Journal of Food Innovation, Nutrition, and Environmental Sciences
November, 2026, Volume 3; Issue 4: 312–336
ISSN No: 3078-5537

REVIEW ARTICLE

Pearl Millet: Nutritional Value, Processing Technologies, Health Benefits, and Value Addition—A Review

Maltase Mutanda[1*], Ndabanye Mathema[2], Pesanayi Zanamwe[2], Tariro Mafirakurewa[2]

[1]Department of Agriculture and Animal Health, University of South Africa, Florida Park, Roodepoort 1710, South Africa
[2]Department of Horticulture and Crop Production Gwanda State University, P.O. Box 30 Filabusi, Gwanda, Zimbabwe

DOI: https://doi.org/10.70851/jfines.2026.3(4).312.336

ABSTRACT

Pearl millet is a climate-resilient cereal crop with considerable potential to contribute to food and nutrition security, particularly in arid and semi-arid regions. The grain is rich in protein, dietary fiber, essential amino acids, minerals, vitamins, and bioactive compounds that may contribute to nutritional quality and biological activity. However, its wider utilization is constrained by the presence of anti-nutritional factors, short flour shelf life, and limited consumer acceptance. Various processing technologies, including soaking, germination, fermentation, decortication, roasting, extrusion, and parboiling, have been investigated to improve nutrient accessibility, reduce anti-nutritional factors, and modify functional and sensory properties. Consequently, pearl millet has been investigated for incorporation into value-added products such as bakery products, breakfast cereals, snacks, beverages, infant foods, and gluten-free formulations. However, most reported applications remain at the laboratory or prototype stage, with comparatively limited evidence of pilot-scale validation, sustained commercial adoption, profitability, consumer acceptance, and market performance. This review synthesizes current evidence on nutritional composition, processing technologies, health benefits, anti-nutritional factors, value addition, commercialization constraints, and emerging research trends in pearl millet. Unlike previous reviews, this study integrates nutritional quality, processing innovations, functional food applications, and value-addition perspectives within a single framework. The evidence indicates the possibility of commercial adoption, profitability and consumer acceptance of pearl millet products. Processing can improve nutrient accessibility and functional properties in some pearl millet-based foods, but the magnitude and direction of these effects vary according to genotype, processing conditions, and product formulation. Therefore, important evidence gaps include insufficient standardization of processing and analytical methods, incomplete understanding of genotype × environment × processing interactions, and inadequate economic evidence. Future research should prioritize standardized processing protocols, well-designed human studies, consumer and market research, and economic assessment of production and commercialization pathways.

Article history
Received:
04 August 2026
Revised:
13 October 2026
Accepted:
15 October 2026

Keywords
Pearl millet; Nutritional composition; Processing technologies; Value addition; Functional foods

*Corresponding author:
Email: 19283849@mylife.unisa.ac.za (Maltase Mutanda)

Peer review under responsibility of Journal of Food Innovation, Nutrition, and Environmental Sciences.

All the articles published by Journal of Food Innovation, Nutrition, and Environmental Sciences are licensed under a Creative Commons Attribution 4.0 International (CC-BY) License Based on a work at https://jfines.org

A Publication of EcoScribe Publishers company Limited, Uganda. www.ecoscribepublishers.com

1. Introduction

Pearl millet (*Cenchrus americanus* (L.) Morrone), formerly known as *Pennisetum glaucum* (L.) R. Br., is one of the oldest domesticated cereal crops and an important member of the *Poaceae* family (Acharya et al., 2024; Vutla et al., 2025). Archaeological and molecular evidence indicates that pearl millet originated and was domesticated in the western Sahel region of Africa, particularly the present-day Mali and Niger, more than 4,000 years ago (Jiménez-Arteaga et al., 2025; Manning et al., 2011). Following its domestication, the crop spread throughout sub-Saharan Africa before reaching the Indian subcontinent through ancient trade routes. Therefore, India is its secondary center of diversification (a place where numerous locally adapted landraces and improved cultivars developed through centuries of farmer selection and contemporary breeding (Sanjana Reddy et al., 2021; Serba et al., 2017).

Botanically, pearl millet is a diploid species (2n = 2x = 14) belonging to the tribe Paniceae and is closely related to other economically important millets, including foxtail (*Setaria italica*) and proso (*Panicum miliaceum*) (Maharajan et al., 2024; Satomura, 2025; Sharma et al., 2021). These species are predominantly cross-pollinated because of a protogynous flowering habit. Cross pollination promotes high levels of heterozygosity and extensive genetic diversity that have been widely exploited in breeding programs (Gupta et al., 2024; Prakash et al., 2026; Sattler et al., 2019; Yadav et al., 2021).

Pearl millet is characterized by a deep and vigorous root system, efficient water-use mechanisms, wax-coated leaves, and a relatively short growth cycle, that collectively enhance adaptation to drought, high temperatures and marginal soils (Bani Hani et al., 2022; Karthik et al., 2024; Passot et al., 2016). These adaptive traits, together with substantial genetic diversity, have positioned pearl millet as an important genetic resource for breeding climate-resilient cultivars capable of maintaining productivity under increasingly variable conditions.

Breeding approaches, including bio-fortification and genomic-assisted selection have improved its grain yield, nutritional quality, and resilience to multiple abiotic stresses. Today, pearl millet is cultivated across tropical and subtropical regions of Africa, Asia, and parts of America, where its resilience to moisture stress enables stable grain production under rain-fed agriculture systems, conditions that frequently limit productivity of major cereals such as maize, wheat, and rice (Akinseye et al., 2024; Jukanti et al., 2016; Satyavathi et al., 2021). Consequently, pearl millet has emerged as a strategic climate-smart crop with considerable potential to strengthen sustainable agricultural production, enhance food and nutrition security, and improve the resilience of farming systems under climate change conditions (Assoumane et al., 2018; Mariac et al., 2006).

Globally, pearl millet is recognized as the sixth most important cereal crop and serves as a staple food for millions of people in the arid and semi-arid regions of Africa and Asia (Jukanti et al., 2016; Karthik et al., 2024). The crop is cultivated on approximately 30 - 35 million hectares(Satyavathi et al., 2021). India is the world's leading producer, contributing more than 40 % of global production, followed by several African countries including Nigeria, Niger, Sudan, Burkina Faso, Mali, Chad, and Senegal (Deevi et al., 2024). Beyond these major production regions, pearl millet is increasingly cultivated in countries such as Ethiopia, Zimbabwe, Namibia, and Mauritania (Thomas & Mpofu, 2013), where its ability to produce reliable yields under low-input production systems supports household food security, income generation, and livelihood resilience.

The International Year of Millets 2023 encouraged scientists, industry, and policy makers to embrace pearl millet as a strategic crop for addressing food insecurity, micronutrient deficiencies and climate resilience. This stimulated multidisciplinary research spanning crop improvement, food processing, nutrition, functional foods, and value-chain development, thereby creating a rapidly expanding body of literature that requires critical synthesis to guide future research and industrial applications.

Climate change is expected to increase the frequency and intensity of drought, heat waves and drought stress, posing major threats to global cereal production (Mutanda et al., 2025). Compared with many staple cereals, pearl millet exhibits superior adaptation to these challenging environments. (S. K. Gupta et al., 2015; Saleem et al., 2021; Sithole et al., 2025). Nevertheless, significant genotype × environment interactions influence grain yield, nutritional quality, and bioactive compound accumulation (Howarth et al., 2021), highlighting the need for integrated breeding programsthat ensure stable performance across diverse production environments.

In addition to its agronomic resilience, pearl millet has exceptionally rich nutritional composition (Nibhoria et al., 2024; Pei et al., 2022). The grain contains relatively high levels of protein, dietary fiber, slowly digestible starch, resistant starch, essential amino acids and beneficial lipids compared to many conventional cereals (Jukanti et al., 2016; Nibhoria et al., 2024; Pei et al., 2022). It is also an excellent source of essential minerals, including iron, zinc, magnesium, phosphorus, potassium and calcium, and important vitamins such as thiamine, riboflavin and niacin (Jacob et al., 2024; Nibhoria et al., 2024). Pearl millet grains also contain diverse phytochemicals, including phenolic acids, flavonoids and other antioxidant compounds(Nambiar et al., 2012). These characteristics have increased interest in pearl millet as a functional food ingredient and as a target for biofortification and nutritional improvement programs. However, considerable variation in nutritional composition among genotypes, production environments, and post-harvest processing conditions has resulted in inconsistent findings across studies, highlighting the need for integrated evaluation of the available studies. Table 1 compares the nutritional composition of pearl millet with other cereals.

Growing evidence suggests that pearl millet may contribute to improved nutritional and metabolic health when incorporated into balanced diets. Its high dietary fiber and resistant starch contribute to improved digestive health and better glycemic regulation, making pearl millet-based foods potentially suitable for individuals with diabetes and metabolic disorders (Pei et al., 2022). Bioactive phenolic compounds and flavonoids exhibit strong antioxidant properties that may help reduce oxidative stress and may contribute to lowering the risk of cardiovascular diseases and certain chronic conditions (Lutz et al., 2019; Stachelska et al., 2025). Again, pearl millet is naturally gluten-free, making it an ideal cereal for individuals with celiac

disease (Nibhoria et al., 2024). Moreover, recent advances in breeding and biofortification have produced cultivars with enhanced iron and zinc concentrations, thereby strengthening the crop's potential to combat hidden hunger and micronutrient deficiencies in resource-limited populations (Gangashetty et al., 2021; Govindaraj et al., 2019).

Despite its potential, the wider utilization of pearl millet remains constrained by several technological and consumer-related challenges. The grain contains anti-nutritional compounds such as phytates, tannins, oxalates, and enzyme inhibitors that reduce mineral bioavailability and protein digestibility when consumed without appropriate processing (Meena et al., 2024; Nibhoria et al., 2024). In addition, the shelf life of its flour is limited by rapid lipid oxidation, while its characteristic flavour, colour, and texture reduce consumer acceptance in markets dominated by refined cereal products (Goyal & Chugh, 2017; Sruthi & Rao, 2021). Addressing these constraints has become a major focus of food science research, leading to the development of conventional and emerging processing technologies including soaking, germination, fermentation, decortication, roasting, extrusion, parboiling and novel thermal treatments, that improve nutrient availability, reduce anti-nutritional factors, enhance functional and sensory properties, and extend product shelf life (Bachate et al., 2025; Gatkal et al., 2026). The emerging technologies, including high-pressure processing, cold plasma, infrared heating, and other non-conventional approaches, are also being investigated for their potential to modify nutritional, functional, and bioactive properties of pearl millets products while improving product stability. In parallel, foodomics and metabolomics approaches provide increasingly powerful tools for characterizing compositional changes and identifying molecular responses associated with processing, genotype, and food functionality (Le, 2025; Toulabi et al., 2026). Despite these advances, differences in processing protocols, analytical methods, cultivar selection, and experimental designs continue to limit direct comparisons among studies.

Several recent reviews have addressed important aspects of pearl millet, including nutritional composition, value addition, industrial applications, processing, phytochemicals, functional properties, and product development (Nengparmoi et al., 2024; Singh et al., 2023). (Olamiti & Ramashia, 2025) further reviewed the nutritional and bioactive composition, processing, and products of millets in sub-Saharan Africa. However, these reviews differ in crop coverage, geographic focus, search period, and the extent to which nutritional, technological, analytical, and commercial dimensions are integrated. Therefore, the present study reviewed existing literature integrating nutritional composition, bioactive and anti-nutritional factors, processing, functional food development, biofortification, emerging analytical approaches, value addition, and commercialization. Rather than treating these themes as independent aspects of pearl millet utilization, the review is structured around three questions: (i) which processing approaches provide the most favourable balance between reducing anti-nutritional factors and retaining or improving nutritional and functional quality; (ii) how genotype, processing conditions, analytical methods, and food formulation contribute to variability among reported findings; and (iii) which pearl millet-based products have progressed beyond laboratory-scale development to demonstrate evidence of sensory quality, consumer acceptance, shelf-life stability, scalability, or commercial potential. The review therefore emphasizes comparative evidence, condition-dependent responses, methodological limitations, and the extent to which reported improvements have been validated beyond laboratory settings.

Table 1. Nutritional composition of pearl millet compared with wheat, rice, maize, sorghum, and finger millet (approximate values per 100 g edible portion).

Nutrient	Pearl millet	Finger millet	Wheat	Rice	Sorghum	Maize
Protein (g)	11.6-11.8	7.3	11.8	6.8	10.4	9.4
Fat (g)	4.8-5.0	1.5	1.5	0.5	3.1	4.7
Dietary fibre (g)	8-11.3	3.6–11.5	12.2	0.6	6.7	7.3
Energy (kcal)	363	328–336	340	365	329	365
Carbohydrates (g)	67	66–72	71.2	78.2	72.1	74.3
Calcium (mg)	42	344	30	10	25	7
Iron (mg)	8.0	3.9	3.5	0.7	4.4	2.7
Zinc (mg)	3.1	2.3	2.7	1.2	1.6	2.2
Magnesium (mg)	137	137	138	35	165	127
Phosphorus (mg)	296	283	346	115	289	210
Potassium (mg)	307	408	363	115	363	287
Sodium (mg)	10.9	13.73- 42.47	17.1	5	7.3	51.7
Minerals (g)	2.2-2.3	2.5–3.5	1.5	0.6	1.6	0.8
Thiamine (mg)	0.38	0.42	0.39	0.07	0.35	0.39
Riboflavin (mg)	0.21	0.19	0.12	0.05	0.14	0.20
Niacin (mg)	2.8	1.1	5.1	1.6	4.3	3.6

1.1 Methodology

This review was developed through a comprehensive search of peer-reviewed literature published primarily in English using major scientific databases, including Web of Science, Scopus, PubMed, Google Scholar, and ScienceDirect. The search was conducted using a combination of keywords such as "pearl millet", "nutritional composition", "processing technologies", "functional foods", "health benefits", "anti-nutritional factors", "bioactive compounds", "value addition", "commercialization", "foodomics", and "metabolomics".

Additional searches incorporated terms relating to other major cereal crops, including "millet", "sorghum", "maize", "wheat", "rice", and "barley", where comparative evidence was relevant to the interpretation of pearl millet research. Search terms were combined using Boolean operators (AND/OR) and adapted to the syntax of each database. Searches were conducted primarily in the title, abstract, and keyword fields where these fields were available. The literature considered in this review spanned food science, nutrition, agriculture, cereal technology, food processing, and plant metabolomics. Studies directly investigating pearl millet were prioritized when discussing its nutritional composition, bioactive compounds, anti-nutritional factors, processing characteristics, health-related properties, and technological applications. Literature from other cereal crops was selectively incorporated where pearl millet-specific evidence was limited or where studies provided relevant comparative, methodological, mechanistic, or technological context. Findings from other cereals were treated as comparative or contextual evidence and were not assumed to be directly transferable to pearl millet without consideration of relevant biological, compositional, and technological differences.

The studies were considered eligible when they addressed one or more themes within the scope of the review, including nutritional composition, bioactive compounds, anti-nutritional factors, processing or value-addition technologies, functional food applications, health-related properties, commercialization, foodomics and metabolomics. Peer-reviewed original research articles, review articles, and relevant authoritative reports were considered. Original research articles were prioritized when evaluating experimental findings, whereas review articles and authoritative reports were used to contextualize established knowledge and broader research trends. Studies involving other cereal crops were included when they provided information relevant to comparative interpretation, analytical approaches, processing technologies, biological mechanisms, or emerging applications discussed in relation to pearl millet. Publications that were unrelated to the thematic scope of the review or did not provide sufficient information to support interpretation were excluded. Greater emphasis was placed on studies published during the last decade (2016 – 2026), while earlier landmark publications were included to provide historical context or foundational knowledge. The database searches yielded 1,486 records, including 412 records from Web of Science, 356 from Scopus, 214 from PubMed, 327 from Google Scholar, and 177 from ScienceDirect. After removal of 386 duplicate records, 1100 records remained for title and abstract screening. Of these, 742 records were excluded because they were outside the thematic scope of the review or did not meet the eligibility criteria. The full texts of 358 potentially relevant publications were evaluated by reading the full text, subsequently 178 publications were included in the review. Additional relevant references identified through citation tracking and reference-list screening were also considered where they provided important support or foundational evidence. All four authors contributed to the screening, interpretation, and critical assessment of the retrieved literature, with discussions among the authors used to resolve differences in interpretation and determine the relevance of studies to the scope of the review. The retrieved sources were evaluated according to the study objectives, experimental or analytical approaches, methodological strengths, methodological limitations, major findings and consistency of reported findings. The attention was given to genotype or cultivar, processing conditions, experimental design, analytical methods, sample preparation, biological models, and study scale.

