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An Update on Plant-Based Functional Foods: Nutrition, Sensory, Nutraceutical and Biotechnology Potentials

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Abstract— *With the rise of vegan diets and increased reports of lactose intolerance, plant-based diets, including plant-based milk products (PBMP), offer an interesting alternative. In addition, PBMP, as a treasure trove of bioactive compounds, is reported to improve human health by promoting food sustainability, reducing environmental pollution, and supporting an eco-friendly approach. PBMP are milk analogues produced from plant sources, comprising dispersed particles of plant matrices. They are water-soluble extracts of plants formulated to mimic animal milk. A wide range of PBMPs that are convenient, affordable, sustainable, and rich in nutrients are now being developed by the food industry. The current review focuses on the current knowledge in this important area of food technology, with implications for improving nutrition and health. By reviewing the background literature on sources, the subsequent chapter focuses on the sensory and physico-chemical properties. The nutrition and health aspects, coupled with the bioavailability of these fortified milks, are discussed in detail. The biotechnological prospects and current trends form the last section. In summary, these plant-fortified milks are a complete package of health- and nutrition-promoting, environmentally sustainable milk products.*

Keywords— Plant-based milk, Functional foods, Bioactive compounds, Nutraceuticals, Biotechnology, Sustainability, Food fortification.

I. INTRODUCTION

The global population explosion is estimated to increase to about 10 billion people by 2050, and the nutrition transition is steadily putting more pressure on food supply worldwide (McClements et al., 2019). Furthermore, recent global developments such as war, drought, pandemics, and climate change call for a more robust food security system, capable of addressing the demand-supply chain needs while ameliorating climate change and mitigating environmental pollution. In this context, plant-based milk products (PBMP) are plant-based milk alternatives, comprising a colloidal system with a continuous phase consisting of water and particles in a 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 (McClements and Grossmann, 2021; Reyes-Jurado et al., 2021).

The production of PBMP is environmentally friendly, promoting reduced carbon emissions when compared to animal milk products, meat, eggs, fish and their derivatives (Poore and Nemecek, 2018). However, the qualities of PBMP are plant-specific, meaning the content varies among plant sources and even varieties; the environment in which it is grown impacts the nutritional, nutraceutical and sensory qualities. In this context, several reports have demonstrated the potential of these PBMP to meet human nutritional needs and promote health. A recent report indicated that the PBMP accounted for 40% of the over 5 billion total sales of the plant−based food market (Zheng et al., 2021). PBMP market value is estimated to reach US 5 *billion total sales of the plant−based food market* (*Zheng et al*, 2021). *PBMP market value is estimated to reach US* 30.79 billion by 2031 (Aydar et al., 2021).

Aside from these advantages, consumers who are lactose intolerant, have cholesterol-related conditions, are allergic to cow's milk protein, and vegetarians also prefer PBMP to animal milk and other dairy products. PBMP are a source of bioactive compounds such as phenolic compounds and peptides, and possess significant health properties, including antioxidant, anti-hypercholesterolaemic, immunostimulatory, antihypertensive, anti-microbial, anti-cancer and anti-anaemic activities (Zujko and Witkowska, 2014; Paul et al., 2019). These important properties of PBMP have resulted in an increased consumer demand. This has further increased the demand for PBMP to an all-time high (Vallath et al., 2022). This review aimed to discuss PBMP, with emphasis on its sources, production, and nutritional, nutraceutical, and sensory qualities.

II. MILK AS A SOURCE OF HUMAN NUTRITION

Milk, alongside dairy products, such as cream, whey, yoghurt, buttermilk, cheese and butter, is one of the most important foods in the human diet (Lambrini et al., 2020). Milk and its products are among the well-established wholesome foods that ensure a balanced nutrition, impacting positive health outcomes (Zhang et al., 2021; Smith et al., 2022). It is a rich dietary source of protein, lipid, carbohydrate, mineral and vitamin. Water forms the major part of milk (Kumar et al., 2016). Milk provides energy to the body through lactose. The vitamins in milk are both water and fat-soluble affecting the fat contents of dairy products and vary based on the animal diet and season (Mehra et al., 2021). Milk lipids exist as emulsified globules, and their contents largely determine the milk's cost, physical qualities, nutritional content and sensory value. Hence, they are largely consumed globally as an essential part of dietary recommendations (Chauhan et al., 2021).

