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Pre-processing interventions to improve Nutri-cereal nutritional profile: A review

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Abstract
Millets are drought tolerant, climate resilient, and sustainable cereal crops that are staple foods in arid and semi-arid regions of the world. Due to their superior nutrition to rice and wheat, millets have gained a reputation as 'miracle grains' and are therefore referred to as nutrient dense foods. Millets are excellent sources of protein, dietary fibre, energy and important minerals such as iron and calcium, as well as different types of bioactive compounds including phenolic acids, flavonoids and phytosterols. These compounds have hypoglycemic, antioxidant and alkaline forming properties thus, protecting against chronic lifestyle disorders like diabetes, obesity, heart disease and certain types of cancer. Even though millets have significant potential they remain underutilized because of their coarse texture and the presence of anti-nutritional factors that limit nutrient bioavailability. This article will critically review historical and contemporary methods of processing millets including decortication, soaking, germination, fermentation, milling, roasting, and extrusion, and how they impact the nutritional quality, techno-functionality and anti- nutritional factors of millets. Research shows that some forms of intensive processing, specifically, milling; would remove nutrients by removing the bran and germ of the kernel. On the contrary, controlled pre-processing methods such as germination and fermentation increase mineral bioavailability, reduce anti-nutritional factors, and improve the viability of probiotic microorganisms.

Keywords: Antinutritional factors, functional properties, health benefits, millets, nutritional value, processing strategies

1. Introduction
Millets are small in size, round in shape, and minor cereals of the small grass family called Poaceae. It is characterized by their remarkable ability to survive in less fertile soil, drought-resistant, resistance to pest's diseases, and short growing season and cultivated round the year and all over the world. Millet is the sixth-highest yielding grain in the world. The total millet production of the world in 2018 was estimated to be 31,019,370 tonnes (Yousaf *et al.*, 2021) [34], India was the largest millet producer followed by Niger, Sudan, and other countries.

1.1 Importance of millets as nutrient-dense grains

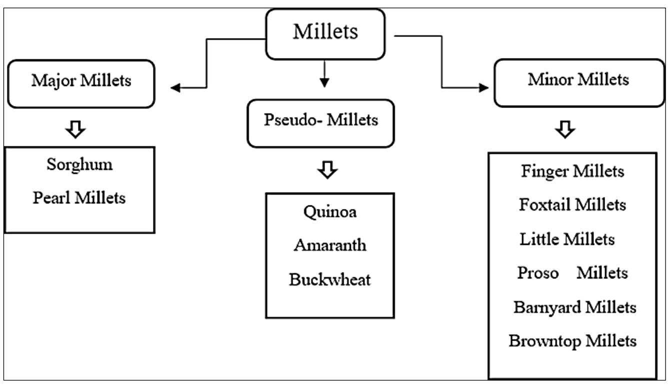

Fig 1: Classification of millets (Srilekha *et al.*, 2019) [29].

Millets are having good nutritional profile balanced amino acids, complex carbohydrates with low GI, dietary fiber, high quality of invisible fat, and also higher levels of calcium, magnesium, potassium, iron, manganese, zinc, and B-complex vitamins. In general millets contain 65% carbohydrates, 9% proteins, 3% fat, and 2 -7% crude fibre (Ambati *et al.*, 2019) [5]. Millets are good source of essential amino acids except for lysine and threonine but are relatively high in sulphur containing amino acids methionine and cysteine. Major millets possess a thin, bran-like pericarp, whereas minor millets are characterized by the presence of a distinct hull and bran layer that encloses the endosperm. Major millets include pearl millet (Pennisetum glaucum), sorghum (Sorghum bicolor), and finger millet (Eleusine coracana). Both major and minor millets are recognized as nutrient-dense grains, containing appreciable amounts of vitamins, minerals, and phenolic compounds, which contribute to their functional and health-promoting properties (Hasan *et al.*, 2019) [10].

