pearl millet is known as a "nutri-cereal" due to its high protein, fiber, mineral, fatty acid, and bioactive compounds content, which contribute to health benefits beyond its basic nutritional value (Pei et al., 2022; Punia et al., 2020; Dias-Martins et al., 2018). This cereal is naturally gluten-free, making it a potential functional and economical alternative for people with celiac disease, non-celiac gluten sensitivity (NCGS), and individuals with wheat allergies. Furthermore, pearl millet has been reported to retain its alkaline properties after cooking, making it ideal for people with wheat allergies and able to maintain the body's pH balance (Punia et al., 2020; Dias-Martins et al., 2018).

Micronutrient-wise, pearl millet contains vitamins A and E (±2 mg/100 g), as well as essential minerals such as calcium, phosphorus, magnesium, manganese, zinc, iron, and copper, levels of which are influenced by soil conditions (Hassan et al., 2021). Magnesium contributes to blood pressure regulation and cardiovascular function, while phosphorus plays a role in bone formation and ATP synthesis (Pei et al., 2022; Hassan et al., 2021). However, the presence of phytate, oxalate, and polyphenols can affect iron bioavailability (Hassan et al., 2021).

Pearl millet is rich in phenolic compounds with antioxidant activity, including flavonoids that have the potential to inhibit tumor growth (Huang & Ferraro, 1992 in Punia et al., 2020). Its phenolic acid content (64.8 mg/kg) is reported to be higher than that of sorghum (27.3 mg/kg, with a dominant distribution in the pericarp (N'Dri et al., 2013 in Dias-Martins et al., 2018). Therefore, consumption in the form of whole grains or bran is recommended to obtain optimal bioactive benefits (Chandrasekara & Shahidi, 2011b in Dias-Martins et al., 2018). Phenolic compounds in whole grains are also reported to have relevant immunomodulatory potential in the development of functional foods.

Antinutrient Properties of Pearl Millet

The main anti-nutritional compounds in pearl millet include phytic acid and C-glycosylflavones, such as apigenin, glucosyl vitexin, glucosylorientin, and vitexin (Taylor, 2016). Phytic acid is a natural antioxidant in grains that plays a role in retaining inorganic phosphorus and protecting the grains from oxidation. However, high consumption can reduce the availability of bivalent minerals such as zinc, calcium, and manganese through chelating mechanisms, and can also potentially inhibit protein digestibility due to protease enzyme inhibition in the digestive tract (Gupta *et al.*, 2015). The phytic acid content of pearl millet ranges from 588-1382 mg/100g (Gabaza *et al.*, 2018), relatively comparable to corn and sorghum, but higher than oats, rice, barley, rye, and wheat (Dias-Martins *et al.*, 2018).

C-glycosyl flavones in pearl millet have been reported to inhibit the enzyme thyroid peroxidase (TPO), which plays a role in thyroid hormone synthesis (Mezzomo & Nadal, 2016 in Dias-Martins *et al.*, 2018). Animal studies have shown reduced thyroid hormone production in rats fed pearl millet, which is associated with high levels of C-glycosyl flavones, particularly glucosyl vitexin, glucosylorientin, and vixetin (±1020 mg/kg). However, scientific evidence in humans is still limited, so the consumption threshold that causes similar effects has not been established.

Despite containing anti-nutritional factors, pearl millet still has potential as an alternative food ingredient for diversification due to its fiber, mineral, protein, and antioxidant content, which is competitive compared to rice and corn (Gong et al., 2018; Taylor, 2016). Variations in composition are influenced by genotype, agroclimatic conditions, soil fertility, and processing methods. Therefore, pretreatment is necessary to reduce anti-nutrient levels and increase nutritional value. Methods reported to be effective include roasting at 120-180°C for 75-120 minutes, acid treatment (acetic acid, tartaric acid, or dilute HCl), and brief immersion in hot water (±100°C for 10–90 seconds), which can reduce the content of anti-nutritional compounds and increase consumption safety (Dias-Martins *et al.*, 2018).