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 (Haas et al., 2019). Animal milk contains a diverse complement of nutrients (Scholz-Ahrens et al., 2019) and serves as the first food for mammals and the main source of nutrients for mammalian newborns. The bioactive constituents include immunoglobulins, lactoperoxidase, growth factors and immunomodulatory peptides, lysozymes, oligosaccharides, alpha-lactalbumin, and lactoferrin (Cacho and Lawrence, 2017). It is also a source of amino acids and protein, minerals (such as calcium, phosphorus, and potassium), several vitamins (such as vitamins A, B2, B5, and B12), fat, and essential fatty acids. The bioactive compounds play significant physiological and biochemical functions (Khan et al., 2019). Animal (mammalian) milk composition varies depending on species differences and other factors, such as nutrition, food composition, physiology, and milking frequency (Mehra et al., 2021). Its composition also varies based on genetic factors, breed types, and environmental conditions.

Drawbacks of animal milk include health-related concerns such as milk allergies, hypercholesterolemia prevalence and lactose intolerance (Munekata et al., 2020). Animal milk is under increased scrutiny due to its environmental impact, accounting for 8% of global water consumption and contributing predominantly to greenhouse gases. Additionally, air and water pollution, soil degradation and loss of diversity are related issues in animal milk production. Ethical considerations concerning animal welfare are also related to animal milk (Haas et al., 2019).

III. PLANT-BASED MILK PRODUCTS

A wide range of PBMP, which are desirable, convenient, affordable, sustainable, and rich in nutrients, have now been developed by the food industry. Different varieties of PBMP 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 PBMP, derived from the water extraction of these plant materials, is completely free from animal-based ingredients (Silva et al., 2020). PBMP are formulated to have a similar appearance and taste to conventional milk (Mäkinen et al., 2016) and are often presented as a sustainable, healthy and animal-welfare-friendly alternative (Haas et al., 2019). In addition, other plant-based dairy substitutes like cheese, yoghurt, ice cream, and creamer are similarly increasing rapidly globally (Clay et al., 2020).

The PBMP products differ with respect to their nutrients. Therefore, the addition of protein, vitamins, 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). PBMP are an important source of moisture, carbohydrate, protein, and fat, and are rich in unsaturated fatty acids, fibre, vitamins, minerals, and essential fatty acids (McClements and Grossmann, 2021). The 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).

Several PBMP products have health promoting effects. Chickpea milk is rich in minerals and fibre, coconut milk is rich in lipids (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 fibre (Aydar et al., 2020). Soymilk is a good source of B-vitamins, especially niacin, folate, and pyridoxine; minerals, such as iron, copper, magnesium, and zinc; and monounsaturated and polyunsaturated fats (Mazumder and Hongsprabhas, 2016; Zandona et al., 2021). Hemp milk contains molybdenum, and coconut milk provides chromium and selenium (Astolfi et al., 2020).

Several authors have compared different animal sources for milk quality and PBMP. Aly et al. (2022) evaluated the antioxidant activity, cholecystokinin (CCK) and glucagon-like peptide-1 (GLP-1) release of some PBMP after in vitro digestion. The study concludes that the PBMP could adequately replace cow's milk, based on their antioxidant and satiety effectiveness. In another study, Aydar et al. (2023) assessed the in vitro phenolic bioaccessibility, sensory quality and fatty acid profiles. The study documented protein (1.92%–2.32%), α-linolenic acid (25.66%–27.78%), and palmitic acid (18.95%–23.08%) contents. Further, the study observed an overall sensory acceptance ranging from 2.9 to 4.1 out of 10. PBMP provide many attractive qualities to consumers, such as lactose-, dairy allergen- and cholesterol-free properties (Hartmann et al., 2018; Cichonska and Ziarno, 2022); high content in essential nutrients (vitamins and minerals), bioactive compounds and dietary fibre, with pre-probiotic properties (Roselló-Soto et al., 2019). The PBMP also allay consumers' safety concerns relating to antibiotic residues and hormones (Pua et al., 2022) and promote vegan-friendly attributes (Mendly-Zambo et al., 2021). Figure 1 illustrates diverse nutraceutical benefits of plant-based milk.