2 Nutritional Composition of Pearl Millet

2.1 Carbohydrates

Carbohydrates constitute approximately 67 g per 100 g of the dry weight of pearl millet grain and serve as the principal source of dietary energy (Singh et al., 2023). The carbohydrate fraction consists mainly of starch, together with smaller amounts of soluble sugars and non-starch polysaccharides that contribute to both the nutritional and structural properties of the grain (Hassan et al., 2021). Pearl millet starch is characterized by relatively high amylose content (Prasad et al., 2023), which generally slows enzymatic starch hydrolysis(Cabeza et al., 2025). However, the amylose concentration varies considerably among cultivars and is influenced by genotype, growing environment, and grain maturity (Champagne et al., 2004; Ribeiro et al., 2024). This resistant starch escapes digestion in the small intestine and undergoes fermentation in the colon, producing short-chain fatty acids that have been associated with effects on colonic fermentation and gut microbial metabolism (Rajalakshmi et al., 2026). Evidence from studies of pearl millet-based foods indicates that starch digestibility and glycaemic responses can be influenced by the amylose content and resistant starch fraction; however, these responses cannot be inferred from grain composition alone and may change substantially after processing and food preparation. Thus, compositional differences in amylose and resistant starch should be interpreted in relation to processing and food matrix, while physiological effects require direct dietary or human evidence.

2.2 Protein

Pearl millet is recognized as a protein-rich cereal (Jukanti et al., 2016), with protein concentrations generally ranging from 11.6 to 11.8% of grain dry weight depending on genotype, environmental conditions and agronomic management. Makarana et al. 2017 found that the yield of pearl millet decreases as the salt level increases. Moreover, the variety AVKB-19 had higher proteins compared to ICMV-15111 (Makarana et al. 2017). In another study, Prasad et al. (2014), reported a variation of protein content between cultivars, with 12.31, 11,17 and 10.79 for Pioneer 86M86, Kaveri Super Boss and ICTP-8203, respectively. The protein concentration of pearl millet is generally comparable to or higher than maize and rice and is similar to wheat, highlighting the potential of pearl millet as an important plant-based protein source, particularly in regions where access to animal-derived foods is limited (Jukanti et al., 2016; Meena et al., 2024; Nibhoria et al., 2024).

The pearl millet proteins consist primarily of prolamins, glutelins, albumins, and globulins, which differ in their amino acid composition, solubility, digestibility, and functional properties (Jahan-Mihan et al., 2011). Among these fractions, prolamins and glutelins constitute the major storage proteins and contribute significantly to grain protein accumulation and food-processing characteristics. However, protein quality is influenced by essential amino acid balance, protein structure and interactions with phenolic compounds and anti-nutritional factors such as phytates and tannins, which can reduce protein digestibility and amino acid availability (Tara et al., 2017).

Therefore, total protein concentration provides only a partial indication of protein quality.

Furthermore, the protein digestibility also varies according to genotype, grain preparation, and the analytical approach used. Earlier studies reported true protein digestibility values of approximately 94.6–95.9% in rats fed dehulled pearl millet, whereas apparent protein digestibility of a pearl millet-based diet was substantially lower (52.9%) in an older human study, illustrating the influence of experimental design, food matrix, and dietary context on estimates of protein utilization (FAO, 1995). In vitro studies likewise demonstrate that processing can modify protein digestibility. Malting increased in vitro protein digestibility by approximately 14–26% (Archana et al., 2001), with the greatest improvement observed after 72 hours of germination, while fermentation of germinated pearl millet has been reported to produce protein digestibility values exceeding 90%.In a controlled study involving nine healthy young men, (Fakiha et al., 2020) used the amino acid oxidation method to estimate lysine availability from pearl millet that had been soaked overnight and steamed at approximately 90 °C for 52 min. Lysine availability was 97% under these specific processing conditions, although lysine remained the limiting indispensable amino acid. Therefore, protein quality should be interpreted using amino acid composition, limiting amino acids, digestibility, and amino acid availability, rather than total protein concentration alone.

2.3 Lipids

Lipids constitute approximately 1.5 – 6.8% of the dry weight of pearl millet grain, making it one of the most lipid-rich cereal crops compared to maize, rice, wheat, and sorghum (Hassan et al., 2021; Nibhoria et al., 2024). Although lipids represent a relatively small proportion of the grain, they contribute substantially to its nutritional quality, energy density, sensory attributes, and functional properties. Pearl millet lipids are composed predominantly of triacylglycerols, phospholipids, glycolipids, free fatty acids, and minor bioactive constituents, including tocopherols and phytosterols, which collectively influence both nutritional value and storage stability (Nibhoria et al., 2024; Slama et al., 2020) The relatively high lipid content distinguishes pearl millet from many other cereals and contributes to its value as an energy-dense food, particularly in populations where dietary fat intake is limited.

The fatty acid profile of pearl millet is characterized by a predominance of unsaturated fatty acids, particularly linoleic acid, oleic acid, and smaller amounts of linolenic acid, together with saturated fatty acids such as palmitic and stearic acids (Selvan et al., 2025; Shanmugam et al., 2026; Slama et al., 2020) . Linoleic acid represents the major fatty acid fraction and serves as an essential polyunsaturated fatty acid required for normal growth, cell membrane integrity, and numerous physiological functions (X. Wang et al., 2024). The predominance of unsaturated fatty acids contributes to the nutritional value of pearl millet, while the established physiological roles of these fatty acids provide a mechanistic basis for potential cardiovascular and metabolic benefits (Slama et al., 2020) . However, these general effects of unsaturated fatty acids should not be interpreted as demonstrated health benefits of consumption of pearl millet without direct dietary evidence.

In addition, naturally occurring tocopherols and phytosterols contribute to antioxidant activity that protect lipids against oxidative deterioration while providing additional health-promoting properties (Poudel et al., 2023). Despite the oxidative protection, the abundance of unsaturated fatty acids increases susceptibility to oxidative deterioration following milling. Lipid oxidation results in the formation of undesirable volatile compounds that reduce flour quality, shelf life, and consumer acceptability (Dias et al., 2026), representing one of the principal challenges limiting the large-scale commercialization of pearl millet-based products (Mane et al., 2025). The nutritional value of pearl millet lipids must therefore be considered alongside their susceptibility to oxidation, particularly after milling, making processing and storage conditions important determinants of flour stability.

2.4 Dietary fiber

Dietary fibre is one of the distinguishing nutritional attributes of pearl millet and contributes significantly to its health-promoting properties. Pearl millet grain contains approximately 8-11.3% dietary fibre (Meena et al., 2024), comprising both soluble and insoluble fractions, although the exact concentration varies with genotype, growing conditions, and grain processing. Insoluble fibre, including cellulose, and lignin, constitutes the major proportion of total dietary fibre and plays an important role in promoting gastrointestinal motility, increasing faecal bulk and preventing constipation. Soluble fibre, although present in smaller quantities, contributes to the regulation of blood glucose, serum cholesterol concentrations, and gut microbial activity through the production of short-chain fatty acids during fermentation in the colon (Kanimozhi et al., 2026; Zayed et al., 2025). These physiological functions are well established for dietary fiber; however, the magnitude of these effects following pearl millet consumption depends on fiber composition, processing, dose, food matrix and individual dietary context. The complementary physiological functions of soluble and insoluble fibre enhance the nutritional value of pearl millet and provide a mechanistic basis for its potential contribution to digestive and metabolic health.

Dietary fibre also influences the technological and functional properties of pearl millet flour by affecting water absorption, swelling capacity, viscosity, and dough characteristics, thereby influencing the quality of processed food products (Meena et al., 2024). These functional characteristics contribute to the suitability of pearl millet for the development of bakery products, gluten-free foods, breakfast cereals, and other value-added products that require desirable water-holding and textural properties. In addition, fibre slows gastric emptying and carbohydrate digestion, which can contribute to lower postprandial glycaemic responses and greater satiety. Although these effects were generally established for dietary fibre, the magnitude, attributable to pearl millet, requires direct dietary or human intervention evidence (Nibhoria et al., 2024). Therefore, the functional significance of dietary fibre depends on its composition and interactions with the food matrix, including resistant starch and phenolic compounds.

2.5 Vitamins

Pearl millet is an important source of several essential vitamins that support normal growth, metabolism, immune function, and overall human health. The grain contains appreciable amounts of both water-soluble and fat-soluble vitamins, although their

concentrations vary according to genotype, environmental conditions, grain maturity, and post-harvest handling (Nibhoria et al., 2024; P. Singh et al., 2023). Among the water-soluble vitamins, pearl millet is particularly rich in B-complex vitamins, including thiamine (B_1), riboflavin (B_2), niacin (B_3), pyridoxine (B_6), and folate (B_9), which function as essential coenzymes in energy metabolism, nucleic acid synthesis, nervous system function and red blood cell formation (Boda et al., 2026). These vitamins contribute significantly to the nutritional quality of pearl millet, particularly in populations that rely heavily on cereal-based diets.

In addition to B-complex vitamins, pearl millet contains vitamin E (tocopherols), a group of fat-soluble antioxidants that protect cellular membranes against oxidative damage by scavenging reactive oxygen species (Asharani et al., 2010). Beyond their antioxidant role, tocopherols contribute to immune function, thereby enhancing both the nutritional and functional quality of the grain.

Vitamin A is absent in pearl millet, however, it can be made available when pearl millet is consumed as part of diversified diets or through biofortification strategies aimed at increasing the concentration of provitamin A . The nutritional contribution of vitamins depends not only on their concentration in the grain but also on their stability, availability, and interactions with other dietary components. Consequently, preserving vitamin content during food preparation and processing remains an important consideration for maximizing the nutritional benefits of pearl millet-based foods.

2.6 Minerals

Pearl millet is widely recognized as one of the most mineral-rich cereal grains and provides substantially higher concentrations of several essential minerals than commonly consumed cereals such as rice, maize, and wheat (Meena et al., 2024; Nibhoria et al., 2024). The grain is an excellent source of iron, zinc, calcium, phosphorus, magnesium, potassium, and manganese, together with smaller amounts of copper and selenium, all of which play indispensable roles in human growth, metabolism, immune function, and physiological homeostasis (Hemanth et al., 2025; R. Krishnan & Meera, 2018a). The naturally high mineral density of pearl millet has attracted considerable attention because of its potential to alleviate micronutrient deficiencies, particularly in low- and middle-income countries where cereal-based diets predominate. However, high mineral concentration does not necessarily translate into improved micronutrient status because absorption is influenced by phytates, tannins, dietary composition, processing, and individual nutritional status. Evidence demonstrating improved iron, zinc or other mineral status specifically following pearl millet consumption remains limited.

Iron is among the most nutritionally significant minerals in pearl millet because of its essential role in haemoglobin synthesis, oxygen transport, cognitive development, and immune function (Kalpana et al., 2025). Likewise, zinc supports enzyme activity, protein synthesis, wound healing, and immune competence, whereas calcium and phosphorus are essential for skeletal development and maintenance (Kanimozhi et al., 2026). Magnesium functions as a cofactor in numerous enzymatic reactions involved in energy metabolism and nucleic acid synthesis, while adequate intake of potassium contributes to fluid balance, nerve impulse transmission, and normal muscle function (Sarić, et al., 2025) The nutritional significance of these minerals depends on both their concentration and availability.

Although pearl millet contains high concentrations of essential minerals, their nutritional contribution depends on bioavailability rather than total concentration alone (Kalpana et al., 2025). Interactions between minerals and naturally occurring anti-nutritional compounds influence intestinal absorption, emphasizing the importance of considering both mineral content and mineral utilization when evaluating nutritional quality. Substantial variation in mineral composition has been reported among pearl millet cultivars, reflecting the genetic influence. In a study with 281 advanced breeding lines bred at ICRISAT and evaluated across two seasons, Pujar et al., 2022 reported a variability of 35–116 mg kg^{-1} for Iron and 21–80 mg kg^{-1} for Zinc. This variability provides opportunities to identify nutritionally superior germplasm while enhancing the contribution of pearl millet to diversified and micronutrient-rich diets.

2.7 Essential Amino Acids

Pearl millet possesses a relatively balanced amino acid profile compared with many other cereal grains and is particularly recognized for its higher concentrations of essential amino acids such as lysine, methionine, threonine, leucine, isoleucine, valine, and phenylalanine (Jukanti et al., 2016; P. Singh et al., 2023). These amino acids are indispensable because they cannot be synthesized in sufficient quantities by the human body and must therefore be obtained through the diet. The comparatively favourable amino acid composition enhances the nutritional quality of pearl millet and distinguishes it from several staple cereals that are deficient in one or more essential amino acids.

Among the essential amino acids, lysine is particularly important because it is often the first limiting amino acid in cereals such as maize and wheat. Pearl millet generally contains higher lysine concentrations than these cereals, although its lysine content remains lower than that of legumes, making it a valuable component of cereal-based diets when consumed alone or in combination with complementary protein sources (Jukanti et al., 2016). Methionine, another nutritionally important amino acid, contributes to protein synthesis, methyl-group transfer, and antioxidant defence through its role in glutathione metabolism. Branched-chain amino acids, including leucine, isoleucine, and valine, are essential for muscle protein synthesis, tissue repair, and energy metabolism, while threonine supports immune function and intestinal health (Kanimozhi et al., 2026). These established physiological roles provide a nutritional basis for the importance of an adequate essential amino acid supply, but they should not be interpreted as direct evidence that pearl millet consumption independently improves muscle, immune or intestinal health. Therefore, amino acid composition provides useful information on protein nutritional quality, but its nutritional significance should be interpreted together with, bioavailability and the presence of limiting amino acids. The complementary amino acid composition of pearl millet also supports its use in composite foods, where it can enhance the overall protein quality of cereal-based products when combined with legumes or other protein-rich ingredients. This character increases its potential

for application in functional foods and nutrition-sensitive product development.

2.8 Bioactive Compounds

Pearl millet is a rich source of diverse bioactive compounds that contribute substantially to its nutritional and functional properties. These phytochemicals include phenolic acids, flavonoids, tannins, lignans, phytosterols, carotenoids, tocopherols, and other antioxidant metabolites that collectively enhance the health-promoting potential of the grain (Table 2). Unlike essential nutrients that primarily support normal physiological functions, these bioactive compounds exert multiple biological activities that have been demonstrated in biochemical, cellular and other experimental models and may be relevant to human health through antioxidant, anti-inflammatory, antimicrobial, and metabolic regulatory mechanisms (Kalpana et al., 2025). Consequently, pearl millet has attracted increasing attention as a functional food ingredient with potential applications beyond basic nutrition, although the clinical significance of these activities remains insufficiently established.

Table 2. Major bioactive compounds identified in pearl millet and their health benefits.