Latest Technology and Processed Pearl Millet Products

The thermal characteristics of PMS are similar to those of corn starch, offering potential applications in heat processed foods (Sandhu & S Siroha, 2017). PMS has potential uses as a thickener, stabilizer, or fat substitute in foods and beverages, edible films/coatings, nanoparticles for drug delivery, pharmaceutical and medical applications, and enzyme production (Punia *et al.*, 2021). Pearl millet remains underutilized in many developed countries due to the lack of readily available, ready to eat processed foods. Furthermore, the fibrous, yellow-to-grey seed coat of pearl millet imparts a bitter taste, making products made from whole millet flour unpopular with consumers, especially those accustomed to rice or wheat.

These challenges can be overcome by pre-processing before consumption or use in food products. This processing aims to improve organoleptic qualities and extend shelf life. Replacing wheat flour with pearl millet flour in food products can be a healthy option for health-conscious individuals. Therefore, it is important to start substituting millet in daily menus (Kulkarni et al., 2021). Pearl millet processing using various methods such as milling, malting, fermentation, blanching, and acid and heat treatments has been shown to increase mineral absorption, reduce bitterness and unpleasant odors, and prevent rancidity during flour storage (Rani et al., 2018). Furthermore, pearl millet can be processed through milling, peeling, germination, fermentation, heating, and extrusion methods to produce various products such as flour, snacks, biscuits, pasta, and non-dairy probiotic drink (Dias-Martins et al., 2018). Various pearl millet processing methods and their effects on flour quality are summarized in Table 3. Among these methods, the combination of fermentation and malting has been identified as the most effective for improving nutritional and functional properties of pearl millet flour (Akinola et al., 2017), while combined thermal near-infrared (HT-HTh-NIR) treatment demonstrated the best shelf-life extension by inactivating lipase (47.8%), lipoxygenase (84.8%), and polyphenol oxidase (100%) activities (Padmaja et al., 2023).

Table 3. Effect processing methods on the quality and stability of pearl millet flour.

No	Treatment	Results	Source
1	Treatment of pearl millet seeds: • Blanching: cleaned and soaked in hot water • Debranning: soaking in water at 50°C; 18 hours • Fermentation: soaked in water (3days) without changing the water • Malting: millets are soaked in water and allowed to germinate in damp muslin cloth	Fermentation and malting treatments demonstrated the best results in terms of the nutritional and functional properties of millet flour. The combination of the two produces pearl millet flour with high viscosity, improved protein content, and high digestibility, making it ideal for industrial applications and supporting food security	(Akinola et al., 2017)

	After that, samples from each treatment will be crushed, washed, dried (to a moisture content of 5%), and ground into flour.		
2	Pearl millet grains were subjected to the following treatments: a. Roasting with a twin-screw extruder (100˚C; 60 sec) b. Hydrothermal: soaked in 1:1 boiling water for 15 min, then dried (60˚C; 2 hours) until the moisture content reached approximately 5.63%. the resulting flour was then packaged in 10-µm-thick LDPE bags and stored under two conditions: • Room temperature: 33.1˚C; RH 84.4% • Controlled conditions: 30˚C; RH 50%	Both treatments significantly reduce the lipid acidity by 8% and 12%, the phytic acidity by 10% and 4% and the trypsin inhibitor activity by 9% and 5% in pearl millet flour. However, hydrothermally treated millet flour could be stored for up to 30 days (at room temperature) and up to 45 days (controlled conditions) without significant quality degradation	(Jalgaonkar et al., 2016).
3	Germination: Pearl millet seeds were sorted, oven-dried at 60˚C for 8 hours, then germinated by spreading on moistened jute sacks at room temperature for 3 days. Germinated grains were washed with distilled water, drained, oven-dried (60˚C), milled, and stored in an airtight container	Germination significantly improved the nutritional quality of pearl millet flour, with protein content increasing from 10.57% to 11.87% and crude fiber from 1.07% to 2.55%, while fat content decreased from 7.69% to 2.30%. Antinutritional factors were also reduced, with phytate content decreasing from 17.72 to 7.00 mg/g. Antioxidant activity (DPPH) improved from 49.95% to 64.01% after germination, indicating enhanced functional properties of the germinated flour	(Owheruo et al., 2019)
4	Pearl millet grains treated with microwave at 18% moisture content for 80 sec	Lipase activity reduces by 92.9% resulting in significantly lower free fatty acid (FFA) value in treated flour compared to untreated flour throughout 30 days of storage	(Yadav et al., 2012)
5	Pearl millet grains subjected to: • Pearling: removal of outer pericarp layer • Heat treatment: dry heat at 100˚C for 60 sec • Fermentation: soaked in water for 3 days	Head treatment (100˚C, 60 sec) was the most effective pre-milling treatment. Fat acidity and free fatty acid (FFA) were minimized, phytic acid and total polyphenol significantly reduced, without significant loss of iron and zinc content. Shelf life extended compared to untreated flour	(Tiwari et al., 2014)
6	Decortication at different degrees (1-3% removal of outer pericarp layer)	Loe-level decortication (1-3%) effectively extended pearl millet flour shelf life by removing the lipid-rich aleurone layer and reducing lipase activity, while micronutrient (iron and zinc) loss remained minimal	(Gosmawi et al., 2024)
7	Pearl millet grains subjected to: • Dry heat treatment: 150˚C, 30 min	Combined HT-HTh-NIR treatment reduced lipase activity (47.8%), lipoxygenase (84.8%), peroxidase (98.1%), and polyphenol oxidase	(Padmaja et al., 2023)

