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Plant-based milk substitutes: sources, production, and nutritional, nutraceutical and sensory qualities

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Over the years, humans and the dairy industry have depended mainly on animals, especially cattle, for their milk need. Whether for direct consumption or for the production of value-added dairy products, animal milk seems to be the gold standard, leading to a rise in its price. The exorbitant cost of dairy milk and products, coupled with the susceptibility of some consumers to lactose intolerance, necessitates finding non-dairy milk substitutes to meet human nutritional needs. Thus, to ensure a sustainable food system, in which milk is provided sufficiently and affordably for all, recent studies have demonstrated that plant-based milk substitutes (PBMS) can serve as an alternative to dairy milk in human nutrition. PBMS are prepared from different edible plant sources, including cereals, legumes, nuts, corms, roots and tubers, fruits, and vegetables. Studies have also shown that they are rich sources of nutrients and nutraceuticals, capable of nourishing the body and providing some health benefits. Bioactive compounds, including bioactive peptides, polyphenolics compounds, flavones, and anthocyanins have been reported in PBMS. These bioactive compounds are thought to confer certain health advantages, such as antidiabetic and antihypertensive effects. The sensory qualities of different PBMS have also been reported. The aim of this review was to discuss PBMS in human nutrition, emphasizing their sources, production, and nutritional, nutraceutical and sensory qualities.

KEYWORDS
plant-based milk, dairy milk, non-dairy milk, nutrition, nutraceutical, lactose intolerance

1 Introduction

Consumers' consciousness of nutrition-related non-communicable diseases, such as diabetes, obesity, hypertension and some types of cancer, has stimulated their interest in consuming more of plant-based diets than animal foods. On the other hand, the global population explosion, estimated to increase to about 10 billion people by 2050, the ever-increasing rural-to-urban migrants acquiring more wealth, and nutrition transition are steadily putting more pressure on food supply worldwide (McClements et al., 2019). Recently, the global food supply has been unprecedentedly threatened by COVID-19,

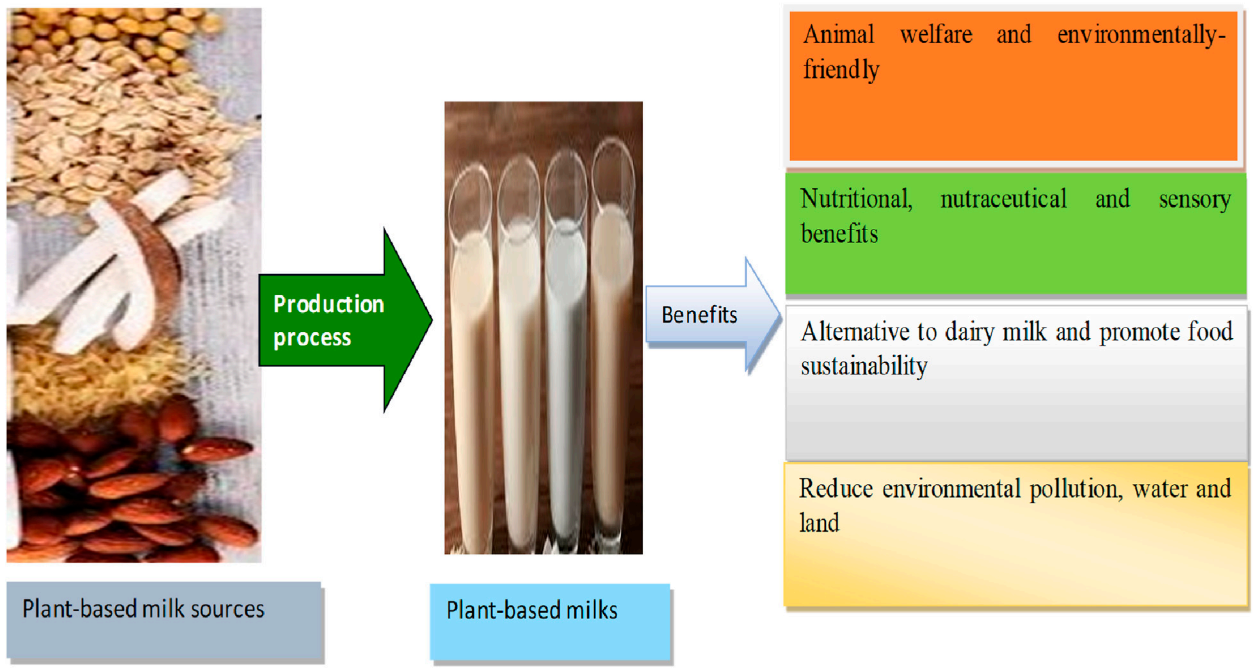

FIGURE 1
Plant-based milk sources and benefits.

Ukraine-Russian war (Irondi et al., 2023; Kubatko et al., 2023) and climate change (Farooq et al., 2023; Mirón et al., 2023), militating against the United Nation's sustainable development goal on food security. These developments call for a more sustainable food system, capable of promoting human and animal health, and mitigating climate change and environmental pollution. In this context, plant-based diets, such as plant-based milk substitutes (PBMS), are a promising option, as they improve human health, promote food sustainability, and reduce environmental pollution, water and land use (Figure 1) (McClements et al., 2019; Willett and Ludwig, 2020; Irondi et al., 2023).

PBMS are milk analogues produced from plant sources (Figure 1), comprising a colloidal system of a continuous phase, consisting of water and particles' dispersed phase. The dispersed particles include starch granules, protein fractions, lipid droplets and solid parts of plant matrices (Briviba et al., 2016; Bocker and Silva, 2022). They are water-soluble extracts of plants formulated to mimic animal milks, often considered as a healthy, animal welfare-friendly and sustainable alternative in human nutrition (Haas et al., 2019; Rasika et al., 2020; McClements and Grossmann, 2021; Reyes-Jurado et al., 2021). The production of PBMS is environmentally-friendly, promoting a reduced carbon emission, when compared to animal milk products, meat, egg, fish and their derivatives, which are notably a major contributor to the deleterious impacts of modern food production on the wellbeing of human and the planet (Poore and Nemecek, 2018; Bocker and Silva, 2022).

PBMS are produced from diverse plant sources, including cereals, legumes, nuts, pseudocereals, seeds, corms, roots and tubers, fruits, and vegetables. Cereal sources of PBMS include rice, oat, spelt, kamut, corn, rye, and quinoa; nut sources include coconut, almond, walnut, pistachio, tiger nut and hazelnut; pseudocereal sources include quinoa and amaranth; legume sources include soy, cowpea and peanut; while seed sources include flax, sesame, hemp, sunflower and pumpkin (Mohanty et al., 2016; Clay et al., 2020; Munekata et al., 2020; Zheng et al., 2021). In addition to these sources, there are also reports on PBMS produced from the blends of different plants. Some examples of these are PBMS from the blends of soy bean and almond (Kundu et al., 2018), soy bean and corn (Ajala et al., 2013). Similarly, a study by Oduro et al. (2021) produced PBMS from the blend of peanut, melon seeds, and coconut.

The qualities of PBMS, including the nutritional, nutraceutical and sensory qualities (Figure 1), vary depending on the plant source. In this context, several reports have demonstrated the potential of these PBMS to meet human nutritional need and promote health. For instance, they are an important source of moisture, carbohydrate, protein, fat, unsaturated fatty acid, fiber (Aydar et al., 2020), vitamins, minerals and essential fatty acids (McClements and Grossmann, 2021). PBMS are also prominent for their nutraceutical importance, such as a source of bioactive compounds including phenolic compounds, peptides, and possessing significant health properties, including antioxidant, anti-hypercholesterolaemic, immunostimulatory, anti-hypertensive, anti-microbial, anti-cancer and anti-anaemic activities (Zujko and Witkowska, 2014; Paul et al., 2019; Reyes-Jurado et al., 2021). These important properties of PBMS have resulted in an increased consumers' demand. A recent reported indicated that the PBMS accounted for 40% of the over $5 billion total sales of plant-based food market (Zheng et al., 2021). PBMS' market value is estimated to attain US$ 30.79 billion by 2031, increasing at a CAGR of 8.8% through 2031 (Future Market Insights, 2021; Aydar et al., 2023). Aside these advantages, consumers susceptible to lactose intolerance, cholesterol-related conditions, allergy to cow's milk protein, and vegetarians also prefer PBMS to animal milk and other dairy products. This has further increased the demand for PBMS to an all-time high (Reyes-Jurado et al., 2021; Vallath et al., 2022).