Among different millet species, pearl millet has been reported to contain comparatively higher protein and free lipid content, followed by proso millet, foxtail millet, and barnyard millet. In contrast, millets such as finger millet, kodo millet, and little millet generally exhibit lower protein content but are particularly rich in dietary fiber and phenolic compounds (Hasan *et al.*, 2019) [10].

Millets are also good sources of different phenolic compounds such as phenolic acids and flavonoids. The principal phenolic acids present in millets are hydroxybenzoic acids are gentisic acid, vanillic acid, protocatechuic acid, and syringic acid and hydroxycinnamic acids are p-coumaric acid, sinapic acid, ferulic acid, and cinnamic acid, and flavonoids are catechin, quercetin, apigenin, and taxifolin (Akanbi *et al.*, 2019) [3]. Different studies have revealed that the bioactive compounds in millets are responsible for the antioxidant activity, antimicrobial activity, and medicinal properties of millets (Singh & Sarita, 2016) [27].

1.2 Importance of Pre-processing in Millets and Its Health Implications

The nutritional composition and health functions of millets are predominantly influenced by pre-processing techniques applied to the raw grains, which contain naturally occurring anti- nutritional compounds like phytates, tannins and oxalates that limit the absorption of minerals as well as the digestibility of macronutrients. Numerous studies have found that a variety of processing techniques, such as soaking, germinating, fermenting, malting and dehulling, can significantly reduce the levels of these anti-nutritional compounds through leaching and enzymatic hydrolysis, particularly by activating the endogenous phytases (Amadou *et al.*, 2017) [4].

Preprocessing of millets decreases anti-nutrients, improves the nutrient value of millets and increases the amount of protein found in millets. Malting and germination have been shown to improve the amount of protein in pearl millet compared to unprocessed millet (Amadou *et al.*, 2017) [4]. The decrease in moisture content and changes in the fibre composition of millets from using dehulling and heating helps to maintain their quality for longer periods because they will not spoil from lipid oxidation or rancidity (Krishnan, 2023) [15].

This review was conducted by adapting a previously reported methodology with minor modifications. The topic was selected based on an extensive literature survey aimed at identifying gaps in existing research on the effects of processing treatments on specific nutrient components of millets, with particular emphasis on the Indian context.

The primary objective of this review was to evaluate various millet processing interventions to identify appropriate treatments that ensure maximum nutrient retention. Studies focusing exclusively on millet processing methods such as dehulling, fermentation, germination, parboiling, cooking, puffing, popping, malting, and extrusion were included.

2. Methodology

The required data were searched and collected online, including previously published data in journals, textbooks, periodicals, websites, and databases such as Wiley, Google, PubMed, Google Scholar, Science Direct, Web of Science, SIIC Data Bases, BIOSIS, CAB International, Cambridge Scientific Abstracts, Chemical Abstracts, Food Science and Technology Abstracts, Research Alert, Science Citation Index, Science Citation Index Expanded, and Scopus-indexed journals, as well as other online sources (Paramasivam *et al.*, 2024)[23]. The keywords used in this search included millets, pre-processing techniques, soaking, germination, fermentation, milling, roasting, extrusion, decortication, nutritional quality, anti-nutritional factors, mineral bioavailability, functional properties, and processing strategies in millets. The inclusion criteria for articles are as follows:

1. The article is focusing on pre-processing of millets techniques such as soaking, germination, fermentation, milling, roasting, decortication, and extrusion applied to millets were included (Singh *et al.*, 2024) [28].
2. Research evaluating the impact of these processing methods on nutritional composition, mineral bioavailability, and the reduction of anti-nutritional factors in millets was considered relevant.
3. Studies examining the effect of processing techniques on bioactive compounds, including phenolic compounds and their antioxidant activity in millets, were also included in the review (Ofosu *et al.*, 2020) [21].