		• Combined treatment: hydrothermal + thermal near infrared (HT-HTh-NIR); stored in laminated packaging under modified atmosphere (Nitrogen gas)	(100%) compared to individual treatments. Modified atmosphere packaging further extended shelf life by removing oxygen. Hydrothermal treatment alone extended shelf life up to 50 days at ambient conditions

In West Sulawesi, pearl millet is used in traditional foods such as porridge and cakes, and can be processed into other products such as couscous, bread, non-alcoholic beverages, and beer (Taylor. 2016 in Karim et al., 2019). In addition, to date, the use of pearl millet flour in the manufacture of several processed foods has begun to be widely researched (Table 4.). The application of pearl millet in processed food products offers several advantages. Its naturally gluten-free nature makes it suitable for individuals with celiac disease and wheat allergies, as demonstrated in gluten-free bread formulations (de Aguiar et al., 2024). Pearl millet also contributes notable nutritional value to products, including high protein, iron, zinc, and dietary fiber content, as evidenced in fermented milk beverages (Samtiya et al., 2026) and cookies (Kulkarni et al., 2021). Additionally, its starch properties particularly after modification provide functional benefits such as improved cold storage stability, high gel hardness, and thickening capacity suitable for vermicelli and white sauce applications (Widaystuti, 2021; Shaikh et al., 2020).

However, several challenges limit its wider application. The bitter taste and grey-to-yellow colour of pearl millet flour reduce consumer acceptance, particularly whe used as a complete wheat flour substitute. Studies indicate that pearl millet-based products achieve optimal sensory acceptance only at partial substitution levels, such as 40:60 wheat-to-pearl millet ratio in cookies (Kulkarni et al., 2021). Furthermore, the lower viscosity of pearl millet flour compared to wheat flouar requires modification or blending to achieve desired textural properties in products such as extrudates and baked goods (Kharat et al., 2019). Standardization of processing parametes across different pearl millet varieties also remains a challenge, as physicochemical properties vary significantly among cultivars.

Table 4. Application of pearl millet in processed food products.

No	Product	Processing Method	Result	Source
1	Vermicelli	Modified starch with heat-moisture treatment (oven-heating at 100°C; 7h)	Modified millet starch exhibits an ideal starch profile of vermicelli production due to its lower peak viscosity and breakdown viscosity than native starch, high cold paste viscosity, and the highest gel hardness	(Widyastuti, 2021)
2	Extrudate	Pearl millet is processed into flour	The use of pearl millet flour as a base for extruded products demonstrates a good expansion ratio and low bulk density. The flour has a low peak viscosity, facilitating the extrusion process and high paste stability, making it suitable for a variety of applications. Pearl millet extruded products also exhibit good physicochemical properties, with a moderate water absorption index (WAI) and a high water solubility index (WSI), which supports product texture and quality	(Kharat et al., 2019)
3	Cookies	Pearl millet grains are processed through a series of stages: sorting, cleaning, grading,	Using pearl millet flour (PMF) as a substitute for wheat flour in cookie production has proven effective in improving the nutritional and sensory quality of the product. Cookies made	(Kulkarni et al., 2021)