The rising popularity of PBMS, occasioned by its increased consumers' demand, enhanced qualities (nutritional, nutraceutical, physicochemical and sensory), and viability for food security, calls for a comprehensive review on the PBMS. Therefore, this review aimed at discussing PBMS, with emphasis on their sources, production, and nutritional, nutraceutical and sensory qualities. This review also suggested pragmatic approaches to enhance PBMS' quality.

2 Milk in human nutrition: animal milk *versus* PBMS

Milk and its products are among the well-established wholesome foods that ensure a balanced nutrition, impacting positive health outcomes (Gil and Ortega, 2019; Marangoni et al., 2019; Zhang et al., 2021; Smith et al., 2022). It is a rich dietary source of protein, lipid, carbohydrate, mineral and vitamin (Chalupa-Krebzdak et al., 2018; Chauhan et al., 2021). Furthermore, milk alongside diary-products, such as cream, whey, yoghurt, buttermilk, cheese and butter, are one of the most important foods in the human diets (Scholz-Ahrens et al., 2019; Lambrini et al., 2020). Hence, they are largely consumed globally as an essential part of dietary recommendations (Haas et al., 2019; Chauhan et al., 2021), with the potential to protect against the most prevalent chronic diseases (Thorning et al., 2016).

Furthermore, milk provides energy to the body through its carbohydrate content; that is, lactose comprising a molecule each of D-galactose and D-glucose. The vitamins in milk are both water- and fat-soluble; they affect the fat contents of dairy products and vary based on the animal diet and season (Mehra et al., 2021). The lipids in milk exist as emulsified globules and their contents majorly determine the milk's cost, nutritional content, sensory value and physical qualities (Chauhan et al., 2021). In addition to the organic nutrients in milk, water is another constituent that forms the major part of milk (Kumar et al., 2016).

2.1 Animal milk

Animal milk is obtained from different animal species, such as goat, camel, cow, sheep and mare (Willett and Ludwig, 2020; Oussadou and Djerdjar, 2022). Among these animal species, Cattle have been the most important species in the production of milk and its milk has served as an essential part of human nutrition for the past 8,000 years (Haas et al., 2019). Typically, whole cow's milk is approximately composed of 87.5% water, 4.8% lactose, 3.9% fat, 3.4% protein and 0.8% minerals (Tetrapak, 2020). Cow's milk represents 85% of the annual milk supply of the world. It is followed by buffalo's (11%), goat's (3.4%), sheep's (1.4%) and camel's (1.4%) milk (Chauhan et al., 2021). Animal milk serves as the first food for mammals and the main source of nutrient for mammalian newborns. It contains a diverse complement of nutrients (Scholz-Ahrens et al., 2019), providing all the necessary nutrients and energy required for their proper growth and development (Lambrini et al., 2020).

The animal (mammalian) milk composition varies, depending on species differences and some other factors, such as nutritional, food composition, physiological and milking frequency (Mehra et al., 2021). Its composition also depends on genetic, types of breeds, environmental condition, as well as on other external and internal factors occurring during lactation (Chauhan et al., 2021). Further, it is one of the most valuable agricultural raw materials worldwide (Haas et al., 2019).

Its nutrient composition completely and ideally satisfies the energy and metabolic need of each mammalian species offspring during the early postnatal life (Scholz-Ahrens et al., 2019). It also promotes postnatal health by delivering maternal messages of a sophisticated signaling system (Mecocci et al., 2022) and aiding the newborn mammal's immune system development. These properties of milk are ascribed to the presence of bioactive constituents, such as immunoglobulins, lactoperoxidase, growth factors and immunomodulatory peptides lysozymes, oligosaccharides, alpha-lactalbumin and lactoferrin (Cacho and Lawrence, 2017; Chauhan et al., 2021; Mecocci et al., 2022). These bioactive constituents are rich in colostrum, the first milk secreted by the mammalian female after giving birth, protecting the newborn against pathogen by building passive immunity (Chauhan et al., 2021). Furthermore, animal milk consumption has a nutritional advantage in adult as a result of the presence of intestinal beta-galactosidase (Scholz-Ahrens et al., 2019). It is a rich dietary source of bioavailable amino acid and high-quality protein, mineral (such as calcium, phosphorous and potassium), several vitamins (such as vitamins A, B2, B5, and B12), fat, essential fatty acids, as well as several bioactive compounds that play significant physiological and biochemical functions (Khan et al., 2019; Smith et al., 2022).

2.2 Animal milk drawback

Animal milk is under increased scrutiny due to its environmental impact and ethical considerations concerning animal welfare (Haas et al., 2019). Additionally, air and water pollution, soil degradation and loss of diversity are the main environmental issues related to animal milk production (Haas et al., 2019). Aside these environment-related issues, in some susceptible consumers, there are some health-related concerns, such as increasing cow's milk allergies, hypercholesterolemia prevalence and lactose intolerance (Munekata et al., 2020). In addition to these health-related concerns (lactose intolerance, hypercholesterolemia, and milk allergies) associated with animal milk consumption, there is an increase in consumers switch to animal milk substitutes (Haas et al., 2019) due to the need for healthier food (Grant and Hicks, 2018) and food practices as seen among the vegetarianism and veganism (Jeske et al., 2017a). These concerns have aroused interest in animal milk substitutes, leading to a growing demand for diary alternatives (Haas et al., 2019; Munekata et al., 2020).

Moreover, since livestock account for 8% consumption of global water supplies and contribute predominantly to greenhouse gasses, such as methane (CH_4) and nitrous oxide (N_2O), transitioning from animal-based to plant-based diets could promote sustainability management (Krizanova et al., 2021; Aydar et al., 2023). Livestock and fisheries production are known to account for the largest proportion (31%) of the total global greenhouse gas emissions ascribed to food production (Ritchie, 2019), further exacerbating climate change threat. However, in line with the European court of justice in June 2017, the term "milk" is not allowed to be used for the products of plant origin, but to be exclusively used for fluid secreted by the mammary gland of higher animals (mammals) (Scholz-Ahrens et al., 2019). Hence, terms, such as drinks, diary substitutes and beverages are been used to refer to the plant-based fluid, although exceptions, such as coconut milk, have been permitted because the term milk has been used for a long time for some plant's fluid (Scholz-Ahrens et al., 2019).

2.3 Plant-based milk substitutes (PBMS)

A wide range of PBMS, which are desirable, convenient, affordable, sustainable and rich in nutrients are now been developed by the food industry (McClements et al., 2019). There has been an increasing popularity of PBMS over the past 10 years. Apart from the traditional soymilk, different varieties of PBMS have been produced from many other plant sources including cereals (e.g., rice, oat, spelt, kamut, corn, rye, quinoa), legumes (e.g., cowpea and peanut), nuts (e.g., coconut, almond, walnut, pistachio and hazelnut), pseudo cereals (quinoa, and amaranth) and seeds (e.g., flax, sesame, hemp, sunflower and pumpkin) (Munekata et al., 2020). The PBMS, derived from the water extraction of these plant materials, is completely free from animal-based ingredients (Silva et al., 2020). PBMS are formulated to have a similar appearance and taste with the conventional milk (Mäkinen et al., 2016; Silva et al., 2020) and are often presented as sustainable, healthy and animal-welfare-friendly alternative (Haas et al., 2019). In addition, other plants-based diary substitutes like cheese, yogurt, ice cream and creamer are similarly increasing rapidly (Good Food Institute, 2018; Clay et al., 2020). The PBMS products available in the market differ with respect to their nutrients. Therefore, the addition of protein, vitamin and minerals, such as calcium, to make them comparable to cow milk is the common practice (Mäkinen et al., 2016). Sugar content, serving as a natural sweetener, is the most important attribute of plant milks (Haas et al., 2019). PBMS are an important source of moisture, carbohydrate, protein and fat and are rich in unsaturated fatty acid, fiber content (Aydar et al., 2020), vitamins, minerals and essential fatty acids (McClements and Grossmann, 2021). Their major fatty acids are stearic acid (18:0) and palmitic acid (16:0), α-linolenic acid (18:3), linoleic acid (18:2) and oleic acid (18: 1) (Aydar et al., 2020).