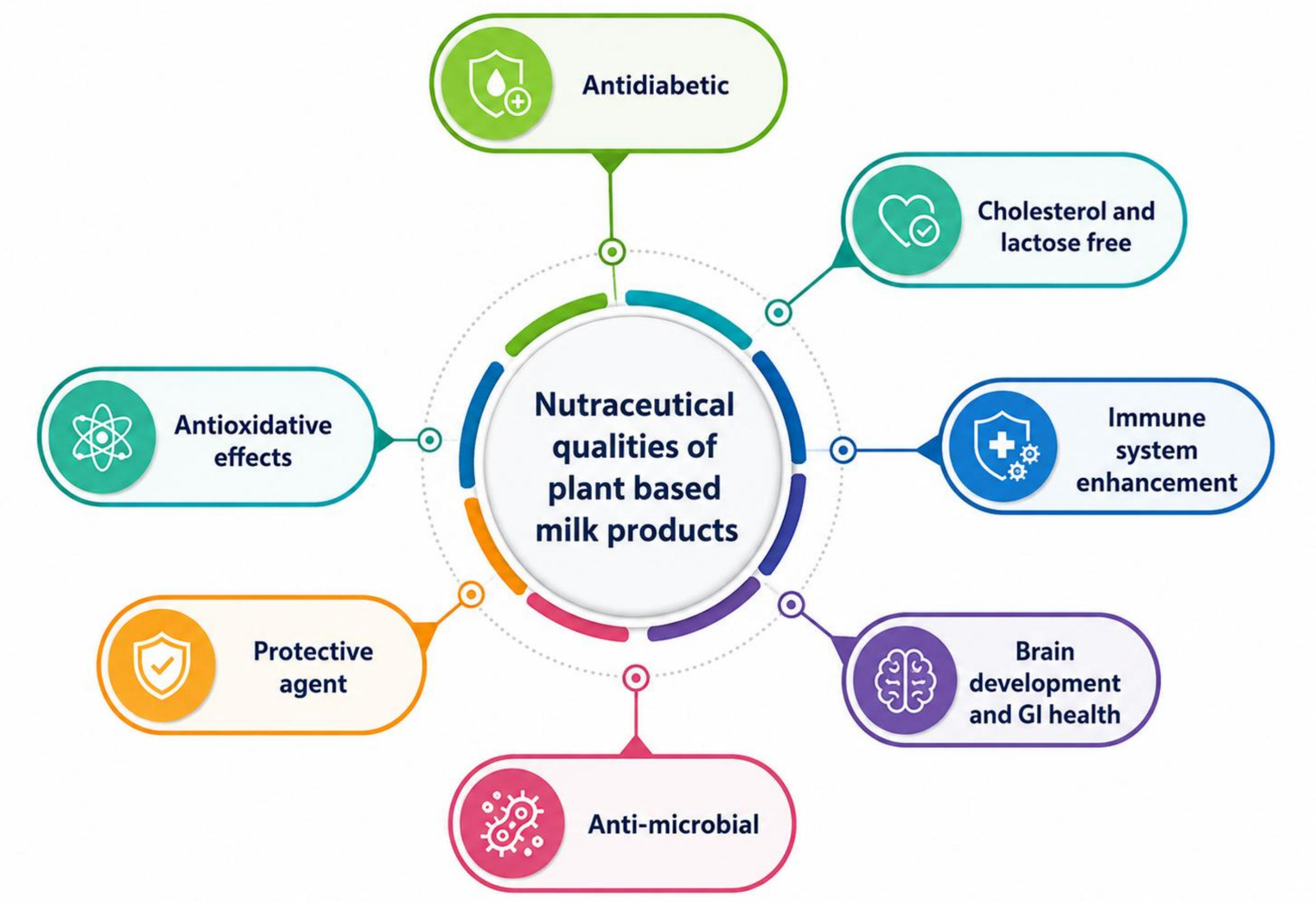

FIGURE-1: Diverse nutraceutical benefits of plant based milk

3.1 Sources of PBMP and Production Methods

Diverse plant sources from which PBMP including 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 (Anitha and Manivannan, 2013). 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; Zheng et al., 2021). Aside the sources listed above, PBMP are also produced from the blends of different plant source such as soy bean and almond (Kundu et al., 2018), soy bean and corn (Ajala et al., 2013), peanut, melon seeds, and coconut (Oduro et al., 2021).

Depending on the initial raw material and intended final product quality, the process of producing PBMP may vary (Penha et al., 2021). The production process typically involves several common steps, which include sourcing and pre-processing raw materials, grinding and extraction, emulsification and stabilisation, flavouring and fortification, pasteurisation, packaging and storage, as well as quality control testing. To ensure the quality of the raw materials, it is essential to consider several critical factors. The origin and variety of the plant-based ingredients, along with their growing conditions, significantly influence their 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). In addition, the methods used for processing, which include cleaning, sorting, and preparation, influence both the overall quality and the possibility of contaminants. Proper storage conditions and preservation methods further protect against spoilage and help keep the nutritional properties of the raw materials intact. Consistent quality testing is vital for identifying contaminants such as pesticides, heavy metals, and microbial agents, thereby ensuring the safety and purity of the raw materials (Mäkinen et al., 2016). By conscientiously considering these factors, PBMP processors can opt for high-quality plant sources, resulting in superior PBMP products that effectively cater for consumers' demands for taste, high nutrients, and sustainability.