Bioactive compound	Evidence/model	Experimental exposure or dose	Observed effect or outcome	Evidence level and interpretation	Key references
Phenolic acids	In vitro antioxidant and biochemical assays	Varies among studies	Scavenging of reactive oxygen species, metal-ion chelation and modulation of oxidative/inflammatory pathways	Mechanistic evidence; antioxidant activity in vitro does not establish clinical antioxidant or disease-preventive effects in humans	(Babypriyanka et al., 2024; Nambiar et al., 2012)
Flavonoids	In vitro biochemical and enzyme-inhibition assays	Study-dependent	Antioxidant activity, modulation of inflammatory mediators and inhibition of α-amylase and α-glucosidase	Mechanistic/in vitro evidence; effects on glucose metabolism should not be interpreted as demonstrated clinical glycaemic control	(Nambiar et al., 2012)
Tannins	In vitro digestion and antioxidant assays; other experimental models where reported	Study-dependent	Interaction with digestive enzymes, antioxidant activity and modification of starch/protein digestion	Experimental evidence; effects depend on tannin concentration, structure, food matrix and processing. Potential health effects in humans remain insufficiently established	(Hemanth et al., 2025)
Lignans	Chemical and biochemical studies; human evidence not established from the cited source	Not consistently reported	Antioxidant and phytoestrogenic activity; conversion to enterolignans by gut microbiota	Mechanistic evidence; proposed effects on cancer, cardiovascular health or hormonal function should not be presented as demonstrated clinical outcomes	(C. B. Yadav et al., 2021)
Dietary fibre	Human dietary studies and experimental studies where available	Varies with fibre type, food formulation and dose	Effects on gastrointestinal function, satiety, glucose absorption and cholesterol metabolism have been reported	Physiological effects are plausible and supported for dietary fibre generally, but the magnitude attributable specifically to pearl millet depends on fibre composition, processing, dose and food matrix	(Kaur et al., 2024)
Resistant starch	In vitro digestion, fermentation studies, animal studies and acute feeding studies where reported	Study- and food-dependent	Reduced starch digestibility, colonic fermentation and increased short-chain fatty acid production; effects on postprandial glycaemic response vary with processing and food matrix	Mechanistic and short-term physiological evidence; improved insulin sensitivity, body-weight regulation or long-term metabolic outcomes should not be inferred without appropriate human intervention evidence	(Vidhyalakshmi et al., 2024)
Bioactive peptides	In vitro enzyme-inhibition and antioxidant assays	Study-dependent peptide concentration	ACE inhibition, antioxidant activity and modulation of oxidative or immune-related pathways	Predominantly in vitro evidence; potential effects on blood pressure or cardiovascular outcomes require bioavailability and human intervention evidence	(Agrawal et al., 2021)
Vitamin E (tocopherols)	Chemical/compositional studies and antioxidant assays	Dependent on tocopherol concentration and dietary intake	Inhibition of lipid peroxidation and protection of polyunsaturated fatty acids from oxidative damage	Established biochemical antioxidant function; specific cardiovascular, immune or ageing-related effects from pearl millet consumption require direct human evidence	(Nibhoria et al., 2024)

Phenolic compounds represent the dominant class of bioactive constituents in pearl millet and consist mainly of phenolic acids, including ferulic, caffeic, p-coumaric, protocatechuic, and gallic acids, together with flavonoids such as quercetin, catechin, luteolin, and apigenin (Elsafy et al., 2024; Nambiar et al., 2012). These compounds are concentrated predominantly in the bran and seed coat, where they function as natural antioxidants by scavenging reactive oxygen species, chelating transition metals, and inhibiting lipid peroxidation. In addition to their antioxidant activity, phenolic compounds influence cellular signalling pathways associated with inflammation, glucose metabolism, and cardiovascular function, providing plausible mechanisms through which these compounds may influence disease-related pathways. However, evidence from isolated compounds or experimental models cannot be equated with demonstrated disease-preventive effects of pearl millet consumption in humans.

Tannins are another important group of phenolic compounds present in pearl millet. While tannins have traditionally been regarded as anti-nutritional factors because of their ability to reduce protein digestibility and mineral bioavailability, growing evidence indicates that they also possess antioxidant, antimicrobial, anti-inflammatory, and anticancer properties when consumed at appropriate dietary levels (Sharma et al., 2021). This dual role highlights the importance of balancing nutritional limitations with potential health benefits when evaluating the functional value of pearl millet. Phytosterols and tocopherols also enhance its functional properties. Phytosterols have been associated with reductions in intestinal cholesterol absorption and improvements in serum lipid profiles, whereas tocopherols protect cellular membranes against oxidative damage through their antioxidant activity (Pradeep and Guha, 2011). Collectively, these compounds strengthen the nutritional profile of pearl millet and support its application in functional foods and food formulations with potential functional properties.

Recent advances in metabolomics and foodomics have considerably improved the characterization of pearl millet phytochemicals, providing deeper insights into their diversity, biological functions and potential applications in functional food development. These approaches are expected to facilitate the identification of biomarkers associated with grain quality, nutritional value and health-promoting properties.

3. Health Benefits of Pearl Millet

Pearl millet has gained increasing attention as a functional cereal because of its potential to contribute to human health beyond basic nutrition (Hashem & Ibrahim, 2025). However, while numerous experimental biochemical and dietary studies indicate beneficial physiological effects, the strength of evidence varies considerably among studies. Many reported benefits are derived from in vitro assays, animal studies or short-term dietary interventions, and may not be interpreted as definitive therapeutic effects (Jacob et al., 2024; Kalpana et al., 2025; Ray et al., 2026) . The biological activity of pearl millet depends on multiple factors, including genotype, cultivation environment, processing method, food formulation and bioavailability of bioactive compounds (Jayalaxmi & Vijaya, 2024). Accordingly, the health-related evidence discussed below is interpreted according to study type and evidence strength, with compositional and mechanistic findings distinguished from outcomes demonstrated in human studies. This section evaluates reported effects on glycaemic regulation, cardiovascular health, gastrointestinal function, oxidative stress, inflammation, and other physiological outcomes, while distinguishing experimental evidence from human dietary evidence.

3.1 Diabetes Management

Pearl millet has attracted considerable attention as a functional cereal because of its potential role in supporting glycaemic regulation and reducing metabolic risk factors associated with Type 2 diabetes (Pei et al., 2022) . Unlike refined cereal grains, whole-grain pearl millet retains the bran and germ fractions, which contribute fibre, resistant starch, minerals, and phytochemicals that collectively influence glucose metabolism (Tanwar et al., 2026). These characteristics make pearl millet particularly relevant in dietary strategies aimed at improving glycaemic control and reducing metabolic disturbances associated with excessive postprandial glucose fluctuations.

Dietary fibre, resistant starch, and slowly digestible carbohydrates present in pearl millet contribute to improved glucose regulation by influencing digestion, nutrient absorption, and glucose availability (Ayushi & Sonali, 2024; Chisbert et al., 2024; Kumar et al., 2026). Fibre increases intestinal viscosity and delays gastric emptying (Akhlaghi, 2024) Again, fibre produces short-chain fatty acids that influence sensitivity to insulin and metabolic regulation. Resistant starch prevents Type 2 diabetes Mellitus and obesity through gut microbiota by modifying selective microbial composition to produce starch-degrading enzymes, promoting the production of intestinal metabolites, and improving gut barrier function (Liu et al., 2020). The combined effects of these carbohydrate fractions highlight that the glycaemic benefits of pearl millet arise from the interaction between grain structure, carbohydrate digestibility and physiological responses.

Beyond carbohydrate characteristics, pearl millet phytochemicals may provide additional mechanisms relevant to diabetes management (El Kourchi et al., 2024). Phenolic compounds, including phenolic acids, flavonoids, and tannins, have been reported to inhibit carbohydrate-digesting enzymes such as α-amylase and α-glucosidase, thereby reducing starch hydrolysis and slowing glucose release (Krishnan et al., 2022). These findings suggest that the potential antidiabetic activity of pearl millet involves both carbohydrate-related mechanisms and bioactive compound-mediated regulation of metabolic pathways. Furthermore, the experimental and dietary intervention studies indicate that replacing refined cereals with whole-grain pearl millet products may improve glycaemic responses (Pei et al., 2022). However, the magnitude of these effects varies according to cultivar characteristics, food formulation, dietary patterns, and individual physiological responses. Therefore, these findings support the potential of pearl millet as a dietary component for glycaemic management, however, the magnitude of the benefits depends on cultivar, processing and food formulation.

3.2 Cardiovascular health

Whole-grain pearl millet provides a complex matrix of fibre, unsaturated fatty acids, minerals, and phytochemicals that collectively influence cardiovascular disease (CVD)-related

risk factors (Biradar et al., 2024; Nibhoria et al., 2024). Rather than acting through a single mechanism, the cardioprotective potential of pearl millet is likely associated with synergistic interactions among multiple grain components. One important mechanism underlying the cardiovascular potential of pearl millet is its influence on lipid metabolism. Soluble dietary fibre contributes to cholesterol regulation by binding bile acids in the intestine, increasing their excretion and promoting the utilization of circulating cholesterol for bile acid synthesis (Ghavami et al., 2023; van Bennekum et al., 2005). This mechanism has been associated with reductions in LDL cholesterol; However, the magnitude of anycholesterol lowering effect specifically attributable to pearl millet consumption requires direct human evidence.

The mineral composition of pearl millet further supports cardiovascular function. Adequate intake of potassium contributes to blood pressure regulation through electrolyte balance and vascular tone, whereas adequate intake of magnesium plays important roles in vascular relaxation and cardiac function (Haddy et al., 2006). However, the presence of these minerals in pearl millet does not demonstrate a cardiovascular benefit, as their physiological effects depend on dietary intake, bioavailability, and the overall dietary pattern.

Furthermore, the bioactive compounds present in pearl millet provide additional cardiovascular benefits through antioxidants and anti-inflammatory mechanisms (Sadh et al., 2024). Phenolic compounds neutralize reactive oxygen species and regulate pathways associated with oxidative stress and inflammation, processes that contribute to endothelial dysfunction and cardiovascular disease progression (Lutz et al., 2019). Therefore, the available studies provide mechanistic support for potential cardiovascular health but the contribution of pearl millet itself remains dependent on dietary context and requires direct human validation.

3.3 Obesity

Obesity has emerged as a major global public health challenge, increasing the prevalence of diabetes, cardiovascular diseases, and other chronic metabolic disorders (Ahmed & Mohammed, 2025). Dietary strategies that improve satiety, regulate energy intake and support metabolic balance, are increasingly recognized as important components of obesity prevention and management strategies. Whole-grain pearl millet contributes to healthier dietary patterns because of its complex food matrix which promotes slower digestion and prolonged nutrient availability (Rajalakshmi et al., 2026). Unlike refined cereal products that are rapidly digested and may contribute to fluctuations in glucose and insulin concentrations, whole-grain pearl millet provides dietary fibre, resistant starch, and slowly digestible carbohydrates that support gradual nutrient release (Pragyani, 2013). The slower digestion characteristics of pearl millet foods may contribute to satiety; however, direct evidence suggesting that regular pearl millet consumption reduces energy intake or body weight remains limited. Furthermore, the resistant starch fraction of pearl millet may further influence obesity-related pathways through interactions with the gut microbiota. Fermentation of resistant starch produces short-chain fatty acids that contribute to intestinal health, regulate inflammatory responses, and influence host energy metabolism (den Besten et al., 2013). These mechanisms provide a rationale for investigating pearl millet within dietary strategies for weight management, although pearl millet-specific effects on body weight and appetite remain insufficiently characterized.

3.4 Gastrointestinal health

Pearl millet contributes positively to gastrointestinal health because of its dietary fibre, resistant starch, and bioactive compounds, that may support digestive function and modulate gut microbial composition (Nibhoria et al., 2024). Whole-grain pearl millet promotes normal bowel function by increasing faecal bulk and improving intestinal transit, effects largely attributed to its dietary fibre content (Suresh et al., 2024). Nevertheless, these benefits are expected to vary according to processing method, fibre retention, habitual dietary intake, and individual differences in gut microbiota composition. Resistant starch present in pearl millet undergoes microbial fermentation in the colon, producing short-chain fatty acids, particularly butyrate, which is generally known to support epithelial barrier integrity and contribute to immune regulation (Chen et al., 2024; Kumar et al., 2026). These physiological effects are well established for dietary fiber and resistant starch more broadly but should not be interpreted as evidence from a pearl millet-specific clinical trial**.** Although several studies suggest that pearl millet exhibits prebiotic potential by promoting beneficial microbial populations (Theodoro et al., 2025), the magnitude and consistency of these microbial changes remain uncertain because of the differences in cultivar, food formulation, processing conditions, and analytical approaches which limit direct comparisons among studies.

Emerging evidence also indicates that pearl millet polyphenols interact with the gut microbiota, where microbial metabolism enhances the bioavailability of certain phenolic compounds while simultaneously influencing microbial diversity and metabolic activity (Babypriyanka et al., 2024). However, the specific mechanisms underlying these interactions remain poorly understood and require validation in human studies.

Processing represents an additional source of variability. Fermentation and germination may enhance the availability of fermentable substrates and selected phytochemicals, whereas extensive refining reduces dietary fibre and other components associated with gut health (Kanimozhi & Sukumar, 2025; Park & Mannaa, 2025). Consequently, gastrointestinal responses should be interpreted in relation to processing level, fibre retention, food formulation, and the gut microbiota. Overall, the available evidence supports a plausible role for pearl millet in gastrointestinal function, but pearl millet-specific clinical evidence remains limited.

3.5 Antioxidant Activity

Pearl millet possesses considerable antioxidant potential because of its diverse array of phenolic compounds and other bioactive constituents that contribute to its ability to counteract oxidative stress (Yadav et al., 2021). These compounds are predominantly concentrated in the outer grain layers, particularly the bran fraction, which are retained in whole-grain pearl millet products and contribute substantially to their functional properties. Experimental evidence consistently demonstrates that pearl millet exhibits high antioxidant activity, although the magnitude of this activity varies considerably among cultivars and analytical methods used to quantify antioxidant capacity. Several in vitro studies have reported strong free-radical scavenging capacity and reducing power in

pearl millet extracts (Pushparaj & Urooj, 2014), while animal studies suggest that pearl millet consumption may enhance endogenous antioxidant defence systems (Borah et al., 2026). However, these findings should be interpreted cautiously because antioxidant activity measured under laboratory conditions does not necessarily translate into comparable physiological effects in humans. Reported antioxidant capacity differs substantially among pearl millet cultivars because of genetic and environmental influences (Babypriyanka et al., 2024; Hassan et al., 2020; James et al., 2022). Moreover, differences in extraction procedures and antioxidant assays hinder direct comparisons across studies and contribute to inconsistent estimates of its antioxidant potential.

3.6 Anti-inflammatory Activity

Pearl millet-derived bioactive compounds have been investigated for their potential to modulate inflammatory pathways through effects on oxidative stress and immune signalling (Kumar & Peddha, 2026; Saifi & Kalpana, 2026). Consequently, dietary components capable of modulating inflammatory pathways have received increasing attention as potential strategies for supporting long-term health. Experimental studies indicate that pearl millet consumption may attenuate inflammatory responses through modulation of oxidative stress and immune signalling pathways (Tomar et al., 2025). Several studies have reported reductions in selected pro-inflammatory mediators following exposure to pearl millet-derived bioactive compounds (Ambriz-Perez et al., 2016; Babypriyanka et al., 2024; Singh et al., 2020) . However, most available evidence originates from cell culture experiments or animal models, and its translation to human health remains uncertain. Again, reported anti-inflammatory effects differ among studies because of variations in pearl millet genotypes, experimental models, intervention duration, and inflammatory biomarkers measured. These methodological differences make direct comparisons difficult and partly explain the inconsistency in reported outcomes.

3.7 Potential chemo-preventive effects

Pearl millet contains bioactive constituents that have been investigated for their potential effects on biological pathways associated with carcinogenesis (Giri et al., 2024;Gupta et al., 2023; Nambiar et al., 2012). The studies indicated that pearl millet contains several bioactive constituents capable of influencing biological pathways associated with carcinogenesis (Giri et al., 2024; Jacob et al., 2024). However, most of this evidence has been generated under experimental conditions and direct evidence from human studies remains limited. Experimental investigations have shown that pearl millet-derived extracts can modulate cellular processes involved in tumour initiation and progression, including oxidative damage, cell proliferation, apoptosis, and inflammatory signalling (Hajri et al., 2024). These findings provide a biological basis for further investigation but should not be interpreted as evidence of cancer prevention in humans. Several studies have also reported antiproliferative and pro-apoptotic activities following exposure to pearl millet phytochemicals. Interpretation of these findings requires caution because most experiments employ isolated compounds or extract concentrations that may not be achieved through normal dietary intake. Differences in cultivar, phytochemical composition, and experimental design further contribute to variation in the reported biological responses. Besides, these findings provide a basis for mechanistic investigation but do not establish cancer-preventive or therapeutic effects of pearl millet consumption in humans.