Among the PBMS, chickpea milk is rich in mineral and fibers, coconut milk is rich in lipid (Jeske et al., 2017b; Rincon et al., 2020), while soymilk is rich in protein (Vanga and Raghavan, 2017). Oat, cashew and soymilk have a higher level of dietary fiber than the other PBMS alternatives (Aydar et al., 2020). Soymilk is a good source of B-vitamin especially niacin, folacin and pyridoxine, minerals, such as iron, copper, magnesium and zinc, as well as monounsaturated and polyunsaturated fats, such as linoleic (18: 2) and linolenic acids (18:3) (Mazumder and Hongsprabhas, 2016; Zandona et al., 2021). Hemp milk contains Molybdenum and coconut milk provides Chromium and Selenium (Astolfi et al., 2020). A novel PBMS from chickpea and coconut blend also showed a good nutritional composition, including lipid, calcium and protein content in fact compared to cow's milk (Rincon et al., 2020).

Several studies have compared different quality attributes of animal milk and PBMS. For instance, Aly et al. (2022) evaluated the antioxidant activity, cholecystokinin (CCK) and glucagon-like peptide-1 (GLP-1) release of some PBMS, including soy, tiger nut and hazelnut milks, after *in vitro* digestion, in comparison with cow's milk. The study concluded that the PBMS could adequately replace cow's milk, based on their antioxidant and satiety effectiveness. Aydar et al. (2023) assessed the *in vitro* phenolic bioaccessibility, sensory quality and fatty acid profile of PBMS from two kidney bean varieties (oval and cherry). The study documented protein (1.92%–2.32%), α-linolenic acid (25.66%–27.78%), and palmitic acid (18.95%–23.08%) contents in kidney bean milk. Further, the study observed an overall sensory acceptance ranging from 2.9 to 4.1 out of 10 for the kidney bean milk. The study concluded that kidney bean milk had a rich bioaccessible antioxidant property, with a high fatty acid profile, and could be an alternative for the food industry.

As is evident from the foregoing, PBMS provide many attractive qualities to consumers. These include the PBMS' lactose-, dairy allergens- and cholesterol-free properties (Yadav et al., 2017; Hartmann et al., 2018; Cichonska and Ziarno, 2022); high content in essential nutrients (vitamins and minerals), bioactives compounds and dietary fibre, with pre-probiotic property (Roselló-Soto et al., 2019; Cichonska and Ziarno, 2022). The PBMS also allay consumers' safety concerns relating to antibiotic residues and hormones (Pua et al., 2022) and promote vegan-friendly attributes (Yadav et al., 2017; Roselló-Soto et al., 2019; Mendly-Zambo et al., 2021).

3 PBMS: sources and production

3.1 Sources of PBMS

As earlier mentioned, there are diverse plant sources from which PBMS are produced. These include cereals, legumes, nuts, pseudocereals, corms, roots and tubers, seeds, fruits, and vegetables. Among these sources, cereals, including rice, oat, spelt, kamut, corn, rye, and quinoa; and nuts, including coconut, almond, walnut, pistachio, tiger nut and hazelnut, have been reported (Munekata et al., 2020). Similarly, pseudocereals including quinoa and amaranth; legumes, including soy, cowpea and peanut; and seeds including flax, sesame, hemp, sunflower, pumpkin and potato roots, have also been reported (Mohanty et al., 2016; Clay et al., 2020; Zheng et al., 2021; Anitha and Manivannan, 2013).

Aside the sources listed above, PBMS are also produced from the blends of different plant source. Such blends include soy bean and almond (Kundu et al., 2018), soy bean and corn (Ajala et al., 2013), chickpea and coconut (Rincon et al., 2020), peanut, melon seeds, and coconut (Oduro et al., 2021). Tiger nut milk substitute flavoured with extract of *Moringa oleifera* leaf was also reported by Adebayo-Oyetoro et al. (2019). Blending different plant raw materials has been noted as an innovative and practical approach to developing

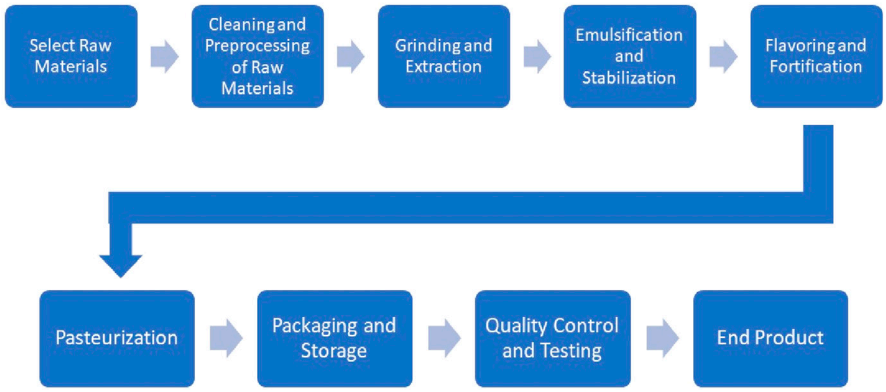

FIGURE 2
Flowchart of plant-based milk process (Romulo, 2022) modified.

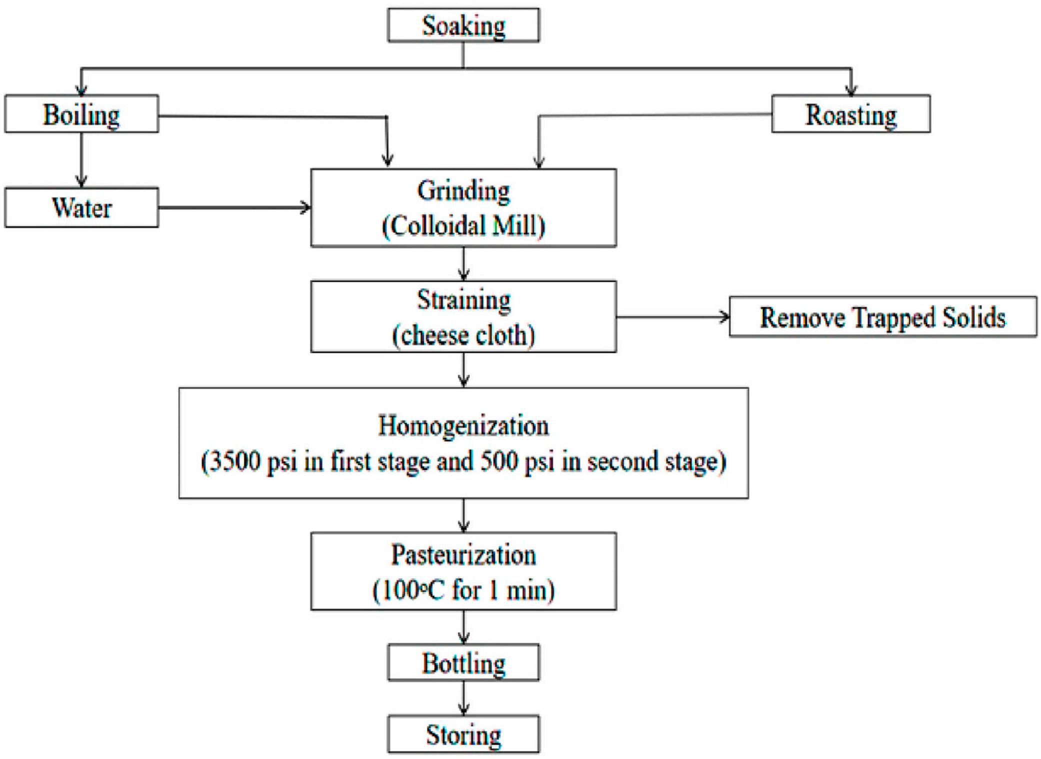

FIGURE 3
Flow chart of plant-based milk alternatives processing (Mäkinen et al., 2016; Navicha et al., 2017; Vallath et al., 2022).

novel PBMS with enhanced protein content and sensory qualities (Oduro et al., 2021).