3. Pre-processing strategies involved in millet grains

3.1 Primary Processing of Millets

Primary processing of millets refers to the unit operations carried out at the producer’s level or in the vicinity of the farm to improve grain quality and convert raw harvested grains into more usable and stable forms. These operations play a crucial role in preserving the nutritional value of millets while enhancing their storability, safety, and suitability for further processing. Common primary processing steps include cleaning, grading, drying, dehusking (decortication), and basic milling. Cleaning and grading remove extraneous matter such as dust, stones, chaff, and immature grains, thereby improving physical quality and market value.

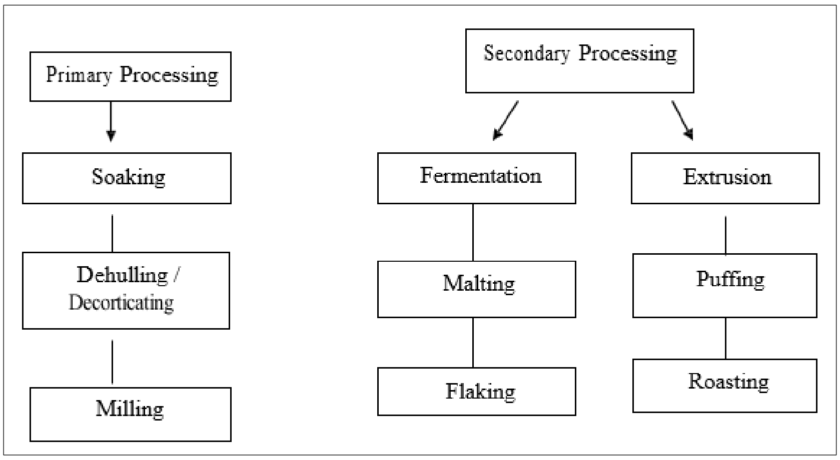

Fig 2: Pre-processing strategies (Singh *et al.*, 2024) [28]

3.1.1 Cleaning

The millet grains are first cleaned to remove any impurities, such as stones, sand, or dust. This can be done manually by handpicking or by using a winnowing basket to separate the grains from the debris.

3.1.2 Soaking

Soaking is an effective way to enhance the nutritional value of millets through the reduction of anti-nutritional factors or nutrients like water-soluble components in the pre-processing stage. Soaking has been reported to reduce polyphenolic compounds in pearl millet and finger millet through the activation of polyphenol oxidase, thereby improving mineral absorption and protein digestibility. Recent studies on kodo millet further demonstrated that hydrothermal pre-treatment, including soaking, facilitated dehulling efficiency and improved nutritional characteristics by reducing anti-nutritional components (Singh *et al.*, 2024) [27]. In addition, soaking improves the digestibility of starch by preventing the inhibitors of amylase and is still a common domestic method for preparing infant and complementary foods because of its simplicity and efficiency.

3.1.3 Dehulling / Decortication

Dehulling is the major removal of the inedible outer husk to enhance palatability and shorten cooking time while retaining the nutrient-rich bran and germ (Kaushik *et al.*, 2021) [14]. Decortication is the more intensive removal of the pericarp and bran layers to improve palatability, although it tends to be accompanied by greater losses of fiber and minerals (Kaushik *et al.*, 2021) [14].

In addition, the effectiveness of hydrothermal treatment (parboiling) on proso millet demonstrates an increase in the hardness of the endosperm, making it easier to remove the husk and improve milling yield by approximately 24%. Overall, these findings demonstrate that by optimally using dehulling, decortication, and hydrothermal or soaking processes, an improvement in the bioavailability, digestibility, and processing characteristics of millet species will occur.