3.2 Cleaning and Pre-Processing of Raw Materials

Raw materials are subjected to cleaning and pre-processing, which encompass vital steps in the production of plant-based milk. The cleaning and sorting stage begins with the raw materials being 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 soften, hydrate, and swell 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 seeds 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 PBMP. Blanching can be used for seeds and nuts, such as almonds, soybeans, coconuts, peanuts, sesame, quinoa and rice, by briefly immersing the raw materials in hot/boiling water, which helps preserve their colour, texture, and nutritional properties (Aydar et al., 2020). Relative to water soaking, the advantages of blanching the raw material include enzyme (for example, lipases) inactivation, microbial load reduction (Sethi et al., 2016), and reduction in antinutrients and off-flavours (Pua et al., 2022). PBMP are produced by size-reduction methods, in which the original structure of plant tissue is broken down by mechanical, chemical, and enzymatic methods (Zheng et al., 2021). More often, the mechanical extraction of the raw material is applied due to its scalability and low cost, having a low technological barrier (Mäkinen et al., 2016; Yadav et al., 2017). It is effective in dispersing the raw material ingredients for optimum extraction, allowing for the extraction process standardisation. The tissue structure breakdown following grinding results in the release of oil bodies in PBMP seed and nut sources, such as cashews, soybeans, coconuts, oats and almonds.

3.3 Grinding and Extraction

Grinding and extraction are key processes in the production of plant-based milk. For optimal texture, the soaked and blanched raw materials are finely ground to create a smooth, consistent mixture. This grinding helps release flavours and nutrients effectively. Depending on the raw material, grinding may be carried out by dry-milling or wet-milling. For PBMP produced using flour, dry-milling is typically performed first, and the resulting flour is then reconstituted and/or further extracted to yield the PBMP (Mäkinen et al., 2016). For PBMP in which the whole raw material is subjected to aqueous extraction without first being converted into flour, the raw material is typically pulverised into a 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 additional size standardisation or reduction to enhance stability and texture (Kizzie-Hayford et al., 2015). Subsequently, various extraction methods are employed to extract the milk from the ground mixture, depending 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, unwanted materials (mainly coarse particles) are separated or removed through gravity-facilitated sedimentation, centrifugation, decanting, or (ultra) filtration, concentrating the desirable components, such as nutrients (McClements et al., 2019).

3.4 Emulsification and Stabilization

Emulsification and stabilization are crucial steps in producing PBMP, ensuring a smooth and uniform product. During the process, agents like lecithin or gums are added as emulsifiers and stabilisers to form a stable emulsion, preventing water and plant fats from separating during storage. These emulsifiers also improve the texture and mouthfeel of the milk. Homogenization and mixing further enhance the product by breaking down fat globules and distributing them evenly, resulting in a creamy, well-blended plant-based milk that offers a satisfying drinking experience (Ma and Boye, 2013). Homogenization plays a significant role in defining the microstructure of the extracted PBMP (Gul et al., 2017).

3.5 Flavoring and Fortification

Flavouring and fortification are important steps in production, enhancing both taste and nutritional value. During flavouring, processors may use natural or artificial flavouring agents to impart various flavours to the milk, catering to different consumers' preferences (McClements et al., 2019). Animal milk contains higher levels of minerals than PBMP and other plant-based beverages (Bocker and Silva, 2022). For instance, plant-based beverages contain about 30%–50% lower levels of minerals such as phosphorus, calcium, magnesium, potassium and sodium than animal milk (Astolfi et al., 2020). The low mineral levels in PBMP are coupled with the presence of antinutrients, such as tannins, oxalates, phytate, saponins and lecithin. These antinutrients diminish the digestibility and absorption of essential minerals, including Ca, Zn, Fe, Cu and Mg, by binding to them to form insoluble complexes (McClements et al., 2019). Hence, to improve the PBMP nutritional quality, fortification with essential nutrients, including vitamins and minerals, is important. Pasteurization, either by conventional or emerging innovative processing technologies, is a critical step in the production of PBMP to ensure its safety and extend its shelf life. It reduces the PBMP microbial and enzyme load to levels that are safe for human consumption (Bocker and Silva, 2022).