3.2 Production process of PBMS

Depending on the initial raw material and intended final products quality, the process of producing PBMS may vary (Penha et al., 2021). However, there are some common basic steps frequently adopted in the production process. These, including raw materials sourcing and pre-processing, grinding and extraction, emulsification and stabilization, flavouring and fortification, pasteurization, packaging and storage, as well as quality control testing, are presented in this section. A flow chart of the process is depicted in Figures 2, 3.

3.2.1 Raw material sourcing

The production of PBMS involves a meticulous selection of raw materials derived from a diverse array of common plant sources, such as soybeans, almonds, coconuts, rice, oats, and cashews. Each source offers distinct flavours and characteristics, with soymilk standing out for its high protein content; almond milk renowned for its nutty flavour and smooth texture; and coconut milk offering a rich and creamy taste. Rice milk's hypoallergenic properties render it suitable for sensitive individuals, while oat milk's popularity is attributed to its creaminess and versatility. Cashew milk contributes a naturally sweet and buttery taste (Bennett, 2016).

To ensure the quality of raw materials, manufacturers must consider several critical factors. The origin and variety of the plant-based ingredients, alongside their growing conditions, significantly influence taste and nutritional content. Careful harvesting and handling during transportation and storage are essential in preserving the freshness and integrity of the raw materials (Mäkinen et al., 2016). Moreover, the processing methods employed, encompassing cleaning, sorting, and preparation, impact the overall quality and potential contaminants. Adequate storage conditions and preservation techniques further safeguard against spoilage and help maintain the nutritional properties of the raw materials. Regular quality testing is essential to detect contaminants such as pesticides, heavy metals, and microbial agents, ensuring the safety and purity of the raw materials (Mäkinen et al., 2016). By conscientiously considering these factors, PBMS processors can opt for high-quality plant sources, resulting in superior PBMS products that effectively cater for consumers' demands for taste, high nutrients, and sustainability.

3.2.2 Cleaning and pre-processing of raw materials

Cleaning and pre-processing of raw materials are crucial steps in the production of plant-based milk. In the cleaning and sorting stage, the raw materials are thoroughly inspected, and any impurities, foreign particles, or damaged components are removed to ensure the highest quality ingredients. Following this, soaking and blanching are performed to prepare the raw materials for further processing. Water soaking helps in softening, hydrating and swelling the raw material, making it easier to blend and extract, and consequently reducing the apparent amylose level (Padma et al., 2018). It can be used for different raw materials, including seed and grains, such as soybeans, rice, sesame seeds, and nuts, such as hazelnuts, tiger nuts, peanuts and almonds (Aydar et al., 2020). Water soaking also increases the extraction yield of the PBMS. Taking tiger nuts milk substitute for instance, water soaking was reported to increase the extraction yield (Kizzie-Hayford et al., 2016).

Blanching can be used for seeds and nuts, such as almonds, soybeans, coconuts, peanuts, sesame, quinoa and rice (Aydar et al., 2020). It involves briefly immersing the raw materials in hot/boiling water, which helps preserve their colour, texture, and nutritional properties. Relative to water soaking, the advantages of blanching the raw material include enzymes (for example, lipases) inactivation, microbial load reduction (Pardeshi et al., 2014; Sethi et al., 2016), reduction in antinutrients and off-flavours (Pua et al., 2022). Blanching can also affect the functionality and nutritional quality of the final product (Ferawati et al., 2021). For instance, after boiling and roasting pulses, the resulting flours displayed a two-to-three fold increase in water absorption capacity and a higher rate of gelation than raw pulses' flour (Ferawati et al., 2019). Overall, these preparatory steps lay the foundation for producing PBMS with optimal taste and consistency (Srivastava et al., 2023).

3.2.3 Grinding and extraction

Typically, PBMS are produced by size-reduction methods, in which the original structure of plant tissue is broken down by mechanical, chemical, as well as enzymatic methods (Zheng et al., 2021). However, mechanical extraction of the raw material is more often applied. It is effective in dispersing the raw material ingredients for an optimum extraction, allowing for the extraction process standardization. Furthermore, it is scalable and low-cost, having a low technological impediment (Mäkinen et al., 2016; Yadav et al., 2017). The tissue structure breakdown following grinding results in the release of oil bodies in PBMS seed and nut sources, such as cashews, soybeans, coconuts, oats and almonds. The oil bodies so-released are colloidal materials having a triglyceride-rich core, which is coated with a phospholipid/protein layer (Tzen, 2012; Nikiforidis, 2019).

Grinding and extraction are key processes in the production of plant-based milk. In the grinding process for optimal texture, the soaked and blanched raw materials are finely ground to create a smooth and consistent mixture. The grinding ensures the ingredients release their flavours and nutrients effectively. Depending on the raw material, grinding may be by dry-milling or wet-milling. Usually for PBMS produced using flour, dry-milling is first carried out, and the resulting flour is subsequently reconstituted and/or further extracted to yield the PBMS (Mäkinen et al., 2016). For PBMS in which the whole raw material is subjected to aqueous extraction without first converting into flour, typically the raw material is pulverized into slurry through wet-milling, releasing finely suspended or soluble constituents (Yadav et al., 2017). However, both milling methods result in a non-homogeneous particle size distribution, which may require an additional size standardization or reduction, to enhance stability and texture (Kizzie-Hayford et al., 2015). Some recent superfine pulverization technologies, including jet-milling, ball-milling and colloid-milling, are gaining popularity for plant flour materials (Guo et al., 2021; Vogelsang-O'Dwyer et al., 2021).

Subsequently, various extraction methods are employed to extract the milk from the ground mixture, varying based on the plant-based source. For instance, pressing is used for nuts and seeds, while blending and straining are common for grains. These extraction techniques play a vital role in determining the final taste, consistency, and nutritional content of the plant-based milk (Pua et al., 2022). In this step, involving gravity-facilitated sedimentation, centrifugation, decanting, or (ultra) filtration, unwanted materials (mainly coarse particles) are separated or removed, concentrating the desirable components, such as nutrients (McClements et al., 2019; Rinaldoni et al., 2014). Excess lipids are also removed to prevent oil bodies and phase separation coalescence, promoting a consistent lipid proportion and the PBMS' stability (Briviba et al., 2016; Tangyu et al., 2019).

3.2.4 Emulsification and stabilization

Emulsification and stabilization are essential steps in the production of PBMS, ensuring a smooth and consistent product. In the addition of emulsifiers and stabilizers, suitable agents like lecithin or gums are introduced to create a stable emulsion, preventing separation of water and plant-based fats during storage. These emulsifiers enhance the texture and mouth-feel of the milk. Homogenization and mixing further improve the product's uniformity by breaking down fat globules and evenly distributing them throughout the milk. These processes contribute to the creamy and well-blended nature of the plant-based milk, providing a satisfying and enjoyable drinking experience (Ma and Boye, 2013).