3.1.4 Milling

The act of milling is to make flour from grain to prepare different food products. The main purpose of milling is to separate the endosperm from the bran and germ while reducing the size of the particle in producing fine flour. Hammer mills typically produce flour with larger size particles and therefore produce food products with a coarser texture, while roller mills produce flour with a finer texture that is better suited for baking, steaming, or cooking porridge (Oghbaei & Prakash 2016) [22]. The grinding action employed in milling can also cause damage to starch granules resulting in changes in starch structure, thus increasing the ease with which starch can be enzymatically hydrolyzed, and improving digestibility of starch. Further to this, reduction in the size of the particle during milling increases the surface area of starch granules thus enhancing their interaction with digestive enzymes and thereby promoting faster enzymatic hydrolysis. Optimization of milling conditions is critical to producing high-quality millet flour with improved nutrition and functional properties. Excessive milling removes micronutrients and dietary fiber-rich outer bran layers.

3.2 Secondary Processing of Millets

Secondary processing of millets is done after primary processing and is used to convert grains into edible and value-added food products. Secondary processing of millets includes milling, soaking, germination, fermentation, roasting, puffing, and extrusion. These processes increase the digestibility, organoleptic properties, shelf life, and functional properties of millet-based foods. Milling is used to produce flour and grits, but excessive milling can decrease the dietary fiber and mineral composition.

3.2.1 Germination (Malting)

Germination also known as malting is a viable biological pre-treatment that can enhance the nutritional, functional, and bioactive properties of millets through the process of soaking millet seeds in water for 8-12 hours followed by controlled sprouting for 24-96 hours, which utilizes endogenous enzymes such as amylases, proteases, and phytases activated by water absorption to convert starches, proteins, and phytate complexes into more easily digestible forms (Chethan Kumar *et al.*, 2022) [8]. The majority of germination studies have reported that, as a result of germination, there is an increase in protein digestibility, free amino acids, soluble sugars, B-complex vitamins, vitamin C, and soluble dietary fiber and that mineral bio accessibility has been significantly improved (Bhavadharani & Gurumoorthi 2025) [6]. According to (Sharma *et al.*, 2024) [25], the germination of kodo millet at approximately 38.75 °C for about 36 hours led to increases in protein content from 6.7% to 7.9%, increases in minerals and dietary fibre, and large reductions in phytates and tannins. Similarly, optimised conditions for germinating foxtail millet

for approximately 46.5 hours resulted in an approximately 30% increase in the amount of protein and 58% increase in the amount of dietary fibre, with correspondingly higher iron, magnesium, and calcium levels (Kaushik *et al.*, 2021) [15].
Proso millet has been germinated for up to 96 hours and produces higher levels of biosynthesis of phenolic acids like ferulic acid and vanillic acid compared to ungerminated proso millet (Xiang *et al.*, 2019) [33]. In addition, proso millet has higher levels of access to minerals after being germinated than does ungerminated proso millet. Germination was noted to greatly enhance the ability for proso millet to act as an antioxidant through production of phenolic acids (Karki *et al.*, 2025) [12].

3.2.2 Malting of Millets

In millets, malting has been used as an important processing step to improve enzymatic activity, nutritional quality, digestibility, and functional properties. The malting of millets has been carried out by steeping whole grains in four times volume of water for 20-24 h and germinating at 25-30 °C up to 72 h (Amadou *et al.*, 2017) [4]. Germinated grains are then washed, sun- or hot-air dried, lightly toasted or kiln dried at moderate temperature, abraded to remove rootlets, milled, and finally stored in an airtight condition. (Taylor & Duodu 2015) [30] This process activates a number of hydrolytic enzymes such as α- and β-amylases and proteases that act on starch and protein fractions to improve the nutritional and technological quality of millets.