3.6 Pasteurization

In the conventional pasteurisation stage, methods such as high-temperature short-time (HTST) or ultra-high temperature (UHT) pasteurisation are employed to eliminate harmful bacteria and pathogens. However, applying high temperatures (from 60°C to 130°C) can cause undesirable alterations in the nutritional, physical, chemical, and sensory characteristics of the PBMP (Aydar et al., 2020). Therefore, proper temperature and time considerations are essential during pasteurisation, as the PBMP needs to be heated to a specific temperature for a certain duration to achieve effective sterilisation without compromising its taste and quality.

3.7 Packaging, Storage and Quality Control

Packaging and storage are essential steps in PBMP production, focusing on preserving product quality and safety. During this phase, appropriate packaging materials such as cartons, bottles, or pouches are chosen carefully to shield the milk from external contaminants and light (Liu et al., 2022). The selection of packaging not only affects the shelf life but also the sustainability of the PBMP. Equally important are proper storage conditions, which help keep the milk fresh and safe for consumption. It is recommended to store PBMP in a cool, dry place, away from direct sunlight, and at specific temperatures to prevent spoilage and maintain its flavour and nutritional value throughout its shelf life (Liu et al., 2022). Additionally, quality control and testing play a vital role in ensuring the product's consistency and safety. Rigorous testing and monitoring are conducted at various stages — from raw material procurement to final packaging — to verify that the PBMP meet standards, comply with regulations, and are free from contaminants.

IV. NUTRITIONAL QUALITIES OF PBMP

PBMP are reported as a good dietary source of some important nutrients, such as protein, calcium, vitamins, and fibre (Craig and Fresán, 2021). They serve as an alternative for dairy milk due to their perceived nutritional and health importance (Pandey and Poonia, 2020). The nutritional values of PBMP vary, depending on the raw material type and quality, formulation, processing method, and fortification. This attributes a unique set of nutritional qualities, making them a suitable option for health-conscious individuals (Craig et al., 2022). Major advantages of PBMP 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).

PBMP are also reported to be lactose- and cholesterol-free, making them suitable for individuals with lactose intolerance (Facioni et al., 2020). They contain essential micronutrients like vitamin D, B12, and calcium, which are vital for bone and teeth health, immune function, and energy production (Pandey and Poonia, 2020). However, PBMP such as almond, rice, and oats have lower nutritional quality, offering minimal amounts of protein, iron, and calcium compared to cow's milk (Singhal et al., 2017). The high nutrient and fiber content of legumes has made them an appealing base for developing nutrient-rich PBMP (Chandra-Hioe et al., 2016). Their protein is incomplete, unlike the complete protein found in animal milk (Rincon et al., 2020). The generally lower nutritional value of PBMP versus cow's milk may limit their market appeal, as reliance on them could lead to deficiencies in nutrients like essential amino acids, vitamins (A, D, B2, B12), and minerals (zinc, calcium, iodine). Therefore, PBMP are often fortified with these nutrients to address such deficits. Table 1 is a summary of nutrients and their quantity in plant-based milk.

TABLE 1
SUMMARY OF NUTRIENTS AND THEIR QUANTITY IN PLANT-BASED MILK

Nutrient	Quantity	Reference
Carbohydrate	1.95-54.2 Kcal/1000mL	Irondi et al., 2025
Protein	0.30-3.10 Kcal/1000mL	Irondi et al., 2025
Fat and oil	0.96-4.55 kcal/100mL	Irondi et al., 2025
Fibre	0.10-1.27 kcal/100mL	Irondi et al., 2025
Ash	0.3-0.68 kcal/100mL	Irondi et al., 2025
Minerals		
Calcium	65.32-156.5	Irondi et al., 2025
Potassium	37.1-157.5	Irondi et al., 2025
Sodium	23.9-64.2	Irondi et al., 2025
Phosphorus	14.95-39.46	Irondi et al., 2025
Magnesium	7.76-16.8	Irondi et al., 2025
Iron	0.16-0.62	Irondi et al., 2025
Copper	0.01-0.13	Irondi et al., 2025
Vitamins		
Vitamin A	141.6-195.4 IU/100mL	Irondi et al., 2025

Research evidence has shown that most PBMP contain fewer calories than dairy milk. The carbohydrate contents ranges from 0.42 to 11.05 g per 100 mL, relative to dairy milk (4.78 g/100 mL) for whole milk and 4.96 g/100 mL for skim milk (Jeske et al., 2017b; Walther et al., 2022). PBMP 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 dietary needs (Lopez and Mohiuddin, 2020). The individual amino acids levels vary among the PBMP from different sources (Walther et al., 2022). Studies implicate that cereal milk products contain lower lysine content, while leguminous proteins contain lower methionine and cysteine content (Anitha et al., 2020). Some types of PBMP, such as wheat, nut and soy, contain protein that can trigger allergic reactions in susceptible consumers (Pingali et al., 2023). To improve PBMP protein quality to match that of animal milk, various fortification techniques are frequently used, such as adding enzymes or combining different types of PBMP.