Homogenization immensely imparts the extracted PBMS' microstructure (Gul et al., 2017). However, typical homogenization parameters applied to cow's milk may not be appropriate in PBMS due to the differences in the plant-based ingredients' microstructures and constituent (Pua et al., 2022). Essentially, PBMS' particle heterogeneity demands more aggressive homogenization parameters than that of cow's milk (usually 10–25 MPa) (Mäkinen et al., 2015).

3.2.5 Flavouring and fortification

Flavoring and fortification are important aspects of the production steps, enhancing both taste and nutritional value. In the flavouring stage, processors may use natural or artificial flavouring agents to impart various tastes to the milk, catering to different consumer's preferences (McClements et al., 2019).

Animal milk contains a higher level of mineral than PBMS and other plant-based beverages (Bocker and Silva, 2022). For instance, plant-based beverages contain about 30%–50% lower mineral levels, such as phosphorus, calcium, magnesium, potassium and sodium, than animal milk (Astolfi et al., 2020). The low mineral levels in PBMS are coupled with the presence of antinutrients, such as tannins, oxalates, phytate, saponins and lecithin. These antinutrients diminish some essential minerals' digestibility and absorption, including Ca, Zn, Fe, Cu and Mg, by binding to these minerals to form insoluble complexes (McClements et al., 2019). Hence, to improve the PBMS' nutritional quality, fortification with essential nutrients, including vitamins and minerals is important. Essential nutrients, such as calcium, vitamin D, and B12 may be added to enrich the PBMS' nutritional profile, providing consumers with a wholesome and balanced plant-based alternative to traditional dairy milk (Aydar et al., 2020).

3.2.6 Pasteurization

Pasteurization, either by conventional or emerging innovative processing technologies, is a critical step in the production of PBMS to ensure its safety and extend its shelf life. It decreases the PBMS' microbial and enzyme load to levels that are safe for human consumption (Bocker and Silva, 2022). In the conventional pasteurization stage, different methods like high-temperature short-time (HTST) or ultra-high temperature (UHT) pasteurization are employed to eliminate harmful bacteria and pathogens, while preserving the PBMS' nutritional properties. However, applying high temperatures (from 60°C to 130°C) has the propensity to cause undesirable alterations in the nutritional, physical, chemical, and sensory characteristics of the PBMS (Aydar et al., 2020). Therefore, proper temperature and time considerations are essential during pasteurization, as the PBMS needs to be heated to a specific temperature for certain duration to achieve effective sterilization without compromising its taste and quality. Furthermore, emerging innovative processing (pasteurization) technologies, applying non-thermal or mild-thermal treatments, are available to replace the conventional thermal processes (Bocker and Silva, 2022). These treatments, such as high-intensity ultrasound, microwave, high-pressure processing, pulsed electric field, supercritical carbon dioxide, ultraviolet radiation and ohmic heating (Aydar et al., 2020), could inactivate enzymes and microorganisms without causing an excessive PBMS quality alteration (Gul et al., 2017; Iorio et al., 2019; Bocker and Silva, 2022). Taken together, these measures ensure that the PBMS remains safe, stable, and suitable for consumption (Azizi-Lalabadi et al., 2023).

3.2.7 Packaging and storage

Packaging and storage are vital aspects of the basic steps in PBMS production and they involve maintaining the product quality and safety. In this stage, suitable packaging materials, such as cartons, bottles, or pouches, to protect the milk from external contaminants and light, are carefully selected (Liu et al., 2022). The choice of packaging also impacts the PBMS' shelf life and sustainability. Similarly, proper storage conditions are crucial to ensure the milk remains fresh and safe for consumption. PBMS are preferably stored in a cool, dry place, away from direct sunlight, and at recommended temperatures to prevent spoilage and maintain its taste and nutritional properties throughout its shelf life (Liu et al., 2022).

3.2.8 Quality control and testing

Quality control and testing are another essential components in the production of PBMS and involve maintaining product consistency and safety. Ensuring product consistency and safety involves rigorous testing and monitoring at various stages, from raw material sourcing to final packaging (Grossmann et al., 2021). Quality checks are conducted to ensure that the PBMS meet specific standards, adhere to regulations, and are free from contaminants. Quality assurance procedures are put in place to establish a systematic approach to identify, prevent, and address any potential quality issues. These procedures include documentation, regular audits, and corrective actions, ensuring that the PBMS consistently deliver the expected quality and meet consumer expectations (Grossmann et al., 2021).

4 Qualities of PBMS

4.1 Nutritional qualities of PBMS

PBMS serve as an alternative for dairy milk due to their perceived nutritional and health importance (Pandey and Poonia, 2020). They are reported as a good dietary source of some important nutrients, such as protein, calcium, vitamins, and fibre, as shown in Table 1 (Craig and Fresán, 2021; Craig et al., 2022). The nutritional values of PBMS vary, depending on the raw materials type and quality, formulation, processing method, and fortification, giving each a unique set of nutritional qualities and making them a suitable option for health-conscious individuals (Mäkinen et al., 2016; McCarthy et al., 2017; Jeske et al., 2019; Rincon et al., 2020; Craig et al., 2022). One of the major advantages of PBMS over animal-based milk is its lower saturated fat content (Sethi et al., 2016), making it a healthier and more attractive option for individuals concerned about their cardiovascular health and cholesterol levels (Briggs et al., 2017).

TABLE 1 Nutrients composition of some plant-based milk substitutes.

Nutrient	Quantity	References
Carbohydrate	1.95–54.2 kcal/100 mL	Mäkinen et al. (2016), Sethi et al. (2016), Jeske et al. (2017b), Vitoria (2017), Angelino et al. (2020), Bridges (2018), Walther et al. (2022), and Antunes et al. (2023)
Protein	0.30–3.10 kcal/100 mL	
Fat and oil	0.96–4.55 kcal/100 mL	
Fibre	0.10–1.27 kcal/100 mL	
Ash	0.3–0.68 g/100 mL	Bridges (2018), Chalupa-Krebzdak et al. (2018), and Romulo (2022)
Minerals		
Calcium	65.52–156.5	Vitoria (2017), Bridges (2018), Angelino et al. (2020), Astolfi et al. (2020), Scholz-Ahrens et al. (2020)
Potassium	37.1–157.5	Vitoria (2017), Bridges (2018), Angelino et al. (2020), Astolfi et al. (2020) and Scholz-Ahrens et al. (2020)
Sodium	23.9–64.2	
Phosphorus	14.95–39.46	
Magnesium	7.78–16.8	
Manganese	0.045–0.144	
Zinc	0.04–0.30	
Iron	0.16–0.62	
Copper	0.01–0.13	
Selenium	0.0–2.0	
Vitamins	Indicate unit as reported	Singhal et al. (2017), Vitoria (2017), Vangaand Raghavan (2017) and Bridges (2018)
Vitamin A	141.6–195.4 IU/100 mL	
Vitamin D	38.49–42.94 IU/100 mL	
Vitamin E	1.25–1.67 mg/100 mL	
Vitamin K	-	
Vitamin B_1	0–0.03 mg/100 mL	
Vitamin B_2	0.17–0.18 mg/100 mL	
Vitamin B_6	0–0.04 mg/100 mL	
Vitamin B_{12}	0.25–1.03 g/100 mL	

Additionally, PBMS are reported to be lactose- and cholesterol-free, making them fit for consumption by individuals suffering from lactose intolerance (Facioni et al., 2020; Pandey and Poonia, 2020). They are also reported to contain essential micronutrients, such as vitamin D and B12, and calcium, which are essential for bone and teeth health, the immune system, and energy production (Pandey and Poonia, 2020). Some PBMS nutritional compositions are comparable with animal milk, whereas some others have a lower nutritional quality than animal milk (Scholz-Ahrens et al., 2019; Rincon et al., 2020). For instance, soy-based milk protein content is comparable with the protein content of cow's milk, but PBMS extracted from almond, rice, and oats contain minimal amounts of protein, iron and calcium, relative to cow's milk (Mäkinen et al., 2016; Singhal et al., 2017). Generally, the rich nutrients and fiber content of legumes has made them an attractive option for the development of nutrient-rich PBMS (Chandra-Hioe et al., 2016; Rincon et al., 2020). The study of Vanga and Raghavan (2017) showed that among some PBMS, soymilk had the highest protein content (8.71%), whereas rice milk had the lowest (0.07%).