3.8 Gluten-free properties

Pearl millet is naturally gluten-free, making it a suitable cereal for individuals with gluten-related disorders, including celiac disease, non-celiac gluten sensitivity, and wheat allergy (de Aguiar et al., 2024; S. Prakash et al., 2024) . Its absence of immunogenic gluten proteins allows pearl millet to serve as an alternative grain in gluten-free diets while contributing dietary diversity. Interest in pearl millet has grown because many commercially available gluten-free products are based on refined starches that often provide limited dietary fibre and micronutrients. Therefore, this crop offers an opportunity to improve the nutritional quality of gluten-free diets, although its overall nutritional contribution depends on the final food product and the overall dietary pattern.

4. Anti-nutritional factors

Phytates, primarily present as phytic acid (myo-inositol hexakisphosphate), are among the most abundant anti-nutritional compounds found in pearl millet grains (Boncompagni et al., 2018). Phytic acid serves as the principal storage form of phosphorus in cereal seeds and provides an important phosphorus reserve during germination and early seedling development (Pragya et al., 2025; Wu et al., 2009). The nutritional significance of phytates extends beyond their role in plant physiology because they can influence mineral bioavailability in humans. During digestion, phytates bind positively charged minerals, particularly iron, zinc, calcium, and magnesium (Pires et al., 2023), forming complexes that reduce their absorption in the gastrointestinal tract. This effect is of greatest concern in populations that rely heavily on cereal-based diets, where mineral deficiencies are already prevalent. Evidence also indicates that phytates interact with dietary proteins and digestive enzymes (Selle et al., 2023; Wang & Guo, 2021), which may reduce protein digestibility and nutrient accessibility. The magnitude of these effects, however, depends on phytate concentration, mineral status, meal composition, and habitual dietary patterns rather than the presence of phytates alone.

Although traditionally regarded as anti-nutritional compounds, phytates are increasingly recognized for their potential physiological benefit. Experimental studies suggest that phytic acid exhibits antioxidant activity through metal chelation and may contribute to protection against oxidative stress (Graf et al., 1987; Zajdel et al., 2013). Additional evidence indicates potential roles in regulating glucose metabolism and other disease-related pathways, although these findings are derived largely from experimental models and should not be interpreted as evidence that pearl millet consumption reduces chronic disease risks in humans. Phytate concentration varies considerably among pearl millet genotypes and is influenced by genetic background, environmental conditions, soil fertility, and crop management practices (Boncompagni et al., 2018; Singh et al., 2023). This variability presents opportunities for breeding programmes to develop cultivars with lower phytate concentrations while maintaining grain quality and agronomic performance. Reducing phytate concentration should not be viewed as the sole breeding objective because excessive reductions may also diminish some of its beneficial physiological functions.

4.2 Tannins

Tannins are naturally occurring polyphenolic compounds found in pearl millet grains that influence both nutritional quality and functional properties, depending on their concentration, chemical structure, and interactions with other grain constituents (Abdalla et al., 1998; Goudar et al., 2023). In plants, tannins play an important role in defence against herbivores, pathogens, and environmental stresses (Dehghanian et al., 2022; Iqbal & Poór, 2024). High tannin concentrations may reduce nutrient utilization (Frutos et al., 2004) because they bind proteins and minerals, decreasing protein digestibility and reducing the bioavailability of minerals, particularly iron. Current evidence demonstrates that tannins possess important biological activities. Their antioxidant, antimicrobial, anti-inflammatory and free-radical-scavenging activities have been demonstrated in experimental systems and may contribute to potential biological effects.. This dual role illustrates that tannins should not be regarded solely as anti-nutritional compounds but rather as bioactive constituents whose effects depend largely on concentration and dietary context. Another limitation associated with high tannin concentrations is reduced sensory acceptability (Bheemaiah et al., 2024), because tannins contribute to bitterness, astringency, and undesirable flavours, thereby affecting consumer acceptance. This challenge is particularly relevant for expanding pearl millet products into broader commercial markets.

Tannin content varies considerably among pearl millet genotypes and is influenced by grain colour, genetic background, environmental conditions, and crop management practices (Jukanti et al., 2016). Pigmented cultivars frequently contain higher tannin concentrations, although this relationship is not universal because considerable variation exists among genotypes. Therefore, a complete elimination of tannins is neither practical nor desirable because moderate concentrations contribute to the functional value of pearl millet.

4.3 Oxalates

Oxalates are naturally occurring organic acids found in various plant species where they participate in mineral regulation and may contribute to plant defence responses (Dawood & AbdElaziz, 2026). Oxalic acid can bind divalent minerals such as calcium and magnesium, forming insoluble oxalate salts that reduce mineral availability during digestion (Grąz, 2024). This interaction may contribute to reduced mineral utilization when pearl millet forms a major component of diets with limited dietary diversity. Although oxalates are considered anti-nutritional compounds (Salgado et al., 2023), their significance in pearl millet is generally lower than that of phytates because they occur at comparatively modest concentrations. However, the potential health effects of dietary oxalates depend on total intake, individual susceptibility, mineral status, and overall dietary composition. The oxalate accumulation in pearl millet varies according to genotype, environmental conditions, soil characteristics, and agronomic management practices (Rahman & Kawamura, 2011). Understanding this genetic and environmental variation provides opportunities for selecting cultivars with improved mineral bioavailability while maintaining desirable agronomic performance.

Across phytates, tannins, oxalates, and related anti-nutritional compounds, nutritional significance depends on concentration, chemical form, genotype, food matrix, and processing conditions. Processing can reduce selected compounds and improve mineral or protein bio-accessibility, but reductions are not uniform across technologies or grain fractions. Consequently, anti-nutritional factors should be evaluated in relation to their concentration, nutritional trade-offs, and processing context rather than treated as uniformly detrimental constituents.

5. Processing Technologies

Processing plays a fundamental role in improving the nutritional quality, digestibility, sensory characteristics, shelf life, and commercial value of pearl millet by modifying the physicochemical properties of starch, proteins, lipids, and dietary fibre (Latha Ravi & Rana, 2024; Nengparmoi et al., 2024). Conventional techniques such as cleaning, milling, decortication, soaking, germination, fermentation, roasting, and parboiling have long been employed to enhance grain quality and, depending on processing conditions, may reduce selected anti-nutritional compounds (Sreechithra & Sakhare, 2025), while advanced technologies including extrusion, microwave processing, infrared heating, high-pressure processing, cold plasma, and ohmic heating have expanded opportunities for industrial utilization of cereal grains (Anumudu et al., 2024; Chizoba Ekezie et al., 2017). Table 3 summarizes the processing conditions and reported effects.

Cleaning and milling are essential post-harvest operations that improve food safety, remove contaminants, and determine flour quality, particle size and functional performance. Whole-grain milling preserves fibre, minerals, vitamins and phytochemicals (Jonnalagadda et al., 2011), whereas refined milling improves texture, colour and storage stability but reduces concentrations of bioactive compounds and micronutrients (Hitlamani et al., 2026). Soaking may reduce soluble anti-nutritional factors but can also cause nutrient leaching. Germination may improve phytate degradation and protein digestibility but requires control of duration, moisture, temperature, and microbiological safety. Fermentation depends on microorganism, processing conditions, and final product matrix Fermentation outcomes also depend on the fermentation organism, fermentation duration, temperature, substrate composition, and whether fermentation is spontaneous or conducted using a defined starter culture (Lin et al., 2026). Lactic acid bacteria, yeasts, and mixed microbial communities can modify acidity, phytate degradation, protein hydrolysis, flavour, and other functional properties, but uncontrolled fermentation may produce variable outcomes and increase contamination risks if hygienic conditions are inadequate. These effects should therefore be interpreted in relation to the final product matrix, because the nutritional, sensory, and functional consequences of fermentation may differ among fermented porridges, beverages, doughs, and composite foods.

Decortication presents a trade-off between improved sensory and processing characteristics and losses of bran-associated nutrients and bioactive compounds. Decortication can improve palatability, colour, texture, and processing characteristics by removing the outer grain layers, but it also presents an important nutritional trade-off (Sruthi,et al., 2021). Because the bran and outer grain fractions contain dietary fibre, minerals, phenolic compounds, and other bioactive constituents. The extent of decortication can influence the retention of these components. Greater removal of the outer layers may therefore

improve sensory and processing characteristics while simultaneously reducing the concentration of bran-associated nutrients and bioactive compounds (Nocente & Gazza, 2025).

Thermal processing methods such as roasting, parboiling, puffing and popping can improve flavour, aroma, digestibility, storage stability and sensory quality while contributing to the reduction of anti-nutritional compounds. Roasting can inactivate lipase and lipoxygenase enzymes, lowers moisture content, reduces rancidity and generates desirable flavour and colour (Ma et al., 2023), although excessive heating may degrade heat-sensitive nutrients and reduce protein quality. Parboiling induces starch gelatinization, improves grain hardness, enhances milling recovery, reduces breakage and promotes migration of nutrients into the endosperm, thereby minimizing nutrient losses during subsequent milling (Miah et al., 2002; Ndindeng et al., 2025). Puffing and popping rapidly expand grain structure through internal steam generation, producing lightweight ready-to-eat products with improved crispness, lower bulk density, enhanced digestibility and greater consumer appeal (Swarnakar et al., 2022) These thermal treatments also reduce microbial contamination and partially inactivate enzyme inhibitors and anti-nutritional compounds. Product quality, however, is strongly influenced by processing temperature, grain moisture, treatment duration and grain genotype (Swarnakar et al., 2022). Therefore, appropriate optimization is essential to maximize nutritional retention while maintaining desirable sensory characteristics and functional properties.

Advanced and emerging technologies provide additional opportunities to develop high-quality pearl millet products with improved nutritional value, safety, and storage stability. Extrusion cooking combines high temperature, pressure, and shear forces to produce breakfast cereals, snacks, instant porridges and gluten-free products with enhanced digestibility, improved texture and reduced concentrations of anti-nutritional compounds (Bhattarai et al., 2025; Jain & Goomer, 2023). However, the extent of crop-specific evidence and industrial validation differs substantially among emerging technologies. Extrusion has been comparatively more extensively investigated for pearl millet product development, whereas evidence for high-pressure processing, cold plasma, infrared heating, microwave processing, and ohmic heating remains more limited and is often based on laboratory-scale studies or evidence from other cereal and food matrices. Consequently, reported benefits from these technologies should not be interpreted as directly transferable to pearl millet without crop-specific validation.

Table 3. Summary of pearl millet processing technologies and their effects on nutritional, functional, sensory, and safety attributes.

Processing technology	Key process conditions	Measured change (value/unit)	Product/matrix	Comparator	Evidence scale	Key limitation or trade-off	Reference
Soaking	soaked in water for 90 min without high pressure	Phytic acid reduction by 17%	Grain;	Unsoaked grain	Laboratory	Leaching of water-soluble minerals and other compounds may occur; effects depend on soaking duration and grain fraction	(Himashree & Mahendran, 2025)
	soaked of the bran and endosperm fractions in water	polyphenol reduction of 1–4%. Soaking bran and endosperm reduced phytic acid by 41% and 52%, respectively.	Bran and endosperm; flour				(R. Krishnan & Meera, 2018b)
Germination/malting	Germinated for 48 or 72 hours and then kilned at 50 °C for 24 hours	Reduction in polyphenol by 28% and phytic acids by 38%	Germinated grain	Ungerminated grain	Laboratory	Response varies with germination duration, temperature and cultivar; drying after germination adds another processing step	(Archana et al., 1998)
Fermentation	Fermentation of pearl millet for 24 hours	Phytic acid content significantly ($p < 0.05$) decreases from 647.0 to 310.95 mg/100 g (51.9% reduction)	Flour				(Osman, 2011)
	Natural fermentation at 20, 25 and 30 °C for 72 h	The phytate content was almost eliminated in the flour fermented at 30 °C. An increase in polyphenol content of fermented flour was noticed, the higher the temperature of fermentation the greater was the increase in polyphenol content of pearl millet.	Flour	Unfermented material	Laboratory	Fermentation outcome depends on microorganisms, inoculum, duration, temperature, and substrate; sensory changes may accompany biochemical changes	(Kheterpaul & Chauhan, 1991)
Decortication	Decortication and polishing of grains for 15 min	Reduction in fibre, tannins and phytates by more than 50%, 80% and 30%, respectively	Grain	Grain	Laboratory	Removal of bran and germ can reduce fibre, minerals, and other nutrients concentrated in peripheral tissues	(Bheemaiah Balyatanda et al., 2024)
Roasting	Roasted at three different temperatures (120, 140, and 160 °C) and time intervals (2.5, 5, and 10 min) and then extruded under previously optimized conditions of 140 °C, screw speed of 150 rpm, and moisture content of 30%.	reduction below detectable limits of phytic acid and 97.11% reduction in tannins while simultaneously inhibiting lipase and lipoxygenase by 90.30% and 94.06%, respectively.	roasted flour	Unroasted/raw flour	Laboratory	Effects depend strongly on temperature and duration; severe heating can alter heat-sensitive nutrients and physicochemical properties	(Pathare et al., 2025)
High-pressure soaking	Millet samples were soaked at three pressure levels of 300, 350, and 400 MPa for three different treatment times of 30-, 60-, and 90 min.	There were no significant changes in the nutritional profile of the treated samples, except that longer treatment times reduced the carbohydrate content.	Whole pearl millet; soaked grain	Atmospheric soaking/control	Laboratory	Equipment cost and limited industrial validation; effects on carbohydrate content were observed with longer treatment times	(Himashree & Mahendran, 2025)

Microwave processing, infrared heating, and ohmic heating can provide rapid and potentially energy-efficient alternatives to conventional heating, but their performance depends on equipment configuration, moisture content, treatment uniformity, product geometry, and processing scale. High-pressure processing may offer preservation with limited thermal damage and potential retention of flavour, vitamins, and heat-sensitive phytochemicals; however, the high capital cost of pressure equipment, batch-oriented operation in many systems, throughput limitations, and pressure-transmission characteristics of different food matrices can constrain its large-scale application. Cold plasma technology has also demonstrated potential for reducing microbial contamination, degrading mycotoxins and improving grain sanitation in selected food and cereal applications, but its effectiveness depends on plasma type, treatment intensity, exposure time, surface characteristics, and treatment uniformity. These technologies remain at different stages of validation for pearl millet. Their performance depends on treatment intensity, moisture, equipment configuration, food matrix, processing uniformity, energy requirements, and scale. Consequently, laboratory-scale improvements should not be interpreted as evidence of industrial feasibility. Future comparative studies should report processing capacity, energy consumption, treatment cost, product safety, quality retention, and scale-up performance alongside nutritional outcomes.

6. Value-Added Pearl Millet Products

Value addition has emerged as an important strategy for increasing the commercial value of pearl millet while expanding its application beyond traditional foods. Research and industrial innovation have facilitated the development of a range of experimental and, in some cases, commercially oriented pearl millet-based products, including bread, biscuits, cookies, pasta, noodles, breakfast cereals, snack foods, beverages, infant foods, and composite flours (Amjadi et al., 2025). These products offer opportunities to improve the nutritional quality of cereal-based foods because pearl millet generally contains higher concentrations of dietary fibre, minerals and bioactive compounds than many refined cereals (Asnaashari & Khajeh-Hosseini, 2025; Călinoiu & Vodnar, 2018). The nutritional and technological benefits of individual products, however, depend on the proportion of pearl millet flour, the ingredients used for formulation, processing conditions, and the resulting food matrix Călinoiu & Vodnar, 2018). Furthermore, value addition also creates new market opportunities by increasing product diversity, extending the use of pearl millet beyond traditional consumption patterns and responding to the growing demand for healthier and more sustainable foods. Nevertheless, evidence of sustained commercial adoption remains less extensive than evidence of product development at the laboratory or prototype level.