3.2.3 Fermentation

Fermentation is an ancient bioprocess that produces food through fermentation of millet based on many species of microbes metabolically converting varieties of nutrients, the production of metabolites and the breakdown of nutrients by microbes. There has been numerous reports indicating that fermentation improves nutritional value, functionality and sensory attributes by making minerals more available from these products, protein becoming more easily digestible and increasing the vitamin level while at the same time decreasing the levels of anti-nutrients via microbial acidification and enzymatic degradation (Tharifkhan *et al.*, 2021) [31].
The specific types of microorganisms used to ferment millet can change depending on what variety of millet is being fermented and what conditions exist for fermentation. Pear millet can be fermented to produce lactic acid or, if both alcohol and lactic acid are produced, it is called mixed fermentation. Microorganisms used for fermented starches include lactobacilli and leuconostocs, with primary lactobacilli species being Lactobacillus spp (Achi & Asamudo, 2019) [1]. There are also two yeast species involved in the fermentation process, Saccharomyces cerevisiae and Candida spp. Fermenting pearl millet will lower the content of phytic acid and polyphenols in pearl millet but will improve protein quality (Kumari *et al.*, 2018) [16].
The predominant microorganisms that carry out mixed fermentations of finger millet, along with other grains such as sorghum and pearl millet, are Lactobacillus plantarum, Lactobacillus fermentum, and several species of yeast. Mixed fermentations result in improved mineral extractability, *in vitro* protein digestibility, and improved sensory quality.
Natural or unmodified fermented products from using finger millet as raw material will have L. plantarum and L. fermentum as the primary microorganisms involved in the fermentation process, whereas modified or controlled fermentation processes will use large consortia of Lactobacillus and yeast species (especially Saccharomyces spp.) to provide additional improved nutritional value, improved safety from microorganisms, and improved flavor development (Ajagekar *et al.*, 2023) [2]. On balance, the current collective research supports the concept of fermentation as an important pre-processing strategy to enhance the nutritional quality, functional attributes, and health-related properties of millet-based foods.

3.2.4 Roasting, Cooking, and Boiling of Millets

To make finicky and difficult to digest starchy foods like millet more palatable, easier to digest, functional, and nutrient dense requires heat processing methods such as roasting, boiling, or cooking. Heat processing produces changes in the structure of starches, proteins, lipids, and bioactive components in millets. Types of millet, roasting temperature, time and how intense the heat processed is all play a role in how heat processing and the structure change.
Many studies have reported that when roasting pearl millet grain between 120 o C and 180 °C for different lengths of time there are changes in the functional properties and mineral availability of the roasted grains as compared to their pre-roasting state in the following ways:

1. Roasting pearl millet at 180 °C for 10 minutes has the highest amount of available iron; however potassium is still the most abundant mineral in all roasting treatments.
2. The water solubility index range of pearl millet flour shows an increase with higher roasting temperatures showing increased usefulness for making processed foods (Rani *et al.*, 2018) [24].
3. Using mild roasting of pearl millet at 150 °C for 5 minutes resulted in an increased inaccessibility for total polyphenols from 73.2% to 78.1% as roasted grains compared to unroasted grains, as well as, a significant increase in bio accessible flavanoids showing an increase in the potential antioxidant properties of roasted millet (Hemalatha *et al.*, 2025) [11].

There was a significant decrease in the overall polyphenol content, indicating that phenolic compounds are very sensitive to prolonged exposure to moisture as a result of cooked pearl millet at 15 psi pressure for 15-20 minutes cooking reduced the bioavailability of phenolic compounds, and blanching from 98 °C for just 10-20 seconds decreased free fatty acids, acid value and fat acidity of lipid products (Hemalatha *et al.*, 2025) [11].

3.2.5 Extrusion Processing of Millets

Extrusion is recognised as a contemporary method of thermo-mechanical processing used to create ready-to-cook (RTC), snack, breakfast cereal, and other specialty products from millets, and it has been the subject of many publications. Extrusion is described in multiple studies as a high temperature, high pressure and high shear method, in which millet-based formulations are subjected to combining, kneading, shearing, cooking, forming and expanding as they move through a defined die opening. The combined thermal and mechanical stress being applied to the millets via the extrusion process produces significant physicochemical changes in the millets including: starch gelatinisation, protein denaturation, fat degradation and enzyme, microbial and antinutritional factors inhibition. All of these changes together provide mile-based finished goods with improved digestibility, increased safety and extended shelf life (Tongshuai, 2022) [32].