Furthermore, in terms of protein quality, PBMS protein is an incomplete protein, unlike the animal milk protein that is a complete protein (McCarthy et al., 2017; Rincon et al., 2020). The overall lower nutritional value of PBMS in comparison to animal milk (notably, cow's milk), can pose a limitation on their market value, as dependence on them could predispose their consumer to nutrients deficiencies, such as essential amino acids, vitamins (A, D, B2, B12), and minerals (zinc, calcium, iodine) (Scholz-Ahrens et al., 2019). To compensate for these nutrients, PBMS are usually fortified with the deficient nutrients (Munekata et al., 2020; McClements and Grossmann, 2021).

The nutritional qualities of different PBMS are presented in this section (Table 1), with a view to providing an insight into their associated dietary gains and potential drawbacks in human nutrition.

4.1.1 Carbohydrates quality of PBMS

Carbohydrates are considered the major dietary energy sources that provide energy to cells of the body, especially the brain cells, which are entirely dependent on carbohydrate food (Mata et al., 2019). The composition of carbohydrates in a dietary source is of interest due to the potential for excess dietary energy to increase the risk of nutrition-related chronic diseases, such as hypertension, diabetes mellitus, cancer, obesity and coronary heart diseases (James et al., 2019; Clemente-Suárez et al., 2022). Available evidence has shown that most PBMS contain fewer calories than dairy milk. Their carbohydrate contents range from 0.42 to 11.05 g per 100 mL, relative to dairy milk having 4.78 g/100 mL for whole milk and 4.96 g/100 mL for skim milk (Jeske et al., 2017b; Chalupa-Krebzdak et al., 2018; Walther et al., 2022; Clemente-Suárez et al., 2022).

4.1.2 Protein quality of PBMS

Protein is an important macronutrient that plays an essential role as a structural and functional component to maintain growth and other physiological functions in the human body (Sá et al., 2020). It influences the nutritional quality of food, as its deficiency can lead to a wide range of health complications, such as metabolic diseases, stunted growth and other health-related complications (Wu, 2016). PBMS generally exhibits a lower protein quality than animal milk products, due to the limitation of some essential amino acids (Mäkinen et al., 2016), except for Soy protein. Soy protein has been reported to be a complete protein containing all essential amino acids at sufficient proportions to meet human's dietary needs (Lopez and Mohiuddin, 2020). Generally, the nutritional value of PBMS' proteins depends mainly on the amino acid composition, absorption, and their physiological utilization, as well as their production (Pingali, et al., 2023).

The low quality of PBMS protein can be ascribed to a poorer digestibility, the presence of anti-nutritional factors, lower essential amino acids content (especially leucine), and deficiency in other essential amino acids, such as sulfur-containing amino acids (Park et al., 2021). The individual amino acids levels vary among the PBMS from different plant sources (Walther et al., 2022). Studies have shown that cereal milk products contain lower lysine content, while leguminous proteins contain lower methionine and cysteine content (Anitha et al., 2020). Some types of PBMS, such as wheat, nut and soy, contain protein that can trigger allergic reactions in susceptible consumers (Pingali, et al., 2023). To improve the PBMS' protein quality comparable to that of animal milk, various fortification methods, such as the addition of enzymes or a combination of two or more types of PBMS, are commonly adopted.

4.1.3 Fat quality of PBMS

Fats and oils represent a large number of lipid compounds, including fatty acids, mono-, di-, and triacylglycerols, phospholipids, and sterols) (Antunes et al., 2023). Fatty acids are used as building blocks of both triacylglycerols and phospholipids; they are also used in the synthesis of signaling molecules (eicosanoids) (Antunes et al., 2023). They play an essential role in ensuring adequate energy intake, essential fatty acid intake, and fat-soluble vitamin intake.

Fatty acid profiles of PBMS show that they contain higher levels of mono- and poly-unsaturated fatty acids, except for coconut-based milk. The low saturated fat and high unsaturated fat contents in PBMS make them a better substitute for animal-based milk, as consumption of high saturated fatty acids is linked to LDL-cholesterol, which is implicated in cardio-metabolic diseases and diabetes mellitus (Dehghan et al., 2018; Röös et al., 2020). Polyunsaturated fatty acids are reported to be predominant in soybean and hemp milk, while monounsaturated fatty acids are reported to predominate in rice, cashew, and almond milk (Neelakantan et al., 2020). Saturated fatty acids are reported to be the major fat content of coconut milk (Neelakantan et al., 2020; Romulo, 2022). Report has shown that PBMS are cholesterol-free, as sterol is exclusively a component of animal cells (Antunes et al., 2023). Aydar et al. (2023) reported α-linolenic acid (25.66%–27.78%) and palmitic acid (18.95%–23.08%) contents in kidney bean milk produced from different varieties of kidney bean. Similarly, PBMS from hemp contains 0.4 g/100 mL α-linoleic acid, which translates to 25% of the 1.6 g/day recommended intake of this essential omega-3 fatty acid (Chalupa-Krebzdak et al., 2018; National Institutes of Health, 2018).

4.1.4 Mineral quality of PBMS

Minerals are majorly obtained exogenously from dietary sources and play essential roles in various metabolic and physiological processes in the human system. Their deficiency or excess results in several health complications (Antunes et al., 2023). The range of mineral content of PBMS is presented in Table 1.

Among the various PBMS types soymilk was reported to have a higher concentration of potassium. The phosphorus content of PBMS was reported to be lower than that of animal milk. Most of the high micronutrient contents of PBMS according to studies are as a result of the fortification of the milk with some essential micronutrients (Singhal et al., 2017; Chalupa-Krebzdak et al., 2018; Walther et al., 2022). However, there is a dearth of information on the bioavailability of these micronutrients, especially in children that consume them (Singhal et al., 2017). Additionally, available evidence has also shown that PBMS contains antinutritional factors, such as phytates and oxalates, which form insoluble complexes with the mineral, negatively affecting the mineral's absorption (Muehlhoff and Bennett, 2013).

4.1.5 Vitamins quality of PBMS

Vitamins are essential micronutrients required in minute quantity by the human body, where they play some critical metabolic and physiologic roles. Thus, their deficiency can lead to several health complications (Yaman et al., 2021). Available information on the vitamin contents of PBMS revealed that most of the vitamins reported in PBMS are a result of fortification. Hence, the levels of both fat-soluble and water-soluble vitamins in PBMS vary based on the various plant sources, fortification and formulation employed during their production (Thorning et al., 2016; Bridges, 2018). For example, cobalamin is a water-soluble vitamin exclusively found in foods from animal sources; therefore, its presence in PBMS is a clear evidence of fortification during the PBMS production (Bridges, 2018).