Commercial development of pearl millet products is nevertheless constrained by several technological challenges. The absence of gluten limits dough elasticity, gas retention, and structural integrity in baked products and pasta, often resulting in inferior texture and reduced consumer acceptability at high levels of pearl millet flour substitution (Cappelli et al., 2020; Zampirolli Petri et al., 2026). Several formulation and processing strategies have therefore been investigated to compensate for the absence of gluten, but their effectiveness and acceptable substitution levels vary among product types (Ma et al 2025). Hydrocolloids such as xanthan gum and related structure-forming agents can increase batter viscosity, improve gas-cell stabilization, and enhance loaf volume and crumb structure, although excessive levels may produce dense or gummy textures. Sourdough fermentation can improve dough acidification, flavour, rheological properties, and the sensory quality of gluten-free products while also modifying starch and protein characteristics; however, the magnitude of these improvements depends on the starter culture, fermentation conditions, and proportion of pearl millet flour. Enzyme supplementation, particularly with enzymes that modify starch or strengthen dough structure, can improve gas retention, loaf volume, crumb characteristics, and overall processing performance, although enzyme effectiveness is formulation-dependent (Ma et al 2025). Extrusion provides an alternative approach by combining heat, shear, and pressure to modify starch functionality and produce products such as ready-to-eat cereals and snacks with improved expansion, texture, and digestibility. Composite-flour formulations represent another widely investigated strategy because blending pearl millet with wheat or other cereals and incorporating protein-rich ingredients can improve structural properties and nutritional balance compared with using pearl millet flour alone or at high substitution levels (Ma et al 2025). The effectiveness of these approaches should be evaluated using measurable quality attributes, including specific volume, texture, expansion ratio, cooking loss, crumb characteristics, and sensory acceptability. Reported substitution levels should also be interpreted together with these quality outcomes because the highest acceptable pearl millet incorporation level is product-specific and depends on the formulation, processing conditions, and criterion used to define acceptability. Consequently, substitution levels demonstrated as acceptable for one product should not be generalized to other product categories.

The versatility of pearl millet enables the development of products targeting different consumer groups and market segments. Gluten-free foods may be formulated as gluten-free products, but their suitability for individuals with coeliac disease or other gluten-related disorders depends on validated gluten control and the absence of cross-contact during processing, handling, and storage (Imam et al., 2024; YearAsmin & Emine, 2026). Composite formulations containing legumes, nuts, fruits, or seeds may improve protein quality and micronutrient density, depending on the ingredients and their proportions. Furthermore, pearl millet has also been incorporated into complementary foods for infants and young children, although evidence from compositional and formulation studies alone is insufficient to establish suitability for infant or young-child feeding. For such applications, assessment should also consider phytate reduction and the resulting bioavailability of minerals such as iron, age-appropriate texture and particle size, microbial safety, and the nutritional adequacy of the complete food. Evidence should also indicate whether the formulated products were evaluated in the intended target population rather than relying solely on laboratory measurements or adult sensory panels. However, these applications should be distinguished from evidence of consumer acceptance or commercial success. Where sensory evaluation has been conducted, acceptance depends on product formulation and attributes such as taste, texture, aroma, colour, and appearance, while evidence on storage stability, shelf life, affordability, and market performance remains less consistently reported across product-development studies. Similarly, compositional improvements should not be interpreted as

evidence of clinical benefit unless the product has been evaluated in an appropriate clinical or target-population study. These innovations broaden market opportunities while supporting dietary diversification. Clinical evidence demonstrating the long-term health benefits of many value-added products, however, remains limited, indicating the need for further validation beyond compositional and product development studies.

The global demand for functional foods, clean ingredients, and climate-resilient crops has created opportunities for further development of pearl millet-based food products. Growing recognition of pearl millet as a climate-smart cereal further strengthens its commercial potential in regions seeking resilient and sustainable food systems. Commercial success, however, depends not only on nutritional quality but also on consumer acceptance, product affordability, shelf-life stability, processing cost, scalability, and consistent raw material supply. Consumer familiarity with wheat-based products, limited awareness of pearl millet, and variability in grain quality continue to constrain wider market penetration in many regions. Importantly, the availability of a laboratory-developed product should not be interpreted as evidence of pilot-scale production or commercial availability. Evidence for these stages should therefore be reported separately when assessing the commercialization potential of pearl millet products.

Composite flour technology may provide opportunities for value-chain development and diversification of markets for smallholder farmers and local agro-processing enterprises, including women-led businesses (Hasmadi et al., 2020; Mamat et al., 2025). However, evidence demonstrating increased smallholder income, enterprise profitability, or sustained benefits to women-led businesses remains limited and should not be inferred from product-development studies alone. The economic benefits of composite flours depend on the substitution level, ingredient costs, processing requirements, product quality, consumer willingness to purchase, and market price. Similarly, the potential contribution of pearl millet to public procurement, feeding programmes, and local value-chain development represents a proposed implementation opportunity rather than an established economic outcome unless supported by field-level or programme-level evidence. Commercial viability also depends on product shelf-life, consistency and availability of suitable grain, processing and packaging costs, compliance with food-quality and safety standards, and consumer willingness to pay relative to competing cereal products. Therefore, realizing these opportunities will require coordinated investments in breeding, quality standards, processing infrastructure, product innovation, consumer education, and supportive policy frameworks. These measures should be regarded as proposed pathways for commercialization rather than evidence of established economic outcomes.

7. Challenges

Pearl millet commercialization remains constrained by several interconnected challenges despite its exceptional nutritional value and climate resilience. Consumer acceptance remains one of the principal barriers to the wider adoption of pearl millet-based foods (Lacey et al., 2025). In many regions, pearl millet continues to be perceived as a subsistence crop, while its distinctive colour, flavour, texture and cooking characteristics differ from those of widely consumed cereals such as wheat and rice. These perceptions may influence consumer acceptance and purchasing decisions, although the magnitude of these effects varies among markets and products. Consumer willingness to pay and repeat-purchase behaviour should therefore be assessed directly rather than inferred from nutritional attributes alone. Consumer education, targeted marketing strategies and product innovation may therefore play important roles in expanding market acceptance.

Technical challenges also limit commercial competitiveness. The relatively high lipid content of pearl millet, together with lipase and lipoxygenase activity, accelerates oxidative rancidity after milling and shortens product shelf-life (Kumar et al., 2025). Grain characteristics, including small seed size, hardness and variable milling performance, further complicate industrial processing. Although technological advances have improved processing efficiency and product quality, adoption remains limited among small-scale processors because of high capital costs, limited technical capacity and inadequate access to modern processing equipment. From a commercialization perspective, processing costs, achievable shelf-life, packaging requirements, and consistency of raw-material supply are therefore important determinants of product viability. Commercial expansion is further constrained by fragmented value chains, inconsistent grain quality, inadequate processing infrastructure, weak quality assurance systems, limited investment in research and product development and restricted access to profitable markets. The availability and consistency of grain with processing characteristics suited to specific products are particularly important because variability in raw material can affect processing performance and final product quality. Compliance with appropriate food-quality, safety, and labelling standards is also necessary for sustained market participation.

These constraints may limit industrial competitiveness and private-sector investment. Addressing these constraints will require coordinated efforts involving researchers, plant breeders, food processors, industry, policymakers, and development agencies. Priority areas include the development of improved cultivars tailored for food processing, investment in appropriate processing and storage infrastructure, harmonization and enforcement of relevant quality and safety standards, strengthening of local and regional supply chains, and generation of market evidence on consumer acceptance and willingness to pay. Policies supporting the incorporation of pearl millet into appropriate public procurement and food programmes may provide additional market opportunities, but their effectiveness should be evaluated through implementation and economic studies. Expanding collaboration between research institutions and the food industry may also accelerate product innovation and facilitate the translation of scientific advances into commercially viable products. Therefore, these measures represent potential pathways for strengthening the competitiveness of pearl millet and its contribution to food security, nutrition, sustainable agriculture, and rural economic development, but their economic impacts require empirical validation.

8. Conclusions

Pearl millet provides a diverse nutritional profile and a broad platform for processing and value-added food development. However, reported nutritional, functional, health-related, and technological outcomes vary according to genotype, processing

conditions, analytical methods, and food formulation. The evidence base is also uneven, with substantially greater support for compositional and laboratory-scale product outcomes than for long-term human health effects, consumer behaviour, shelf-life, industrial scalability, and commercial performance. Consequently, nutritional and health claims should be interpreted according to the strength and type of evidence available, while product-development findings should be distinguished from demonstrated consumer acceptance and commercial success. Continued integration of breeding, processing, nutrition, metabolomics, and food-product research can strengthen the evidence base and support more reliable translation of pearl millet research into food and commercial applications.

9. Way Forward

Realizing the full potential of pearl millet will require a focused research and development agenda that prioritizes the major evidence gaps according to scientific need, feasibility, and potential for translation into practice. Priority areas include:

Developing high-yielding, climate-resilient, and nutritionally improved pearl millet cultivars through conventional breeding, genomics-assisted selection, and precision breeding

Conventional and emerging processing technologies should be optimized using standardized pearl millet matrices to improve nutrient retention, mineral bioavailability, sensory quality, shelf-life, safety, and processing efficiency.

Well-designed human studies to establish the, physiological effects, and health benefits of pearl millet

Quantification of consumer acceptance and willingness to pay, and market demand for pearl millet products.

Harmonized quality and safety standards, appropriate certification systems, post-harvest and processing infrastructure., Evidence-based commercialization pathways should be strengthened to facilitate wider adoption.

Acknowledgements

The University of South Africa and the Gwanda State University are thanked for their overall research support.

Funding Declaration

The authors declare that no funds, grants, or other support were received during the preparation of this manuscript.

Author contributions

All authors contributed equally to the conceptualization, writing, and editing of the manuscript. All authors reviewed and approved the final manuscript.

Data availability statement

Not applicable.

Ethics declarations

Ethics approval

Not applicable. This study is a review article and did not involve human participants or animal experimentation.

Consent to participate

Not applicable.

Consent for publication

Not applicable.

Clinical Trial Number

Not applicable.

Conflict of interest

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

REFERENCES

Abdalla, A. A., El Tinay, A. H., Mohamed, B. E., & Abdalla, A. H. (1998). Effect of traditional processes on phytate and mineral content of pearl millet. *Food Chemistry*, *63*(1), 79–84. https://doi.org/10.1016/s0308-8146(97)00194-5

Acharya, B., Rama, S., Prajapati, U. B., Srivastava, A., Joshi, R. A., & Tripathi, P. (2024). A review on Bajra/Pearl millet (Cenchrus americanus (L.) Morrone). *Journal of Scientific and Innovative Research*, *13*(1), 1–8.

Agrawal, H., Joshi, R., & Gupta, M. (2021). Optimization of pearl millet-derived bioactive peptide microspheres with double emulsion solvent evaporation technique and its release characterization. *Food Structure*, *29*, 100200. https://doi.org/10.1016/j.foostr.2021.100200

Ahmed, S. K., & Mohammed, R. A. (2025). Obesity: Prevalence, causes, consequences, management, preventive strategies and future research directions. *Metabolism Open*, *27*, 100375. https://doi.org/10.1016/j.metop.2025.100375

Akhlaghi, M. (2024). The role of dietary fibers in regulating appetite, an overview of mechanisms and weight consequences. Critical Reviews in Food Science and Nutrition, 64(10), 3139–3150. https://doi.org/10.1080/10408398.2022.2130160

Akinseye, F. M., Zagre, I., Faye, A., Joseph, J. E., Worou, O. N., & Whitbread, A. M. (2024). Exploring adaptation strategies for smallholder farmers in dryland farming systems and impact on pearl millet production under climate change in West Africa. *Frontiers in Agronomy*, *6*. https://doi.org/10.3389/fagro.2024.1428630

Ambriz-Perez, D. L., Leyva-Lepez, N., Gutierrez-Grijalva, E. P., & Heredia, J. B. (2016). Phenolic compounds: Natural alternative in inflammation treatment. A Review. *Cogent Food & Agriculture*, *2*(1). https://doi.org/10.1080/23311932.2015.1131412

Amjadi, H., Heidari, G., Babaei, S., & Sharifi, Z. (2025). Evaluation of yield, yield components and some quality traits of tuber of potato (Solanum tuberosum L.) under different weed and nutritional management practices. *Frontiers in Plant Science*, *15*. https://doi.org/10.3389/fpls.2024.1495541

Anumudu, C. K., Miri, T., & Onyeaka, H. (2024). Multifunctional Applications of Lactic Acid Bacteria: Enhancing Safety, Quality, and Nutritional Value in Foods and Fermented Beverages. *Foods*, *13*(23), 3714. https://doi.org/10.3390/foods13233714

Archana, Sehga, S., & Kawatra, A. (1998). Reduction of polyphenol and phytic acid content of pearl millet grains by malting and blanching. *Plant Foods for Human Nutrition*, *53*(2), 93–98. https://doi.org/10.1023/A:1008060604880

Archana, Sehgal, S., & Kawatra, A. (2001). In vitro protein and starch digestibility of pearl millet (Pennisetum gluacum L.) as affected by processing techniques. *Food / Nahrung*, *45*(1), 25–27. https://doi.org/https://doi.org/10.1002/1521-3803(20010101)45:1<25::AID-FOOD25>3.0.CO;2-W

Asharani, V. T., Jayadeep, A., & Malleshi, N. G. (2010). Natural Antioxidants in Edible Flours of Selected Small Millets. *International Journal of Food Properties*, *13*(1), 41–50. https://doi.org/10.1080/10942910802163105

Asnaashari, M., & Khajeh-Hosseini, M. (2025). Nutritional Value, Antioxidant, and Antiproliferative Activity of Whole Wheat Grains and Their Brans. *Journal of Food Quality*, *2025*(1). https://doi.org/10.1155/jfq/5516028

Assoumane, A., Blay, C., Alio Sanda, A.-K., Mariac, C., Pham, J.-L., Bezançon, G., & Vigouroux, Y. (2018). Wild crop relative populations hot-spots of diversity are hot-spots of introgression in the case of pearl millet. *Genetic Resources and Crop Evolution*, *65*(4), 1187–1194. https://doi.org/10.1007/s10722-018-0607-8

Ayushi, & Sonali, J. (2024). A review on the potential of pearl millets for diabetes mellitus. *International Journal of Home Science*, *10*(2), 167–171.

Babypriyanka, S., Hepziba, J. S., Pushpam, K. A., Pillai, A. M., Vijayalakshmi, R., & Theradimani, M. (2024). Exploring the bioactive components of millets for their nutraceutical potential. *Food Science and Biotechnology*, *34*(3), 563–575. https://doi.org/10.1007/s10068-024-01707-9

Bachate, A. H., Pawar, V. S., Pawar, G. S., Rodge, S. M., & Joshi, M. M. (2025). Effect of Soaking, Roasting and Germination on Nutritional Quality and Colour Properties of Pearl Millet Flour. *Asian Journal of Dairy and Food Research*, (Of). https://doi.org/10.18805/ajdfr.DR-2371

Bani Hani, N., Aukour, F. J., & Al-Qinna, M. I. (2022). Investigating the Pearl Millet (Pennisetum glaucum) as a Climate-Smart Drought-Tolerant Crop under Jordanian Arid Environments. *Sustainability*, *14*(19), 12249. https://doi.org/10.3390/su141912249

Bhattarai, R. R., Jayasree Joshi, T., Sruthi, N. U., Rao, P. S., & Johnson, S. (2025). Effects of extrusion cooking on nutritional and health attributes of sorghum and millets: special reference to protein and starch digestibility. *International Journal of Food Science and Technology*, *60*(1). https://doi.org/10.1093/ijfood/vvae093

Bheemaiah, B. S., Gowda, N. A. N., Subbiah, J., Chakraborty, S., Prasad, P. V. V., & Siliveru, K. (2024). Physiochemical, Bio, Thermal, and Non-Thermal Processing of Major and Minor Millets: A Comprehensive Review on Antinutritional and Antioxidant Properties. *Foods*, *13*(22), 3684. https://doi.org/10.3390/foods13223684

Bheemaiah Balyatanda, S., Gowda, N. A. N., Subbiah, J., Chakraborty, S., Prasad, P. V. V., & Siliveru, K. (2024). Physiochemical, Bio, Thermal, and Non-Thermal Processing of Major and Minor Millets: A Comprehensive Review on Antinutritional and Antioxidant Properties. *Foods*, *13*(22), 3684. https://doi.org/10.3390/foods13223684

Biradar, V. M., Kumar, P., M, Dr. Y., CS, R., Nayak, Dr. P., Sekhar, M., Bhushan, S., & Babu, Dr. S. (2024). A sustainable nutricereal: A review on nutrient and bio-active composition and its potential health benefits of pearl millet. *International Journal of Advanced Biochemistry Research*, *8*(3S), 30–35. https://doi.org/10.33545/26174693.2024.v8.i3sa.684

Boda, N. R., Kadri, A. S., Desai, S. V., Ramani, K. V., & Parasannanavar, D. (2026). Nutritional Comparison of Pearl Millet, Sorghum, and Finger Millet with Wheat and Rice: A Functional Food Perspective. *Current Research in Nutrition and Food Science Journal*, *14*(01_Special_Issue), 548. https://doi.org/10.12944/CRNFSJ.14.Special-Issue-June.04

Boncompagni, E., Orozco-Arroyo, G., Cominelli, E., Gangashetty, P. I., Grando, S., Kwaku Zu, T. T., Daminati, M. G., Nielsen, E., & Sparvoli, F. (2018). Antinutritional factors in pearl millet grains: Phytate and goitrogens content variability and molecular characterization of genes involved in their pathways. *PLOS ONE*, *13*(6), e0198394. https://doi.org/10.1371/journal.pone.0198394

Borah, T., Deka, S., & Sharma, D. (2026). Millets and food security: a sustainable response to growing population needs. *Frontiers in Plant Science*, *17*. https://doi.org/10.3389/fpls.2026.1796931

Cabeza, C., Ahmed, A.E.G., Minauf, M., Wieland, K. and Harasek, M., 2025. Starch hydrolysates, their impurities and the role of membrane-based technologies as a promising sustainable purification method at industrial scale. *Food Research International*, *209*, p.116300.