The fatty acid profile of PBMP indicates it generally contains higher levels of mono- and polyunsaturated fatty acids, with the exception of coconut-based milk. The low saturated fat and high unsaturated fat contents in PBMP 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 (Romulo, 2022). Report has shown that PBMP are cholesterol-free, as sterols are exclusive components of animal cells (Antunes et al., 2023). Among the various PBMP types, soymilk is reported to have a higher concentration of potassium. The phosphorus content of PBMP is reported to be lower than that of animal milk. Most of the high micronutrient contents of PBMP according to studies are as a result of the fortification of the milk with essential micronutrients (Chalupa-Krebzdak et al., 2018). Similarly, the vitamin contents of PBMP revealed that most of the vitamins reported in PBMP are a result of fortification. Hence, the levels of both fat-soluble and water-soluble vitamins in PBMP vary based on the various plant sources, fortification and formulation employed during their production (Thorning et al., 2016). For example, cobalamin is a water-soluble vitamin exclusively found in foods from animal sources; therefore, its presence in PBMP is a clear evidence of fortification (Bridges, 2018).

V. NUTRACEUTICAL QUALITIES OF PBMP

PBMP have several health-promoting properties for which they can be placed in the nutraceutical and functional food class (Aydar et al., 2020). The bioactive compounds in PBMP are such as polyphenolic compounds, phytosterols, isoflavones, bioactive peptides and saponins (Zandona et al., 2021). These bioactive compounds have been reported to confer on PBMP some significant health benefits, such as promoting brain development and boosting the immune system, reducing the risk of diabetes mellitus, atherosclerosis, coronary heart diseases, neurodegenerative disorders, such as Alzheimer's disease, as well as protecting against some types of cancer (Pistollato et al., 2018). In addition, as a substitute for animal milk, PBMP are beneficial for the management of lactose intolerance and cardiovascular disease that are related to animal milk consumption (Aydar et al., 2020). This is because PBMP are cholesterol- and lactose-free (Zandona et al., 2021).

Phenolic compounds have antioxidant and antidiabetic activity (Irondi et al., 2022). Isoflavones, which are strong antioxidants, have also been reported to be present in soymilk (Mazumder and Begum, 2016). 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). Isoflavones in soymilk were reported to have effects against dermatological, neurodegenerative (Aydar et al., 2020) and anti-inflammatory disorders (Poschner et al., 2017). They also function as chemotherapeutic agent for many types of cancer (Spagnuolo et al., 2015), as well as protect against osteoporosis (Mazumder and Hongsprabhas, 2016). The high dietary fiber in oat, cashew and soymilk PBMP promote a healthy gastrointestinal tract. Furthermore, PBMP 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).

Coconut milk was suggested to be a favourable dairy substitute for patients with chronic kidney disease, due to its low sodium, potassium and oxalate content (Borin et al., 2022). PBMP from soy, coconut and rice are probiotics, carrying some health-benefiting microorganisms, such as Lactobacillus 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). The unsaturated fatty acid contents of cashew, almond, soy, peanut and hazelnut milk are higher than their total saturated fatty acid contents. Unsaturated fatty acids are associated with a decrease in blood lipid concentration (Eslami and Shidfar, 2019). Essential fatty acids, including α-linolenic and linoleic acids, have neuroprotective effects in Alzheimer's disease. Moreover, coconut milk maintains blood vessel elasticity, promotes brain development due to the presence of compounds, such as medium-chain triacyl glycerides and lauric acid (Reyes-Jurado et al., 2021).

Aly et al. (2022) investigated the antioxidant capacity, cholecystokinin (CCK) and glucagon-like peptide-1 (GLP-1) release of some PBMP following in vitro digestion. Results implicate 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). Depending on the plant source, PBMP contain some antinutrients, including phytate, oxalate, saponins, exorphins, tannic acid, goitrogens, trypsin inhibitors, starch-digesting enzyme and 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 digestibility (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.

VI. SENSORY QUALITIES OF PBMP

Consumer acceptability of the PBMP product is driven by sensory attributes (Zandona et al., 2021). Food researchers and scientists have been working to develop plant-based analogs with improved sensory and physical characteristics (Short et al., 2021). A study by Yao et al. (2022) on the sensory, rheological, and physicochemical properties of PBMP from different cereals revealed that the sensory profile and consumer acceptability of the PBMP were high enough for commercial-scale production, with a potential for market viability. Gorman et al. (2021) investigated the consumer acceptability of PBMP in coffee in dairy and plant consumers. Their findings revealed a preference for PBMP in coffee among the plant consumers/vegetarians. Aydar et al. (2023) assessed the sensory attributes of PBMP produced from different varieties of kidney bean and concluded that the PBMP had an overall sensory acceptance ranging from 2.9 to 4.1 out of 10.