4.2 Anti-nutrients quality of PBMS

Depending on the plant source, PBMS contain some anti-nutrients, including phytate, oxalate, saponins, exorphins, tannic acid, goitrogens, trypsin inhibitors, starch-digesting enzyme and

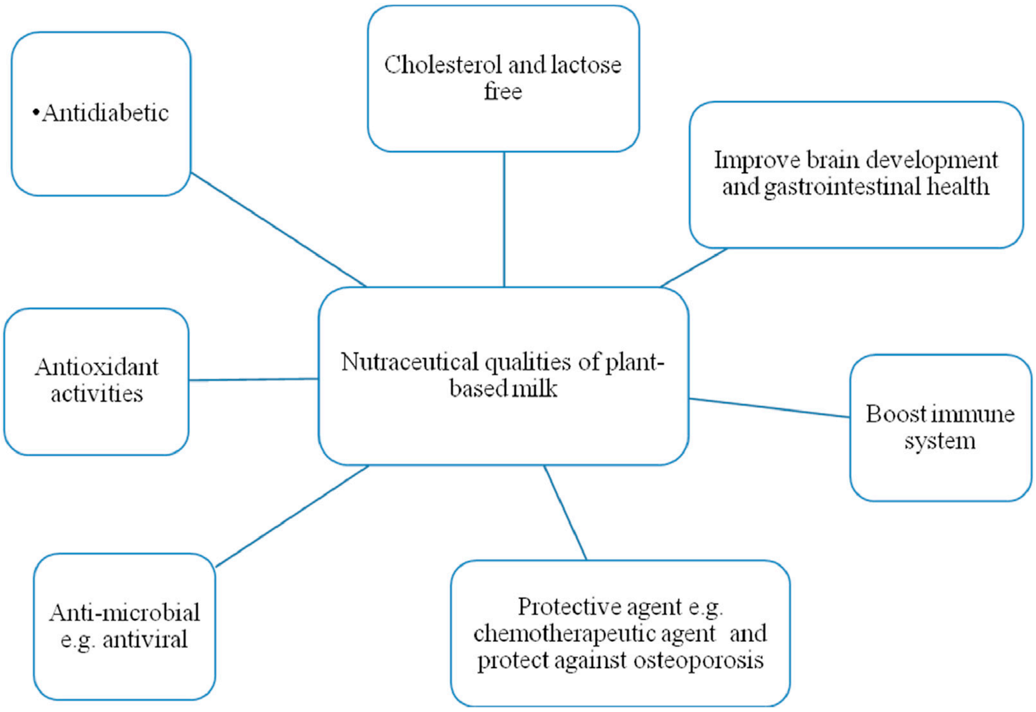

FIGURE 4
Some nutraceutical qualities of plant-based milk.

protease inhibitors, and lectins (Reyes-Jurado et al., 2021). These antinutrients generally interfere with the digestion, absorption and utilization of some important nutrients, although their impact varies, depending on their chemical nature and interaction with specific nutrients (Imam et al., 2024). For example, phytate reduces the bioavailability of essential micronutrients, such as zinc, iron, magnesium, and calcium, while trypsin inhibitors on the other hand reduce the protein's digestibility (Mäkinen et al., 2016; Imam et al., 2024). Lectins, common in soy, peanuts, and other beans, significantly reduce total calorie intake by inhibiting intestinal glucose (Mäkinen et al., 2016). Saponins, commonly present in oats, soy and beans, reduce protein digestibility, especially soy proteins, by forming insoluble saponin-protein complexes that are resistant to digestion.

However, many reports have shown that the influence of these anti-nutrients is significantly reduced through various production methods, such as fermentation, germination, use of chelating agents and heat treatments, employed in milk production (Mäkinen et al., 2016; Imam et al., 2024).

4.3 Nutraceutical qualities of PBMS

Nowadays, the desire for a healthy lifestyle has been one of the reasons consumers are tending toward a plant-based diet (Janssen et al., 2016; Sebastiani et al., 2019), such as PBMS. In addition to their nutritional qualities, PBMS have several health-promoting properties for which they can be placed in the nutraceutical and functional food class (Aydar et al., 2020). In this section, the nutraceutical qualities (Figure 4) of PBMS are presented.

PBMS contain health-benefiting bioactive compounds, such as polyphenolic compounds, phytosterols, isoflavones, bioactive peptides and saponins (Zandona et al., 2021). These bioactive compounds have been reported to confer on PBMS some significant health benefits, such as promoting brain development and boosting the immune system, reducing the risk of diabetes mellitus, atherosclerosis, coronary heart diseases, neuro-degenerative disorders, such as Alzheimer's disease, as well as protecting against some types of cancer (Pistollato et al., 2018; Reyes-Jurado et al., 2021). In addition, as a substitute for animal milk, PBMS are beneficial for the management of lactose intolerance and cardiovascular disease that are related to animal's milk consumption (Aydar et al., 2020). This is because PBMS are cholesterol- and lactose-free (McClements and Grossmann, 2021; Zandona et al., 2021).

A study conducted by Tulashie et al. (2020) revealed that coconut milk contained phenolic compounds and exhibited antioxidant property. Phenolic compounds are remarkable for their diverse health advantages, such as antioxidant and antidiabetic activity (Irondi et al., 2022; Imam et al., 2024). Isoflavones, which are strong antioxidants, have also been reported to be present in soymilk (Mazumder and Begum, 2016; Zandona et al., 2021). According to Hamza and Mahmoud (2013), a portion of 200 g of soymilk contains the following isoflavones: genistein (9.96 mg), daidzein (6.68 mg), and glycitein (0.94 mg). These antioxidants help in protecting cellular molecules, like protein, lipids, carbohydrates and nucleic acid, from free radicals-induced oxidative damage, thereby reducing the risks of and/or defending the body from oxidative stress-induced chronic diseases, such as diabetes, obesity, cardiovascular diseases, and cancer (Maleki et al., 2015; Irondi et al., 2018; Zandona et al., 2021; Irondi et al., 2022; Imam et al., 2024).

In addition, isoflavones in soymilk were reported to have effects against dermatologic diseases and neurodegenerative disorders (Aydar et al., 2020). They also function as anti-aging, anti-inflammatory (Poschner et al., 2017; Sun, et al., 2016), and chemotherapeutic agent for many types of cancer (Spagnuolo et al., 2015), as well as protect against osteoporosis (Mazumder and Hongsprabhas, 2016). Soymilk also renders protective effects against several age-related diseases (Nawaz et al., 2020).

PBMS promote a healthy gastrointestinal tract, due to their dietary fiber content, which was reported to be higher in oat, cashew and soymilk than in other PBMS (Aydar et al., 2020). Dietary fibers improve the hepatic antioxidant status and lipid profile, while reducing the serum glucose of rats (Dabour et al., 2022). In addition, PBMS from soy, coconut and rice are probiotics, carrying some health-benefiting microorganisms, such as *Lactobacillu*s and *Bifidobacterium*. Thus, they render health advantages, such as enhancing gastrointestinal transit, production of B-group vitamins, and transforming insoluble-bound forms of phenolic compounds into more readily-absorbable forms (Rasika et al., 2020). Moreover, an increased fermentative activity of *Lactobacillu*s and *Bifidobacterium* (intestinal bacterial flora), resulting in a higher short-chain fatty acids production (Viebke et al., 2014), could enhance their health-promoting effects.

Coconut milk was suggested to be a favourable diary substitute for patients with chronic kidney disease, due to its low sodium, potassium and oxalate content (Borin et al., 2022). Furthermore, PBMS also can reduce gastrointestinal disease due to their antimicrobial effect, decrease the risk of low bone mass and improve physiological functions (Paul et al., 2019). The polyunsaturated fatty acids content of PBMS also contributes to their nutraceutical qualities (Figure 4). The unsaturated fatty acid contents of cashew, almond, soy, peanut and hazelnut milk were higher than their total saturated fatty acid contents. Unsaturated fatty acids are associated with a decrease in blood lipid concentration (Eslami and Shidfar, 2019; Wang et al., 2019). Essential fatty acids, including α-linolenic and linoleic acids have neuroprotective effects in Alzheimer's disease patients. They also support the dendritic and axonal growth of neurons; speed up the brain development of fetus (during pregnancy) and that of the newborn baby (Gorji et al., 2018). Further, Vanga et al. (2020) reported almond milk to function in weight management and lowering of LDL cholesterol due to its high monounsaturated fatty acid content. Moreso, coconut milk maintains blood vessel elasticity, promotes brain development due to the presence of compounds, such as medium-chain triacyl glycerides and lauric acid (Sethi et al., 2016; Chalupa-Krebzdak et al., 2018; Reyes-Jurado et al., 2021). Soybean milk has been reported to alleviate menopause symptoms, while sesame milk has antiviral, hypocholesterolemic and antitumor activities. Rice milk was reported to ameliorate hypertension and display anti-inflammatory properties. Peanut milk has also showed potential to protect against stroke (Sethi et al., 2016; Reyes-Jurado et al., 2021). Almond milk's prebiotic properties, improve gastrointestinal health, while oat milk delay gastric emptying time, controls blood pressure and body weight, and reduces glycemic response (Makinde and Adebile, 2018; Decloedt et al., 2018; Reyes-Jurado et al., 2021).