Călinoiu, L. F., & Vodnar, D. C. (2018). Whole Grains and Phenolic Acids: A Review on Bioactivity, Functionality, Health Benefits and Bioavailability. *Nutrients*, *10*(11), 1615. https://doi.org/10.3390/nu10111615

Cappelli, A., Oliva, N., & Cini, E. (2020). A Systematic Review of Gluten-Free Dough and Bread: Dough Rheology, Bread Characteristics, and Improvement Strategies. *Applied Sciences*, *10*(18), 6559. https://doi.org/10.3390/app10186559

Champagne, E. T., Bett-Garber, K. L., McClung, A. M., & Bergman, C. (2004). Sensory Characteristics of Diverse Rice Cultivars as Influenced by Genetic and Environmental Factors. *Cereal Chemistry*, *81*(2), 237–243. https://doi.org/10.1094/CCHEM.2004.81.2.237

Chen, Z., Liang, N., Zhang, H., Li, H., Guo, J., Zhang, Y., Chen, Y., Wang, Y., & Shi, N. (2024). Resistant starch and the gut microbiome: Exploring beneficial interactions and dietary impacts. *Food Chemistry: X*, *21*, 101118. https://doi.org/10.1016/j.fochx.2024.101118

Chisbert, M., Castell, A.-L., Vinoy, S., & Nazare, J.-A. (2024). The impact of slowly digestible and resistant starch on glucose homeostasis and insulin resistance. *Current Opinion in Clinical Nutrition & Metabolic Care*, *27*(4), 338–343. https://doi.org/10.1097/MCO.0000000000001044

Chizoba Ekezie, F.-G., Sun, D.-W., Han, Z., & Cheng, J.-H. (2017). Microwave-assisted food processing technologies for enhancing product quality and process efficiency: A review of recent developments. *Trends in Food Science & Technology*, *67*, 58–69. https://doi.org/10.1016/j.tifs.2017.05.014

Dawood, M. F. A., & AbdElaziz, Y. T. (2026). *Oxalic Acid: A Dual Role in Plant Stress Response and Detoxification* (pp. 397–425). https://doi.org/10.1007/978-981-95-8593-9_16

de Aguiar, E. V., Centeno, A. C. L. S., Garcia dos Santos, F., & Capriles, V. D. (2024). Whole grain pearl millet-based gluten-free bread: A novel alternative with nutrition and sensory appeal. *Applied Food Research*, *4*(2), 100520. https://doi.org/10.1016/j.afres.2024.100520

Deevi, K. C., Swamikannu, N., Pingali, P. R., & Gumma, M. K. (2024). Current Trends and Future Prospects in Global Production, Utilization, and Trade of Pearl Millet. In *Pearl Millet in the 21st Century* (pp. 1–33). Springer Nature Singapore. https://doi.org/10.1007/978-981-99-5890-0_1

Dehghanian, Z., Habibi, K., Dehghanian, M., Aliyar, S., Asgari Lajayer, B., Astatkie, T., Minkina, T., & Keswani, C. (2022). Reinforcing the bulwark: unravelling the efficient applications of plant phenolics and tannins against environmental stresses. *Heliyon*, *8*(3), e09094. https://doi.org/10.1016/j.heliyon.2022.e09094

den Besten, G., van Eunen, K., Groen, A. K., Venema, K., Reijngoud, D.-J., & Bakker, B. M. (2013). The role of short-chain fatty acids in the interplay between diet, gut microbiota, and host energy metabolism. *Journal of Lipid Research*, *54*(9), 2325–2340. https://doi.org/10.1194/jlr.r036012

Dias, F. F. G., Oliveira, W. da S., Bogusz Junior, S., & Taha, A. Y. (2026). Integrated Assessment of Lipid Oxidation and Off-Flavor Formation in Plant Protein Powders. *Journal of the American Oil Chemists' Society*, *103*(5), 371–386. https://doi.org/10.1002/aocs.70061

El Kourchi, C., Belhoussaıne, O., Elhrech, H., Harhar, H., Ullah, R., Bari, A., Maggi, F., Caprioli, G., Bouyahya, A., & Tabyaouı, M. (2024). Antidiabetic, antioxidant, and phytochemical profile of Pennisetum glaucum cultivated in central-southern Morocco and imported from India. *Journal of Agriculture and Food Research*, *16*, 101197. https://doi.org/10.1016/j.jafr.2024.101197

Elsafy, M., Othman, M. H., Hassan, A. B., Elkhatim, K. A. S., Hamid, M. G., Rahmatov, M., & Abdelhalim, T. S. (2024). Phytochemical components and antioxidant properties of traditional Sudanese pearl millet non-alcoholic drink. *Food Chemistry Advances*, *5*, 100739. https://doi.org/10.1016/j.focha.2024.100739

Fakiha, A., Tul-Noor, Z., Paoletti, A., Pencharz, P. B., Ball, R. O., Levesque, C. L., Elango, R., & Courtney-Martin, G. (2020). Bioavailable Lysine, Assessed in Healthy Young Men Using Indicator Amino Acid Oxidation, is Greater when Cooked Millet and Stewed Canadian Lentils are Combined. *The Journal of Nutrition*, *150*(10), 2729–2737. https://doi.org/10.1093/jn/nxaa227

FAO. (1995). *Food and Agriculture Organiziation. Sorghum and millets in human nutrition. https://www.fao.org/4/t0818e/t0818e0d.htm. Accessed 01 August 2026*.

Frutos, P., Hervás, G., Giráldez, F. J., & Mantecón, A. R. (2004). Review. Tannins and ruminant nutrition. *Spanish Journal of Agricultural Research*, *2*(2), 191–202. https://doi.org/10.5424/sjar/2004022-73

Gangashetty, P. I., Riyazaddin, M., Sanogo, M. D., Inousa, D., Issoufou, K. A., Asungre, P. A., Sy, O., Govindaraj, M., & Ignatius, A. I. (2021). Identification of High-Yielding Iron-Biofortified Open-Pollinated Varieties of Pearl Millet in West Africa. *Frontiers in Plant Science*, *12*. https://doi.org/10.3389/fpls.2021.688937

Gatkal, N. R., Shelke, M. S., Nalawade, S. M., Deshmukh, M. S., Sahni, R. K., Beňová, K., & Liška, J. (2026). Energy potential, health benefits, antinutrient reduction methods, and nutritional properties of Indian millets: a review. *Frontiers in Nutrition*, *13*. https://doi.org/10.3389/fnut.2026.1676670

Ghavami, A., Ziaei, R., Talebi, S., Barghchi, H., Nattagh-Eshtivani, E., Moradi, S., Rahbarinejad, P., Mohammadi, H., Ghasemi-Tehrani, H., Marx, W., & Askari, G. (2023). Soluble Fiber Supplementation and Serum Lipid Profile: A Systematic Review and Dose-Response Meta-Analysis of Randomized Controlled Trials. *Advances in Nutrition*, *14*(3), 465–474. https://doi.org/10.1016/j.advnut.2023.01.005

Giri, A., Sultana, S., Roy, A., Ray, D., Barui, I., & Sengupta, S. (2024). Potential therapeutic use of millet with broad spectrum anticancer properties: current trends and prospects. *Discover Food*, *4*(1). https://doi.org/10.1007/s44187-024-00264-8

Goudar, G., Manne, M., Sathisha, G. J., Sharma, P., Mokalla, T. R., Kumar, S. B., & Ziouzenkova, O. (2023). Phenolic, nutritional and molecular interaction study among different millet varieties. *Food Chemistry Advances*, *2*, 100150. https://doi.org/10.1016/j.focha.2022.100150

Govindaraj, M., Rai, K. N., Cherian, B., Pfeiffer, W. H., Kanatti, A., & Shivade, H. (2019). Breeding Biofortified Pearl Millet Varieties and Hybrids to Enhance Millet Markets for Human Nutrition.

Agriculture, *9*(5), 106. https://doi.org/10.3390/agriculture9050106

Goyal, P., & Chugh, L. K. (2017). Shelf life determinants and enzyme activities of pearl millet: a comparison of changes in stored flour of hybrids, CMS lines, inbreds and composites. *Journal of Food Science and Technology*, *54*(10), 3161–3169. https://doi.org/10.1007/s13197-017-2752-z

Graf, E., Empson, K. L., & Eaton, J. W. (1987). Phytic acid. A natural antioxidant. *Journal of Biological Chemistry*, *262*(24), 11647–11650. https://doi.org/10.1016/S0021-9258(18)60858-0

Grąz, M. (2024). Role of oxalic acid in fungal and bacterial metabolism and its biotechnological potential. *World Journal of Microbiology and Biotechnology*, *40*(6), 178. https://doi.org/10.1007/s11274-024-03973-5

Gupta, M., Asfaha, D. M., & Ponnaiah, G. (2023). Millets: A Nutritional Powerhouse With Anti-cancer Potential. *Cureus*. https://doi.org/10.7759/cureus.47769

Gupta, S. K., Rai, K. N., Singh, P., Ameta, V. L., Gupta, S. K., Jayalekha, A. K., Mahala, R. S., Pareek, S., Swami, M. L., & Verma, Y. S. (2015). Seed set variability under high temperatures during flowering period in pearl millet (Pennisetum glaucum L. (R.) Br.). *Field Crops Research*, *171*, 41–53. https://doi.org/10.1016/j.fcr.2014.11.005

Gupta, S. K., Yadav, O. P., & Reddy, P. S. (2024). Advances in Pearl Millet Hybrid Breeding and Development of Parental Lines. In *Pearl Millet in the 21st Century* (pp. 87–109). Springer Nature Singapore. https://doi.org/10.1007/978-981-99-5890-0_4

Haddy, F. J., Vanhoutte, P. M., & Feletou, M. (2006). Role of potassium in regulating blood flow and blood pressure. *American Journal of Physiology-Regulatory, Integrative and Comparative Physiology*, *290*(3), R546–R552. https://doi.org/10.1152/ajpregu.00491.2005

Hajri, L., Lewińska, A., Rzeszutek, I., Oklejewicz, B., Wojnarowska-Nowak, R., Krogul-Sobczak, A., Szpyrka, E., Aires, A., Ghodbane, S., Ammari, M., & Wnuk, M. (2024). Anticancer Activity of Encapsulated Pearl Millet Polyphenol-Rich Extract against Proliferating and Non-Proliferating Breast Cancer Cells In Vitro. *Cancers*, *16*(9), 1750. https://doi.org/10.3390/cancers16091750

Hashem, S. M., & Ibrahim, A. A. (2025). Impact of millet as a sustainable functional ingredient on nutritional and functional value of a novel kishk product. *Discover Food*, *5*(1), 225. https://doi.org/10.1007/s44187-025-00502-7

Hasmadi, M., Noorfarahzilah, M., Noraidah, H., Zainol, M. K., & Jahurul, M. H. (2020). Functional properties of composite flour: a review. *Food Research*, *4*(6), 1820–1831. https://doi.org/10.26656/fr.2017.4(6).419

Hassan, Z. M., Sebola, N. A., & Mabelebele, M. (2020). Assessment of the phenolic compounds of pearl and finger millets obtained from South Africa and Zimbabwe. *Food Science & Nutrition*, *8*(9), 4888–4896. https://doi.org/10.1002/fsn3.1778

Hassan, Z. M., Sebola, N. A., & Mabelebele, M. (2021). The nutritional use of millet grain for food and feed: a review. *Agriculture & Food Security*, *10*(1). https://doi.org/10.1186/s40066-020-00282-6

Hemanth, S., Singh, S. P., Singhal, T., Yadav, S., Kapoor, C., Naveen, A., Bhargavi, H. A., Satyam, Anamika, Singh, N., Meena, M. C., Kumar, A., & Satyavathi, C. T. (2025). Nutrient dynamics in pearl millet: Impact of seed soaking on minerals and anti-nutrient contents. *Journal of Cereal Science*, *125*, 104252. https://doi.org/10.1016/j.jcs.2025.104252

Himashree, P., & Mahendran, R. (2025). Effect of high-pressure soaking on the physicochemical, nutritional, and techno-functional properties of pearl millets. *Sustainable Food Technology*, *3*(3), 714–724. https://doi.org/10.1039/D5FB00042D

Hitlamani, V., Gowda M. R., S., Sheikh, S. A., Shetty, N. P., Singh, S. A., & Inamdar, A. A. (2026). Compositional variability in roller-mill processed streams: distribution of macro- and micronutrients, phytochemicals, and contaminants (heavy metals and anti-nutrients). *Sustainable Food Technology*, *4*(1), 1099–1114. https://doi.org/10.1039/D5FB00625B

Howarth, C. J., Martinez-Martin, P. M. J., Cowan, A. A., Griffiths, I. M., Sanderson, R., Lister, S. J., Langdon, T., Clarke, S., Fradgley, N., & Marshall, A. H. (2021). Genotype and Environment Affect the Grain Quality and Yield of Winter Oats (Avena sativa L.). *Foods*, *10*(10), 2356. https://doi.org/10.3390/foods10102356

Imam, Y. T., Irondi, E. A., Awoyale, W., Ajani, E. O., & Alamu, E. O. (2024). Application of legumes in the formulation of gluten-free foods: functional, nutritional and nutraceutical importance. *Frontiers in Sustainable Food Systems*, *8*. https://doi.org/10.3389/fsufs.2024.1251760

Iqbal, N., & Poór, P. (2024). Plant Protection by Tannins Depends on Defence-Related Phytohormones. *Journal of Plant Growth Regulation*, *44*(1), 22–39. https://doi.org/10.1007/s00344-024-11291-1

Jacob, J., Krishnan, V., Antony, C., Bhavyasri, M., Aruna, C., Mishra, K., Nepolean, T., Satyavathi, C. T., & Visarada, K. B. R. S. (2024). The nutrition and therapeutic potential of millets: an updated narrative review. *Frontiers in Nutrition*, *11*. https://doi.org/10.3389/fnut.2024.1346869

Jahan-Mihan, A., Luhovyy, B. L., El Khoury, D., & Anderson, G. H. (2011). Dietary Proteins as Determinants of Metabolic and Physiologic Functions of the Gastrointestinal Tract. *Nutrients*, *3*(5), 574–603. https://doi.org/10.3390/nu3050574

Jain, R., & Goomer, S. (2023). Understanding extrusion technology for cereal–pulse blends: A review. *Cogent Food & Agriculture*, *9*(1). https://doi.org/10.1080/23311932.2023.2253714

James, S., Bagirei, S. Y., James, S. A., Maina, C. Y., Ibrahim-Baba, A., Ilemona, A., & Ozovehe, A. (2022). Total phenolic, flavonoid and antioxidant capacities of processed pearl millet and sorghum flours . *Croatian Journal of Food Science and Technology*, *14*(2), 272–281. https://doi.org/10.17508/cjfst.2022.14.2.12

Jayalaxmi, B., & Vijaya, P. S. (2024). Millet-Derived Bioactive Compounds and Their Role in the

Development of Functional Foods. *Life Science Review*, *8*(1), 4–6.