Multiple past studies have demonstrated that extrusion disrupts the native starch-protein matrix in millets, thereby creating a structure with porosity, which expands upon cooling and has acceptable texture and cooking characteristics. The structural change from the original matrix of the millets to the expanded structure occurs because of the rapid reduction in pressure and rapid evaporation of moisture at the die exit causing a rapid expansion, cooling and formation of the extruded products (Garud *et al.*, 2022) [9].

3.2.6 Popping and Puffing of Millets

Puffed and popped snacks are value-added uses for millets that use the traditional high- temperature short-time (HTST) process. In both processes, grains are heated at a rapid rate to a high temperature, causing moisture to expand within the kernel, leading to the gelatinization of starch and the production of light, porous structures. Processing finger millet and the other millets by popping and puffing has shown reductions in crude fibre, and changes in protein and carbohydrate digestibility, which are due to changes in the structure of starch-protein matrixes as a result of rapid heating (Kaur *et al.*, 2023) [13]. Traditional methods such as high-temperature sand roasting have also successfully been used to process millets. The degree of expansion after popping/puffing is influenced by varietal differences, physicochemical composition, moisture content of the grain, and heat distribution during processing. (Garud *et al.*, 2022) [9].

3.2.7 Flaking of Millets

Flaking is a hydrothermal-mechanical process that involves steeping millet grains in water, followed by steaming or pressure cooking, drying, and flattening using roller flakers. Unlike popping and puffing, flaking does not aim at expansion but instead produces thin, flattened flakes commonly used in breakfast cereals and instant foods.

When hydrated, heated or subjected to mechanical heat and moisture, the combination of heat and mechanical heat increase the digestibility of the protein and starch in the millet; and also, by reducing the phytic acid content will make available more mineral nutrients such as iron, zinc and calcium. Some of the studies show that the digestibility of carbohydrates in flaked millets is decreased because of the formation of resistant starch during the cooling and drying processes of the flaked millet because of the retrogradation of the amylose (Taylor & Emmambux, 2017) [30].

Collectively, these studies underscore that flaking are effective processing strategies for converting millets into shelf-stable, ready-to-eat products with improved digestibility, mineral bio accessibility, sensory appeal, and extended shelf life. (Sharma *et al.*, 2022) [26].

4. Effect of Processing on Nutritional Properties of Millets

Millets are subjected to various traditional and modern processing methods like dehulling, milling, soaking, germination, fermentation, roasting, boiling, steaming, popping, and extrusion are processing, which can reduce the levels of antinutrients and improve in-vitro digestibility of protein. Germination and fermentation have also been shown to increase the protein content and digestibility of pearl, foxtail, proso, and kodo millets due to enzymatic hydrolysis, mobilization of nitrogen reserves, and free amino acid synthesis (Liang & Liang, 2019) [17].

4.1 Effect of Processing on Macronutrients

Millets are recognized as important sources of protein, making them valuable in vegetarian and vegan diets due to their relatively high protein content and low saturated fat levels (Kaur *et al.*, 2014) [13]. However, the presence of antinutritional factors such as phytates, polyphenols, and trypsin inhibitors in raw millets can limit protein digestibility (Sharma *et al.*, 2022) [25]. Biological processes such as germination and fermentation are particularly effective, as they activate endogenous enzymes that hydrolyze storage proteins into simpler amino acids, thereby enhancing protein availability and digestibility in millets such as pearl, foxtail, proso, and kodo millet. Thermal processing methods including roasting, popping, and puffing can further improve protein quality by denaturing proteins and inactivating heat-labile antinutritional factors, although excessive milling or dehulling may lead to protein losses due to the removal of nutrient-rich bran and germ layers (Taylor & Emmambux, 2017) [30].