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. The results imply little variation among the sample groups. Moss et al. (2022) demonstrated that consumer acceptability ratings of PBMP from pea, almond, oat, soy, and coconut were comparable. The acid, bitter and astringent flavours of PBMP are attributed to the presence of compounds flavonoids, glycosylates, phenols, and terpenes (Tang-u et al., 2019). A PBMP 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). Various pre-treatments, such as blanching, soaking, and dehulling, are essential to improve the sensory profiles of PBMP. For instance, the flavours and aromas of the final products of PBMP 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).

Makinde and Adebile (2018) report that blanching almond nuts with hot water for 15 min improved the overall acceptance of pre-treated almond milk, producing better colour, mouth feel, flavour, and overall acceptance compared to steaming. The flavour and smooth, delicate texture of PBMP somewhat differ from those of dairy milk, mainly because PBMP are compactly packed in globular structures that form diverse structures upon reaction with one another. Hence, the PBMP sensory quality is complemented by introducing additives to mimic the mouth feel, texture, and other properties of conventional dairy milk. 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. Blending has been shown to improve sensory quality. Oduro et al. (2021), in which peanut, melon seeds, and coconut were blended, revealed that the blend's PBMP had an enhanced sensory quality.

VII. BIOAVAILABILITY AND BIOACCESSIBILITY OF PLANT-BASED MILKS

Bioavailability refers to the fraction of an ingested micronutrient that reaches systemic circulation. Several factors influence this, expressed as $F = FB \times FA \times FT$, where FB is the fraction released from food into GIT fluids, and FT is the fraction remaining in its bioactive form after chemical transport. Some bioactives are expelled back into intestinal fluids via efflux transporters. The stability of a bioactive in the GIT depends on its molecular environment. Oil-soluble bioactives' bioaccessibility relies on mixed micellar formation in the small intestine that can solubilise them. The food matrix surrounding lipid droplets in emulsions significantly affects the bioavailability of encapsulated hydrophobic bioactives. Consuming them with digestible lipids like triacylglycerols can enhance bioaccessibility. Certain food-grade components, such as spices, medium-chain fatty acids, and surfactants, promote micronutrient absorption by modifying intestinal membrane permeability or influencing active transport and efflux. Incorporating these into functional milk foods might be beneficial.

Muleya et al. (2024) evaluated calcium supply in 25 plant-based products, finding bioaccessibility varied from 0.1% to 50%, with kale, finger millet, and fortified white bread as top sources — kale offering five times more bioaccessible calcium than a serving of skimmed milk. Zhou et al. (2021) studied almond-fortified milk containing micronutrients, noting calcium bioaccessibility was higher with $CaCO_3$ than $CaCl_2$. These findings inform the development of fortified plant-based milks with better nutritional and physicochemical properties. A plant-based chocolate spread, fortified with nano-liposomal vitamin D_3 and omega fatty acids using spray-dried milk powders (soy, lentil, rice), was developed to enhance nutritional quality and bioaccessibility. Azab et al. (2025) reported on this plant-based spread with improved vitamin D_3 bioavailability.

Bioavailability may depend on the matrix components, such as PS ingredients. Vaghini et al. (2016) examined the bioaccessibility of total and individual plant sterols in four commercial PS-enriched fermented milk beverages during in vitro digestion, including mixed micelle formation. Total plant sterol bioaccessibility was highest in samples A and B (16-17%), lower in D (11%), and lowest in C (9%). Total bioaccessibility did not correlate with protein, lipid, or PS content but was inversely related to carbohydrate and fiber content. The bioaccessibility of individual PS varied among samples and was independent of the PS profile. Table 2 is a comparative summary of few plant-based milk and dairy milk.