Jiménez-Arteaga, C., Parque, Ó., Lancelotti, C., Moderato, M., Veesar, G. M., Abro, T., Chandio, A., & Madella, M. (2025). New evidence reveals dispersal of pearl millet from West Africa to South Asia by 2500 BCE. *Scientific Reports*, *15*(1), 32931. https://doi.org/10.1038/s41598-025-20110-w

Jonnalagadda, S. S., Harnack, L., Hai Liu, R., McKeown, N., Seal, C., Liu, S., & Fahey, G. C. (2011). Putting the Whole Grain Puzzle Together: Health Benefits Associated with Whole Grains—Summary of American Society for Nutrition 2010 Satellite Symposium1–3. *The Journal of Nutrition*, *141*(5), 1011S-1022S. https://doi.org/10.3945/jn.110.132944

Jukanti, A. K. ., Gowda, C. L. L., Rai, K. N., Manga, V. K., & Bhatt, R. K. (2016). Crops that feed the world 11. Pearl Millet (Pennisetum glaucum L.): an important source of food security, nutrition and health in the arid and semi-arid tropics. *Food Security*, *8*(2), 307–329. https://doi.org/10.1007/s12571-016-0557-y

Kalpana, K., Saifi, A., Khanna, G. L., Rao, D. B., Rakhra, G., & Tanwar, E. (2025). Effects of pearl millet diet on serum micronutrient status, mental health and meta-cognitive skills in athletes: a randomised controlled trial. *Discover Mental Health*, *5*(1), 159. https://doi.org/10.1007/s44192-025-00224-3

Kanimozhi, N. V, Nagalakshmi, S., & Sukumar, M. (2026). Microbial fermentation strategies for enhancing sensory and nutritional quality of plant-based protein foods. *Food Wellness*, *2*(1), 100046. https://doi.org/10.1016/j.foodw.2026.100046

Kanimozhi, N. V, & Sukumar, M. (2025). Harnessing probiotic fermentation to enhance the bioavailability and health impact of dietary phytochemicals. *Food Wellness*, *1*(1), 100018. https://doi.org/10.1016/j.foodw.2025.100018

Karthik, T. R., Sudha, B., Simhi Samyukta, S. M., Dinesh Kumar, R., Vinodhini, S. M., & Pavithra, G. (2024). Pearl Millet (Pennisetum glaucum): A Climate Resilient and Nutritionally Significant Crop for Global Food Security. *International Journal of Environment and Climate Change*, *14*(10), 381–393. https://doi.org/10.9734/ijecc/2024/v14i104493

Kaur, R., Panesar, P. S., Kaur, B., & Riar, C. S. (2024). Hydrothermal extraction of dietary fiber from pearl millet bran: optimization, physico-chemical, structural and functional characterization. *Journal of Food Science and Technology*, *61*(8), 1536–1546. https://doi.org/10.1007/s13197-023-05921-x

Kheterpaul, N., & Chauhan, B. M. (1991). Effect of natural fermentation on phytate and polyphenolic content and in-vitro digestibility of starch and protein of pearl millet (Pennisetum typhoideum). *Journal of the Science of Food and Agriculture*, *55*(2), 189–195.

Krishnan, R., & Meera, M. S. (2018a). Pearl millet minerals: effect of processing on bioaccessibility. *Journal of Food Science and Technology*, *55*(9), 3362–3372. https://doi.org/10.1007/s13197-018-3305-9

Krishnan, R., & Meera, M. S. (2018b). Pearl millet minerals: effect of processing on bioaccessibility. *Journal of Food Science and Technology*, *55*(9), 3362–3372. https://doi.org/10.1007/s13197-018-3305-9

Krishnan, V., Verma, P., Saha, S., Singh, B., Vinutha, T., Kumar, R. R., Kulshreshta, A., Singh, S. P., Sathyavathi, T., Sachdev, A., & Praveen, S. (2022). Polyphenol-enriched extract from pearl millet (Pennisetum glaucum) inhibits key enzymes involved in post prandial hyper glycemia (α-amylase, α-glucosidase) and regulates hepatic glucose uptake. *Biocatalysis and Agricultural Biotechnology*, *43*, 102411. https://doi.org/10.1016/j.bcab.2022.102411

Kumar, A., Muthuramalingam, P., Verma, L., Kumar, R., Kumar, N., Misra, J., Ravi, K., Shin, H., & Ramesh, M. (2026). Modern genomic and omics-based technologies for millet breeding and genetic improvement. *Frontiers in Plant Science*, *17*. https://doi.org/10.3389/fpls.2026.1782766

Kumar, M. K. P., & Peddha, M. S. (2026). Nutritional Value, Digestibility and Effect of Millet Protein on the Gut Microbiome. In *Millet Proteins* (pp. 88–112). Royal Society of Chemistry. https://doi.org/10.1039/9781837677405-00088

Kumar, R.R., Goswami, S., T, V., Mishra, G.P., Singh, A., Satyavathi, C.T., Tyagi, A. and Praveen, S., 2025. Rogue Enzymes at Work–Unraveling the Interplay Between Lipase and Lipoxygenase in Pearl Millet Flour for Solving the Problem of Rancidity. *Journal of Food Science*, *90*(11), p.e70689.

Kumar, V., Sharma, C., Bhatt, S. C., Rajput, V., Mishra, R., Gupta, A. K., Shikha, D., Kumar, V., & Naik, B. (2026). Fermented millets as next-generation functional foods: insights into microbiota modulation and gastrointestinal health. *Food Production, Processing and Nutrition*, *8*(1), 54. https://doi.org/10.1186/s43014-026-00402-y

Lacey, J., Bray, J. and Hartwell, H., 2025. Influencing factors towards consumer acceptance of millet as a food source. *International Journal of Gastronomy and Food Science*, *40*, p.101171.

Latha Ravi, J., & Rana, S. S. (2024). Maximizing the Nutritional Benefits and Prolonging the Shelf Life of Millets through Effective Processing Techniques: A Review. *ACS Omega*, *9*(37), 38327–38347. https://doi.org/10.1021/acsomega.4c03466

Le, T. H. (2025). Next-generation foodomics: Integrated multi-omics approaches for structural and functional profiling of plant-based proteins and polyphenols. *Journal of Food Composition and Analysis*, *148*, 108634. https://doi.org/10.1016/j.jfca.2025.108634

Lin, Y., Karrar, E., Islam, S., Jin, Z., Muhammad, U. and Xu, M., 2026. Microbial fermentation of cereals: nutritional, techno-functional, and compositional transformations toward data-driven process optimization. *Critical Reviews in Food Science and Nutrition*, pp.1-28.

Liu, H., Zhang, M., Ma, Q., Tian, B., Nie, C., Chen, Z. and Li, J., 2020. Health beneficial effects of resistant starch on diabetes and obesity via regulation of gut microbiota: A review. *Food & Function*, *11*(7), pp.5749-5767.

Lutz, M., Fuentes, E., Ávila, F., Alarcón, M., & Palomo, I. (2019). Roles of Phenolic Compounds in the

Reduction of Risk Factors of Cardiovascular Diseases. *Molecules*, *24*(2), 366. https://doi.org/10.3390/molecules24020366

Ma, Y., Jin, Y., Xiao, Y., Yang, P., Chelliah, R., Shan, L. and Oh, D.H., 2025. A comprehensive review of gluten-free foods: Addressing quality defects and exploring novel enrichment strategies. *Food Hydrocolloids*, p.112261.

Ma, Q., Ye, J., Wu, X., Cao, T., Sun, Y., Ju, W., Qiu, J., & Cao, R. (2023). Effects of thermal processing on physicochemical and storage properties of Tartary buckwheat bran. *Journal of Cereal Science*, *113*, 103752. https://doi.org/10.1016/j.jcs.2023.103752

Maharajan, T., Krishna, T. P. A., Krishnakumar, N. M., Vetriventhan, M., Kudapa, H., & Ceasar, S. A. (2024). Role of Genome Sequences of Major and Minor Millets in Strengthening Food and Nutritional Security for Future Generations. *Agriculture*, *14*(5), 670. https://doi.org/10.3390/agriculture14050670

Mamat, H., Ibrahim, S. N., Ronie, M. E., Abdul Aziz, A. H., Kobun, R., Pindi, W., Fan, H. Y., Roslan, J., Mohammad Ridhwan, N., Mantihal, S., Zainol, M. K., & Putra, N. R. (2025). Composite Flour as An Innovative Food Ingredient in Bakery Products: A Review. *International Journal of Food*, *2*(1), 11–24. https://doi.org/10.51200/ijf.v2i1.5384

Manning, K., Pelling, R., Higham, T., Schwenniger, J.-L., & Fuller, D. Q. (2011). 4500-Year old domesticated pearl millet (Pennisetum glaucum) from the Tilemsi Valley, Mali: new insights into an alternative cereal domestication pathway. *Journal of Archaeological Science*, *38*(2), 312–322. https://doi.org/10.1016/j.jas.2010.09.007

Makarana, G., Yadav, R.K., Kumar, R., Kumar, A., Sheoran, P., Yadav, G., Soni, P.G., Yadav, T., Yadav, M.R., Kushwaha, M. and Gautam, P.B., 2017. Growth, yield and grain quality of pearl millet (Pennisetum glaucum L.) genotypes as influenced by salinity of irrigation water in north western regions of India. *International Journal of Current Microbiology and Applied Sciences*, *6*(6), pp.2858-2874.

Mariac, C., Luong, V., Kapran, I., Mamadou, A., Sagnard, F., Deu, M., Chantereau, J., Gerard, B., Ndjeunga, J., Bezançon, G., Pham, J.-L., & Vigouroux, Y. (2006). Diversity of wild and cultivated pearl millet accessions (Pennisetum glaucum [L.] R. Br.) in Niger assessed by microsatellite markers. *Theoretical and Applied Genetics*, *114*(1), 49–58. https://doi.org/10.1007/s00122-006-0409-9

Meena, K. K., Meena, S., Joshi, M., & Dhotre, A. V. (2024). Nutritional and functional exploration of pearl millet and its processing and utilization: An overview. *Food and Humanity*, *3*, 100334. https://doi.org/10.1016/j.foohum.2024.100334

Miah, M. A. K., Haque, A., Douglass, M. P., & Clarke, B. (2002). Parboiling of rice. Part II: Effect of hot soaking time on the degree of starch gelatinization. *International Journal of Food Science and Technology*, *37*(5), 539–545. https://doi.org/10.1046/j.1365-2621.2002.00611.x

Mutanda, M., Shimelis, H., Chaplot, V., & Figlan, S. (2025). Managing drought stress in wheat (*Triticum aestivum* L.) production: strategies and impacts. *South African Journal of Plant and Soil*, 1–12. https://doi.org/10.1080/02571862.2025.2497229

Nambiar, V. S., Sareen, N., Daniel, M., & Gallego, E. B. (2012). Flavonoids and phenolic acids from pearl millet (Pennisetum glaucum) based foods and their functional implications. *Functional Foods in Health and Disease*, *2*(7), 251. https://doi.org/10.31989/ffhd.v2i7.85

Ndindeng, S. A., Tang, E. N., Twine, E., Taleon, V., & Frei, M. (2025). Rice milling and parboiling trade-offs for economic and nutritional gains with special attention to sub-Saharan Africa: a comprehensive review. *Applied Food Research*, *5*(2), 101274. https://doi.org/10.1016/j.afres.2025.101274

Nengparmoi, Th., Ghorband, A. S., Yadav, P., Sahu, R., Anbarasan, S., Reddy, V. S., & Panotra, N. (2024). Pearl Millet Processing Methods and Products: An in-Depth Analysis. *European Journal of Nutrition & Food Safety*, *16*(8), 180–192. https://doi.org/10.9734/ejnfs/2024/v16i81506

Nibhoria, A., Kumar, M., Arya, R. K., & Siroha, A. K. (2024). Pearl millet for good health and nutrition – An overview. *CABI Reviews*. https://doi.org/10.1079/cabireviews.2024.0041

Nocente, F., & Gazza, L. (2025). Technological Development in Wholegrain Food Processing. *Foods*, *14*(12), 2009. https://doi.org/10.3390/foods14122009

Olamiti, G., & Ramashia, S. E. (2025). Processing Effect on Carbohydrate Structure and Physicochemical Properties of Starch, Dough and Flour of Some Cereals. *Current Nutrition & Food Science*, *21*(7), 769–782. https://doi.org/10.2174/0115734013348401250311033456

Osman, M. A. (2011). Effect of traditional fermentation process on the nutrient and antinutrient contents of pearl millet during preparation of Lohoh. *Journal of the Saudi Society of Agricultural Sciences*, *10*(1), 1–6. https://doi.org/10.1016/j.jssas.2010.06.001

Park, I., & Mannaa, M. (2025). Fermented Foods as Functional Systems: Microbial Communities and Metabolites Influencing Gut Health and Systemic Outcomes. *Foods*, *14*(13), 2292. https://doi.org/10.3390/foods14132292

Passot, S., Gnacko, F., Moukouanga, D., Lucas, M., Guyomarc'h, S., Ortega, B. M., Atkinson, J. A., Belko, M. N., Bennett, M. J., Gantet, P., Wells, D. M., Guédon, Y., Vigouroux, Y., Verdeil, J.-L., Muller, B., & Laplaze, L. (2016). Characterization of Pearl Millet Root Architecture and Anatomy Reveals Three Types of Lateral Roots. *Frontiers in Plant Science*, *7*. https://doi.org/10.3389/fpls.2016.00829

Pathare, A. M., Singhal, R. S., Rao, D. B., & Gokhale, J. S. (2025). Roasting-Assisted Extrusion Efficiently Inhibits Lipolytic Enzymes and Degrades Antinutritional Factors in Pearl Millet (*Pennisetum glaucum*). *Journal of Food Science*, *90*(12). https://doi.org/10.1111/1750-3841.70736

Pei, J., Umapathy, V. R., Vengadassalapathy, S., Hussain, S. F. J., Rajagopal, P., Jayaraman, S., Veeraraghavan, V. P., Palanisamy, C. P., & Gopinath, K. (2022). A

Review of the Potential Consequences of Pearl Millet (Pennisetum glaucum) for Diabetes Mellitus and Other Biomedical Applications. *Nutrients*, *14*(14), 2932. https://doi.org/10.3390/nu14142932

Pires, S. M. G., Reis, R. S., Cardoso, S. M., Pezzani, R., Paredes-Osses, E., Seilkhan, A., Ydyrys, A., Martorell, M., Sönmez Gürer, E., Setzer, W. N., Abdull Razis, A. F., Modu, B., Calina, D., & Sharifi-Rad, J. (2023). Phytates as a natural source for health promotion: A critical evaluation of clinical trials. *Frontiers in Chemistry*, *11*. https://doi.org/10.3389/fchem.2023.1174109

Poudel, P., Petropoulos, S. A., & Di Gioia, F. (2023). Plant Tocopherols and Phytosterols and Their Bioactive Properties. In *Natural Secondary Metabolites* (pp. 285–319). Springer International Publishing. https://doi.org/10.1007/978-3-031-18587-8_8

Pragya, Kumar, P., Singh, D., Tiwari, S. K., Chouayekh, H., & Singh, B. (2025). Phytic acid: biosynthesis, functional attributes and conventional vis-a-vis modern approaches for reduction. *Food Bioscience*, *71*, 107204. https://doi.org/10.1016/j.fbio.2025.107204

Pragyani, B. (2013). *Nutritional Properties of Different Millet Types and their Selected Products*. The University of Guelph.

Prakash, S., Pulivarthi, M. K., & Siliveru, K. (2024). *Pearl Millet: Processing and Value Addition for Gluten-free Markets* (pp. 485–514). https://doi.org/10.1002/9780891184034.ch15

Prakash, U., Yadav, V. K., Mehta, B. K., Dwivedi, K. K., Keerthana, D., Choudhary, R., Shweta, Kaushal, P., & P., S. (2026). Integrating morphological and molecular diversity to develop high-biomass fodder pearl millet composites. *Frontiers in Plant Science*, *17*. https://doi.org/10.3389/fpls.2026.1767075

Prasad, S.K., Samota, A., Singh, M.K. and Verma, S.K., 2014. Cultivars and nitrogen levels influence on yield attributes, yield and protein content of pearl millet under semi-arid condition of vindhyan region. *The Ecoscan*, *6*, pp.47-50.