4.2 Effect of Processing on Micronutrients

Millets are rich sources of micronutrients such as vitamins and minerals, many of which are concentrated in the bran and germ fractions of the grain. They contain significant amounts of B-complex vitamins and vitamin E, along with essential minerals such as calcium and iron. Processing techniques such as soaking, germination, and fermentation have been shown to improve mineral bioavailability by activating endogenous phytase enzymes that degrade phytate-mineral complexes (Taylor & Emmambux, 2017) [30].

High-temperature processing methods such as extrusion, puffing, roasting, and popping may reduce total fiber content due to thermal degradation, although extrusion has been reported to enhance the functional properties of soluble fiber. Therefore, consumption of whole or minimally processed millets is recommended to retain dietary fiber and associated health benefits such as improved glycemic control and reduced risk of chronic diseases (Akanbi *et al.*, 2019) [3].

4.3 Effect of Processing on Phytochemical compounds

Phytochemicals are important bioactive compounds naturally present in millets, contributing to their antioxidant, anti-inflammatory, and disease-preventing properties. These compounds include phenolic acids, flavonoids, tannins, lignans, carotenoids, and anthocyanins, which are primarily concentrated in the outer layers of the grain (Akanbi *et al.*, 2019) [3]. Several studies have reported that the type and extent of processing significantly influence the retention, degradation, or enhancement of these phytochemical compounds in millets. Processing methods are therefore considered an important factor in determining the nutritional and functional quality of millet-based foods (Liang & Liang, 2019) [17].

Mechanical processing techniques such as decortication and milling/dehulling generally lead to a reduction in phytochemicals, including total phenols, flavonoids, tannins, lignans, carotenoids, and anthocyanins. This occurs because many of these compounds are predominantly located in the bran and germ portions, which are removed during these processes (Nanje Gowda *et al.*, 2018) [19]. Similar reports have indicated that removal of the outer layers during decortication significantly decreases the antioxidant compounds and total phenolic content of millets, thereby affecting their overall antioxidant capacity (Longvah *et al.*, 2017) [18].

4.4 Effect of Processing on Antioxidants Activity

Processing methods can significantly influence the antioxidant activity of millets by altering the concentration, availability, and extractability of bioactive compounds. Millets are naturally rich in polyphenols, flavonoids, tannins, carotenoids, vitamin E, and dietary fibre, which contribute to their strong antioxidant properties. These compounds exhibit free- radical scavenging activity, metal-chelating capacity, and reducing power, thereby helping protect against oxidative stress (Ofosu *et al.*, 2020) [21]. Studies have shown that both free and bound phenolic fractions in millets such as kodo, little, proso, foxtail, and finger millet possess considerable antioxidant potential. Among these, kodo and finger millet have been reported to exhibit particularly high antioxidant activity due to their elevated phenolic content (Chandra *et al.*, 2018) [7].

Conclusion and future perspectives

This review article strongly focuses on the fact that millets are Nutri-cereals that are rich in proteins, dietary fibers, minerals, vitamins, and bioactive compounds, which make them useful in fighting malnutrition and micronutrient deficiencies. Soaking, germination, fermentation, and heat processing are useful in improving the bioavailability of nutrients and antinutrients, which is in accordance with the objective of identifying the best processing methods. Millets possess a vast potential for the use of functional ingredients in value-added foods. The future research objectives should be on developing efficient and low-cost processing methods, *in vivo* bioavailability studies, enhancing the support for foods made from millets, and enhancing consumer awareness.

Author Contributions

- **Shreya Kajagar:** conceptualization, literature review, writing-original draft, data curation.
- **M. Rajaduari:** supervision, conceptualization, writing-review and editing.

Conflict interests

The author declares that there is no conflict of interest.

Data Availability Statement

No new data were generated or analyzed in this review. Data sharing is not applicable

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