		and finally, they are processed into semolina, then sieved (40 mesh) to produce pearl millet flour	from a mixture of wheat flour and PMF (40:60) were well-accepted in almost all sensory aspects and had a reasonable economic value.	
4	White sauce	Modified pearl millet starch by hydroxypropylation	The gelatinization temperature was low than that of native starch, and no retrogradation (quality loss due to cold storage) was observed after 14 days. The use of modified pearl millet starch in white sauce as a thickening agent improved the cold storage stability of the white sauce (no syneresis). Sensory characteristics of the product were the highest in consistency, texture, and flavor, demonstrating good consumer acceptance.	(Shaikh et al., 2020)
5	Gluten-free bread	Pearl millet flour (MF) at varying concentrations (50%, 75%, 100%) combined with different water levels (115-130%)	Pearl millet flour demonstrated great potential for producing nutrient-dense and acceptable gluten-free bread. Formulations with 75% MF + 115% water and 100% MF + 130% water showed promising nutrition and sensory features and can be classified as whole grain products	(de Aguiar et al., 2024)
6	Fermented milk beverage	Pearl millet fermented with *Limosilactobacillus fermentum* (MS005) for 16 hours, mixed with milk	The resulting beverage contained high lactic acid bacteria (8.75log10 CFU/ml), with good proximate composition (protein 3.65%, carbohydrates 6.19%) and notable mineral content including iron (7.29 mg/L), zinc (6.44 mg/L), and calcium (1,023.08 mg/L).	(Samtiya et al., 2026)
7	Biscuit	Pearl millet flour subjected to 3 treatments: • Native flour (NF) • Fermented flour (FF) • Malted flour (MF)	Fermentation and malting significantly increased water absorption capacity, oil absorption capacity, and swelling capacity of the flour, resulting higher biscuit hardness (malted: 15.85 N, fermented: 29.31 N vs native: 5.30 N), and improved microstructure, demonstrating its potential as ingredients for gluten-free baked products.	(Adebiyi et al., 2016)

Future Trends in Pearl Millet

Future research and development trends in pearl millet will focus on enhancing the nutritional and functional value of this food ingredient. Research on bioactive compounds such as polyphenols and phytochemicals, as well as the influence of various processing methods on nutrient bioavability, is predicted to grow. In addition to its application in processed food products, pearl millet starch (both native and modified) can also be used for edible coatings/films (Shaikh *et al.*, 2019; Shaikh *et al.*, 2018), nanoparticle development, and pharmaceutical and medical applications (Punia *et al.*, 2021). Based on research by Shaikh *et al.* (2018), edible films made with hydroxypropylated pearl millet starch have improved transparency, water solubility, and flexibility, making them suitable for packaging fresh, ready to eat vegetables. Acetylated pearl millet starch, on the other hand, offers excellent moisture-resistant properties, making them suitable for packaging dry food products. In the health sector, pearl millet can treat gastric ulcers due to its alkalizing properties, thus helping prevent or reduce the effects of gastric ulcers. Its lignin and phytonutrient content also act as potent antioxidants to prevent cardiovascular disease. Furthermore, pearl millet is known to be beneficial for maintaining heart health (Pei et al., 2022).

However, the future development of pearl millet is not without challenges. One major obstacle is low consumer awareness of the benefits of this food compared to more commonly known foods (Nambiar et al., 2011 in Punia et al., 2020). Furthermore, the limited availability of modern processing technology in developing regions is a barrier that needs to be addressed through investment in infrastructure and technology. Market acceptance is also a challenge, as pearl millet-based products must compete with other, more popular foods.

Conclusion

Pearl millet (*Pennisetum glaucum*) is a potential food ingredient rich in nutrients and offers functional benefits. Its tolerance to drought, infertile soil, and extreme temperatures makes pearl millet a superior choice for food security. Processing technologies, such as fermentation, extrusion, and flouring, enhance the nutritional and functional value of pearl millet. Pearl millet's applications in food innovation are also diverse, including gluten-free products, extrudates, vermicelli, and probiotic-based drinks. This suggests that pearl millet can be a relevant raw material for the development of the modern food industry. Several challenges remain in pearl millet's development, such as a lack of public awareness of its benefits and limited processing technology at the local level. Therefore, further research is needed to improve processing efficiency and education to promote pearl millet as a high-value functional food ingredient. Furthermore, research on the safe consumption limits for pearl millet is still limited.

Supporting Information

Additional data are available on request

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Ethical Statement

This study did not involve any human participants or animal subjects; hence, ethical approval was not required. All procedures carried out in this research followed applicable institutional and international guidelines.

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