Prasad, P., Sahu, J. K., & Srivastava, A. K. (2023). Millet Starch–A Potential Functional Ingredient. *International Journal of Plant & Soil Science*, *35*(21), 1060–1065.

Pujar, M., Govindaraj, M., Gangaprasad, S., Kanatti, A. and Shivade, H., 2020. Genetic variation and diversity for grain iron, zinc, protein and agronomic traits in advanced breeding lines of pearl millet [Pennisetum glaucum (L.) R. Br.] for biofortification breeding. *Genetic Resources and Crop Evolution*, *67*(8), pp.2009-2022.

Pushparaj, F., & Urooj, A. (2014). Antioxidant Activity in Two Pearl Millet (Pennisetum typhoideum) Cultivars as Influenced by Processing. *Antioxidants*, *3*(1), 55–66. https://doi.org/10.3390/antiox3010055

Rahman, M. M., & Kawamura, O. (2011). Oxalate Accumulation in Forage Plants: Some Agronomic, Climatic and Genetic Aspects. *Asian-Australasian Journal of Animal Sciences*, *24*(3), 439–448. https://doi.org/10.5713/ajas.2011.10208

Rajalakshmi, S. G., Rai, C. E., Moorthy, M. K., Abirami, S. V., & Viswanathan, P. (2026). Millet-based dietary intervention modulates gut microbiota and inflammatory signalling to support glycemic control and healthy ageing. *Discover Food*, *6*(1), 149. https://doi.org/10.1007/s44187-026-00826-y

Ray, S., Francis, G. A., Jeyakumar, S. S., Chavan, P., Supreethee, S., & Vashishth, R. (2026). Millet: a functional powerhouse against chronic lifestyle disease. *Frontiers in Nutrition*, *13*. https://doi.org/10.3389/fnut.2026.1884184

Ribeiro, N. R., Sousa, M. B. e, Oliveira, L. A. de, & de Oliveira, E. J. (2024). Variability of amylose content and its correlation with the paste properties of cassava starch. *PLOS ONE*, *19*(10), e0309619. https://doi.org/10.1371/journal.pone.0309619

Sadh, P. K., Kamboj, A., Kumar, S., Chawla, P., Kumar, R., Saharan, B. S., Kumar, D., Duhan, S., Nehra, M., Goyal, C., Brar, B., Joshi, S., & Duhan, J. S. (2024). Perspectives of millets for nutritional properties, health benefits and food of the future: a review. *Discover Food*, *4*(1), 187. https://doi.org/10.1007/s44187-024-00266-6

Saifi, A., & Kalpana, K. (2026). Pearl Millet-A Forgotten Ancient Grain with Emerging Immunomodulatory Potential in Sports Nutrition. *Current Nutrition Reports*, *15*(1), 48. https://doi.org/10.1007/s13668-026-00771-3

Saleem, S., Ul Mushtaq, N., Hafiz Shah, W., Rasool, A., Rehman Hakeem, K., & Ul Rehman, R. (2021). Morpho-Physiological, Biochemical and Molecular Adaptation of Millets to Abiotic Stresses: A Review. *Phyton*, *90*(5), 1363–1385. https://doi.org/10.32604/phyton.2021.014826

Salgado, N., Silva, M. A., Figueira, M. E., Costa, H. S., & Albuquerque, T. G. (2023). Oxalate in Foods: Extraction Conditions, Analytical Methods, Occurrence, and Health Implications. *Foods*, *12*(17), 3201. https://doi.org/10.3390/foods12173201

Sanjana Reddy, P., Satyavathi, C. T., Khandelwal, V., Patil, H. T., Gupta, P. C., Sharma, L. D., Mungra, K. D., Singh, S. P., Narasimhulu, R., Bhadarge, H. H., Iyanar, K., Tripathi, M. K., Yadav, D., Bhardwaj, R., Talwar, A. M., Tiwari, V. K., Kachole, U. G., Sravanti, K., Shanthi Priya, M., … Tonapi, V. A. (2021). Performance and Stability of Pearl Millet Varieties for Grain Yield and Micronutrients in Arid and Semi-Arid Regions of India. *Frontiers in Plant Science*, *12*. https://doi.org/10.3389/fpls.2021.670201

Satomura, K. (2025). Tribe Paniceae Cereals with Different Ploidy Levels: Setaria italica, Panicum miliaceum, and Echinochloa esculenta. *Genes*, *16*(4), 426. https://doi.org/10.3390/genes16040426

Sattler, F. T., Pucher, A., Kassari Ango, I., Sy, O., Ahmadou, I., Hash, C. T., & Haussmann, B. I. G. (2019). Identification of Combining Ability Patterns for Pearl Millet Hybrid Breeding in West Africa. *Crop Science*, *59*(4), 1590–1603. https://doi.org/10.2135/cropsci2018.12.0727

Satyavathi, C. T., Ambawat, S., Khandelwal, V., & Srivastava, R. K. (2021). Pearl Millet: A Climate-Resilient Nutricereal for Mitigating Hidden Hunger

and Provide Nutritional Security. *Frontiers in Plant Science*, *12*. https://doi.org/10.3389/fpls.2021.659938

Selle, P. H., Macelline, S. P., Chrystal, P. V., & Liu, S. Y. (2023). The Contribution of Phytate-Degrading Enzymes to Chicken-Meat Production. *Animals*, *13*(4), 603. https://doi.org/10.3390/ani13040603

Selvan, S. S., Mohapatra, D., Kate, A., Tripathi, M. K., & Kar, A. (2025). Fatty acid profiling for discriminating fermented and non-fermented pearl millet (Pennisetum glaucum L.) grains under different storage temperatures. *Scientific Reports*, *15*(1), 34210. https://doi.org/10.1038/s41598-025-15785-0

Serba, D. D., Perumal, R., Tesso, T. T., & Min, D. (2017). Status of Global Pearl Millet Breeding Programs and the Way Forward. *Crop Science*, *57*(6), 2891–2905. https://doi.org/10.2135/cropsci2016.11.0936

Shanmugam, N., Ramalingam, A. P., Mohanavel, W., Vara Prasad, P. V., Felderhoff, T., Muthurajan, R., & Perumal, R. (2026). Metabolome aided genome wide association analysis identifies genetic loci linked to grain nutritional traits in pearl millet. *Journal of Agriculture and Food Research*, *29*, 103111. https://doi.org/10.1016/j.jafr.2026.103111

Sharma, S., Sharma, R., Govindaraj, M., Mahala, R. S., Satyavathi, C. T., Srivastava, R. K., Gumma, M. K., & Kilian, B. (2021). Harnessing wild relatives of pearl millet for germplasm enhancement: Challenges and opportunities. *Crop Science*, *61*(1), 177–200. https://doi.org/10.1002/csc2.20343

Singh, A., & Gupta, M. (2026). Nutritional, functional, rheological and textural properties of processed pearl millet incorporated brittle crunch. *Food Research International: Translational Research*, *1*, 100006. https://doi.org/10.1016/j.frintr.2026.100006

Singh, A., Yau, Y. F., Leung, K. S., El-Nezami, H., & Lee, J. C.-Y. (2020). Interaction of Polyphenols as Antioxidant and Anti-Inflammatory Compounds in Brain–Liver–Gut Axis. *Antioxidants*, *9*(8), 669. https://doi.org/10.3390/antiox9080669

Singh, P., Gupta, N., Hameed, F., & Rahman, R. (2023). Pearl millet as an underutilized source of nutrition: A review on its nutritional composition, value addition and industrial applications. *Indian Journal of Agricultural Biochemistry*, *36*(1), 26–30. https://doi.org/10.5958/0974-4479.2023.00003.5

Sithole, C., Sinthumule, R. R., Gaorongwe, J. L., Ruzvidzo, O., & Dikobe, T. B. (2025). Unraveling the complexities: morpho-physiological and proteomic responses of pearl millet (Pennisetum glaucum) to dual drought and salt stress. *Frontiers in Plant Science*, *16*. https://doi.org/10.3389/fpls.2025.1495562

Slama, A., Cherif, A., Sakouhi, F., Boukhchina, S., & Radhouane, L. (2020). Fatty acids, phytochemical composition and antioxidant potential of pearl millet oil. *Journal of Consumer Protection and Food Safety*, *15*(2), 145–151. https://doi.org/10.1007/s00003-019-01250-4

Sreechithra, T. V., & Sakhare, S. D. (2025). Impact of processing techniques on the nutritional quality, antinutrients, and in vitro protein digestibility of milled soybean fractions. *Food Chemistry*, *485*, 144565. https://doi.org/10.1016/j.foodchem.2025.144565

Sruthi, N. U., & Rao, P. S. (2021). Effect of processing on storage stability of millet flour: A review. *Trends in Food Science & Technology*, *112*, 58–74. https://doi.org/10.1016/j.tifs.2021.03.043

Sruthi, N.U., Rao, P.S. and Rao, B.D., 2021. Decortication induced changes in the physico-chemical, anti-nutrient, and functional properties of sorghum. *Journal of Food Composition and Analysis*, *102*, p.104031.

Stachelska, M. A., Karpiński, P., & Kruszewski, B. (2025). A Comprehensive Review of Biological Properties of Flavonoids and Their Role in the Prevention of Metabolic, Cancer and Neurodegenerative Diseases. *Applied Sciences*, *15*(19), 10840. https://doi.org/10.3390/app151910840

Swarnakar, A.K., Mohapatra, M. and Das, S.K., 2022. A review on processes, mechanisms, and quality influencing parameters for puffing and popping of grains. *Journal of Food Processing and Preservation*, *46*(10), p.e16891.

Suresh, A., Shobna, Salaria, M., Morya, S., Khalid, W., Afzal, F. A., Khan, A. A., Safdar, S., Khalid, M. Z., & Mukonzo Kasongo, E. L. (2024). Dietary fiber: an unmatched food component for sustainable health. *Food and Agricultural Immunology*, *35*(1). https://doi.org/10.1080/09540105.2024.2384420

Sarić, M.M., Sorić, T., Kasap, Ž.J., Šikić, N.L., Mavar, M., Andruškienė, J. and Sarić, A., 2025. Magnesium: health effects, deficiency burden, and future public health directions. *Nutrients*, *17*(22), p.3626.

Tanwar, R., Panghal, A., Kumari, A., & Chhikara, N. (2025). Nutritional, phytochemical and functional potential of pearl millet: a Review. *Chemistry & Biodiversity,* 22(7), e202402437.

Tara Satyavathi, C., Praveen Shelly, Mazumdar Saikat, Chugh, L.K. and Kawatra Asha (2017) Enhancing Demand of Pearl millet as Super grain - Current Status and Way Forward. ICARAll India Coordinated Research Project on Pearl millet, Jodhpur-342304. (n.d.).

Theodoro, J. M. V., da Silva, L. A., de São José, V. P. B., Willis, N. B., Toledo, R. C. L., Grancieri, M., Carvalho, C. W. P., Pierre, J. F., da Silva, B. P., & Martino, H. S. D. (2025). Processed Pearl Millet Improves the Morphology and Gut Microbiota in Wistar Rats. *Foods*, *14*(15), 2752. https://doi.org/10.3390/foods14152752

Thomas, B., & Mpofu, I. D. T. (2013). Competitive environment of the staple food distribution system in Namibia: An assessment of the pearl millet (Pennisetum glaucum) industry. *Agricultural Science Research Journals Vol. 3 (4), 121*, *129*.

Tomar, T., Sachdeva, A., Dutta, J., Al Tawaha, A. R. M., Karnwal, A., Malik, T., & Selvaraj, M. (2025). Fermentation dynamics of millet beverages: Microbial interactions, nutritional enhancements, and health implications. *Food Chemistry: X*, *25*, 102199. https://doi.org/10.1016/j.fochx.2025.102199

Toulabi, S. B., Van Buiten, C., Carolan, M. S., Kantar, M. B., Gore, M. A., Khoury, C. K., Gallo-Franco, J. J., Brinkley, S., McAlvay, A. C., de Haan, S., Holm, D. G., MacLean, P., de la Parra, J., Ahmed, S., & Prenni,

J. E. (2026). Harnessing foodomics for next-generation crop breeding: Advancing sustainable agrifood systems and One Health. *Journal of Agriculture and Food Research*, *31*, 103252. https://doi.org/10.1016/j.jafr.2026.103252

van Bennekum, A. M., Nguyen, D. V., Schulthess, G., Hauser, H., & Phillips, M. C. (2005). Mechanisms of cholesterol-lowering effects of dietary insoluble fibres: relationships with intestinal and hepatic cholesterol parameters. *British Journal of Nutrition*, *94*(3), 331–337. https://doi.org/10.1079/BJN20051498

Vidhyalakshmi, R., Prabhasankar, P., Muthukumar, S. P., Prathima, C., & Meera, M. S. (2024). The impact of addition of pearl millet starch-germ complex in white bread on nutritional, textural, structural, and glycaemic response: Single blinded randomized controlled trial in healthy and pre-diabetic participants. *Food Research International*, *183*, 114186. https://doi.org/10.1016/j.foodres.2024.114186

Vutla, S., Knoll, J. E., Sankuratri, A., Nayak, R. G., Liu, L., Chee, P. W., Karthikeyan, R., Fakrudin, B., Thudi, M., Timper, P., Harris-Shultz, K., Wallace, J. G., Singh, H., Singh, B., & Punnuri, S. M. (2025). Mapping QTLs for Pyricularia leaf spot, nematode resistance, and yield related traits in pearl millet [Cenchrus americanus (L.) Morrone]. *Frontiers in Plant Science*, *16*. https://doi.org/10.3389/fpls.2025.1588485

Wang, R., & Guo, S. (2021). Phytic acid and its interactions: Contributions to protein functionality, food processing, and safety. *Comprehensive Reviews in Food Science and Food Safety*, *20*(2), 2081–2105. https://doi.org/10.1111/1541-4337.12714

Wang, X., Jia, Y., & He, H. (2024). The Role of Linoleic Acid in Skin and Hair Health: A Review. *International Journal of Molecular Sciences*, *26*(1), 246. https://doi.org/10.3390/ijms26010246

Wu, P., Tian, J., Walker, C. E. (Chuck), & Wang, F. (2009). Determination of phytic acid in cereals – a brief review. *International Journal of Food Science & Technology*, *44*(9), 1671–1676. https://doi.org/10.1111/j.1365-2621.2009.01991.x

Yadav, C. B., Tokas, J., Yadav, D., Winters, A., Singh, R. B., Yadav, R., Gangashetty, P. I., Srivastava, R. K., & Yadav, R. S. (2021). Identifying Anti-Oxidant Biosynthesis Genes in Pearl Millet [Pennisetum glaucum (L.) R. Br.] Using Genome—Wide Association Analysis. *Frontiers in Plant Science*, *12*. https://doi.org/10.3389/fpls.2021.599649

Yadav, O. P., Gupta, S. K., Govindaraj, M., Sharma, R., Varshney, R. K., Srivastava, R. K., Rathore, A., & Mahala, R. S. (2021). Genetic Gains in Pearl Millet in India: Insights Into Historic Breeding Strategies and Future Perspective. *Frontiers in Plant Science*, *12*. https://doi.org/10.3389/fpls.2021.645038

YearAsmin, Y., & Emine, M. E. (2026). Gluten-Free Diet in Celiac Disease: Nutrient Imbalances andAlternative Grain Sources. *Wheat Studies*.

Zajdel, A., Wilczok, A., Węglarz, L., & Dzierżewicz, Z. (2013). Phytic Acid Inhibits Lipid Peroxidation *In Vitro*. *BioMed Research International*, *2013*, 1–6. https://doi.org/10.1155/2013/147307

Zampirolli Petri, P., De Souza Silva, P., & Luis Ramírez Ascheri, J. (2026). Rethinking Structure; Challenges in the Development of Gluten-Free Pasta and Baked Goods: A Review. *Discoveries in Agriculture and Food Sciences*, *14*(01), 22–50. https://doi.org/10.14738/tnc.1401.19861

Zayed, A., Abdelkareem, S., Talaat, N., Dayem, D. A., & Farag, M. A. (2025). Tannin in foods: Classification, Dietary Sources, and Processing Strategies to Minimize Anti-Nutrient Effects. *Food and Bioprocess Technology*, *18*(11), 9221–9249. https://doi.org/10.1007/s11947-025-04020-3