In a recent study, Aly et al. (2022) investigated the antioxidant capacity, cholecystokinin (CCK) and glucagon-like peptide-1 (GLP-1) release of some PBMS following *in vitro* digestion. Among the PBMS evaluated, the authors reported that tiger nut milk had the highest CCK stimulant level (228.96 pg/mL), which was followed by that of hazelnut milk (220.04 pg/mL). Pertaining to the antioxidant properties of the PBMS, the authors observed that soymilk possessed the highest total phenolic content and antioxidant activity, which increased after *in vitro* digestion.

4.4 Sensory qualities of PBMS

Human sensory perception is essential in the development of PBMS, as consumer acceptability of the product is driven by sensory attributes (Zandona et al., 2021). Although animal proteins confer unique textural and sensory properties to milk, food researchers and scientists have been working to develop plant-based analogs with improved sensory and physical characteristics (Short et al., 2021). In this section, the sensory qualities of some PBMS are presented.

A study by Yao et al. (2022) on the sensory, rheological, and physicochemical properties of PBMS from different cereals revealed that the sensory profile and consumer acceptability of the PBMS were high enough for commercial-scale production, with a potential for market viability. Gorman et al. (2021) investigated the consumer acceptability of PBMS in coffee between dairy and plant consumers. Their findings revealed a preference for PBMS in coffee among the plant consumers/vegetarians. In another study that assessed the stability and sensory properties of oat milk from one Australian and three Chinese cultivars, the result showed that the Chinese Bayou 01 cultivars were the most stable, suitable, and acceptable for the processing of oat milk (Zhou et al., 2023). Aydar et al. (2023) also assessed the sensory attributes of PBMS produced from different varieties of kidney bean and concluded that the PBMS had an overall sensory acceptance ranging from 2.9 to 4.1 out of 10.

In another study, Vaikma et al. (2021) evaluated the sensory attributes and consumer acceptability of 90 different plant-based beverages in Estonian markets using the Rate-All-That-Apply (RATA) method. They reported a little variation among the sample groups. Furthermore, investigating the attitude and perception of consumers towards six different commercial PBMS using Check-All-That-Apply (CATA) method and nine-point hedonic scales, Moss et al. (2022) demonstrated that consumer acceptability ratings of PBMS from pea, almond, oat, soy, and coconut were comparable, but these were significantly rated higher than the PBMS from cashew. Also, attributes of nutty, creamy, white, smooth and sweet increased consumers' liking of the PBMS, while the PBMS' aftertaste, watery, off-flavour, brown, and beany qualities were detractive (Moss et al., 2022). Pointke et al. (2022) assessed the sensory properties of PBMS using the Lawless and Heymann descriptive method. They concluded that PBMS with no additives were astringent and bitter, but had high health values. Hence, they suggested that additives could be added to reduce the off-flavours and increase the sensory characteristics of PBMS (Pointke et al., 2022).

The acid, bitter and astringent flavours of PBMS are attributed to the presence of some bioactive compounds of plant origin, such as flavonoids, glycosylates, phenols, and terpenes (Tang-u et al., 2019; Reyes-Jurado et al., 2021). A PBMS made from legumes smells earthy and beany and is, thus, considered undesirable for individuals with no traditional consumption of legumes. The off-flavours of the legume milk result from n-hexanol and n-hexanal that develop from the oxidation of plant lipids (Tangyu et al., 2019). Also, a detractive aftertaste arises from PBMS containing isoflavonoids (Tangyu et al., 2019). Various pre-treatments, such as blanching, soaking, and dehulling are essential to improve the sensory profiles of PBMS. For instance, the flavours and aromas of the final products of PBMS can be enhanced by roasting the raw material, while its extraction yield and protein solubility can be reduced by heating. Also, blanching can remove off-flavours from soymilk by inactivating lipoxygenase and trypsin inhibitors (Mäkinen et al., 2016). Studies have discovered that blanching peanuts at approximately 121°C at a pressure of 15 psi for 3 min before soaking and milling increases the taste and aroma acceptance of peanut milk, compared to the traditional method of preparation (Jain et al., 2013). Another study carried out by Makinde and Adebile (2018) to improve the overall acceptance of pre-treated almond milk revealed that blanching almond nuts with hot water for 15 min produced a better colour, mouth feel, flavour, and overall acceptance as compared to steaming.

Cardello et al. (2022) conducted a study to assess the consumer acceptability of some PBMS compared to dairy milk, and the result demonstrated that full-fat dairy milk was generally accepted across all participants, while heterogeneity was observed across the PBMS. The flavour, smooth and delicate texture of PBMS somewhat differ from dairy milk, majorly because the PBMS are compactly packed in globular structures to form diverse structures upon reaction with one another (Reyes-Jurado et al., 2021). Hence, the PBMS sensory quality is complemented by introducing additives to mimic the mouth feel, texture, and other properties of conventional dairy milk (Reyes-Jurado et al., 2021). Adding sugar to cashew nut milk also enhanced its sensory acceptability (Tamuno and Monday, 2019). Another study by Kim and Hong, (2023) demonstrated that additives like chocolate flavouring effectively increased the sensory profile of soymilk through aroma-taste interactions.

There have also been a few studies on the sensory quality of PBMS produced from the blends of different plant raw materials. A study by Oduro et al. (2021), in which peanut, melon seeds, and coconut were blended, revealed that the blend's PBMS had an enhanced sensory quality. Similarly, an optimized chocolate-flavoured peanut-soy beverage using the response surface methodology showed that a better acceptability was observed with the soy protein isolates, as compared with the drink made with soy flour (Sethi et al., 2016). PBMS produced from the blends of tiger nut and different proportions of moringa leaf (95:5, 90:10, and 85:15; tiger nut:moringa leaf extract, respectively) revealed that 95:5 and 90:10 blends had an overall acceptability of 6.5 and 5.0, respectively.

5 Conclusion, recommendation and future perspective

PBMS are produced from different edible plant sources, such as cereals, legumes, roots and tubers, nuts, corms, fruits, and vegetables. Their production is environmentally-friendly, with a reduced carbon emission. Studies have demonstrated that they are rich in nutrients and health-promoting bioactive compounds, conferring on them nutraceutical properties and leading to their increased demand. However, they differ in these qualities, depending on the raw material. To meet this increasing demand for PBMS, several other edible plants and their blends, including cereals, nuts, legumes, corms, fruits, vegetables, roots and tubers, could be investigate for their suitability for PBMS production. The nutritional and nutraceutical qualities of such PBMS can be enhanced through optimization with product development software, including the Design Expert. In doing this, natural food additives can also be added to improve the sensory attributes of the PBMS.

Given the PBMS' high susceptibility to physical, chemical and microbial spoilage, research could be intensified in producing instant PBMS in powdery form, which would have a longer shelf life, with the nutrient and bioactive compounds composition intact. This could be achieved by drying (e.g., spray-drying) and packaging the PBMS.

Author contributions

EI: Supervision, Writing – review and editing, Conceptualization, Writing – original draft. HA: Writing – original draft. YI: Writing – original draft, Writing – review and editing. AB: Writing – original draft. AA: Writing – original draft. AE: Writing – original draft. BK: Writing – original draft. TA: Writing – original draft.

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