TABLE 2
COMPARATIVE SUMMARY OF FEW PLANT-BASED MILK AND DAIRY MILK

Item	Daily Value	Dairy Milk	Pea Milk	Almond Milk	Soy Milk
Protein (g)	50	8.2	7.5	1	6.1
Calcium (mg)	1,300	309	385	449	294
Magnesium (mg)	420	29	0	15	33
Phosphorus (mg)	1,250	252	nd	22	176
Potassium (mg)	4,700	387	421	163	280
Selenium (µg)	55	4.8	nd	0.2	5.2
Zinc (mg)	11	1.1	nd	0.1	0.5
Riboflavin (mg)	1.3	0.33	nd	0.02	0.45
Vitamin D (µg)	20	27	2.5	2.4	2.7

VIII. BIOTECHNOLOGICAL APPROACHES

Biotechnology enhances food using genetic engineering, fermentation, and omics tools to increase nutrient density, create stress-resilient crops, and produce sustainable smart proteins. Tools like CRISPR improve crops to yield higher vitamins or iron (e.g., biofortified staple plants). CRISPR-Cas9 silencing in the IPK1 gene in wheat or NRAMP transporters in rice lowers phytic acid or stops minerals from locking in roots, increasing iron availability in edible grains (Kumar et al., 2022). Microbial and enzymatic systems modify plant proteins and starches to create functional analogs. Several microorganisms consume plant sugars and starches and produce acids, gases, and complex flavor compounds that improve sensory properties (Muhammed et al., 2025). Specific enzymes like proteases and transglutaminases cut or cross-link plant proteins changing elasticity, water retention, and mouthfeel (Kieliszek et al., 2026). These microbial methods increase protein digestibility and unlock bound minerals (Samantaray et al., 2026). Further, they replace chemical additives with natural biological processes.

Genomics and metabolomics identify and amplify specific health-promoting compounds in traditional crops. Researchers have reported successful application of genomics to enhance bioactive and phytoconstituents which would have potential in fortified milk production. Genome editing tools like CRISPR-Cas9 have also been utilized to enhance the amylose content (Sun et al., 2017b). An increased expression of zeaxanthin, violaxanthin and lutein by targeting the downregulation of the epsilon cyclase gene using RNAi technology has been reported in mustard (Yu et al., 2008). Transformation of bHLH transcription factor gene, VvbHLH1 from grapes into Arabidopsis, resulted in an increased accumulation of flavonoids (Wang et al., 2016). A pathway engineering to increase the content of novel flavonoids especially stilbenes in the flesh of the tomato fruit is reported by Schijlen et al., 2006. Metabolomics profiles small-molecule chemical fingerprints in plants to identify health-promoting secondary metabolites like flavonoids, polyphenols, and antioxidants (Suruthi et al., 2025). Researchers can use these chemical maps alongside breeding and microbial treatments to boost nutritional value and stress resilience in traditional crops (Karalija et al., 2025).

IX. RECENT TRENDS AND PROSPECTS

Metagenomic studies of plant-based, fortified milk alternatives evaluate microbial profiles, fermentation dynamics, and how nutrients or plant substrates shape bacterial consortia, safety, and nutrient bioaccessibility. Next-generation 16S rRNA and shotgun metagenomic sequencing map live bacterial and fungal communities in commercial or fermented plant milks (soy, oat, almond, coconut) (Part et al., 2023). Metagenomic surveillance helps detect shifts indicating post-processing contamination or unwanted pathogen survival in neutral-pH, high-moisture plant beverages (Zulqarnain et al., 2026).

Plant-based proteins are becoming innovative and fast-growing ingredients across various food application industries due to a large number of benefits over animal-derived proteins. Various technologies help improve the functional and nutritional properties of plant-based proteins. Engineering high-protein plant milks from soy, pea, and chickpea bases transforms traditional low-protein nut milks into nutrient-dense alternatives, matching dairy milk's protein content (8 g per cup) (Langyan et al., 2022). This method enhances amino acid profiles, texture, and stability through precise blend ratios and functional processing. Combining soy, pea, and chickpea covers individual amino acid gaps, creating a balanced protein profile. It reaches

7 g to 9 g of protein per cup and retains natural dietary fibre, iron, and potassium from the legume bases (Lee et al., 2024). However, drawbacks include protein settling at neutral pH; high-pressure homogenization reduces droplet and particle size to keep emulsions suspended. Lipoxygenase enzymes in raw legumes cause grassy/beany tastes (Snir et al., 2025).

Advanced micronutrient fortification in plant-based or alternative milks uses targeted vitamins like D_3 and B_{12} and minerals to match cow's milk nutrition. This process helps to meet the required level of nutrients without drinking dairy products (Xie et al., 2026). Currently, vitamin D_3, vitamin B_{12} and calcium and minerals are added to help the body absorb calcium and support strong bones and protect nerves and make healthy red blood cells. These formulated products are designed for easy absorption since they have good bioavailability. The benefits are better health and are friendly for people of all types of food habits and nutrient balance (Bagheri et al., 2026). Micronutrient deficiencies continue to be widespread among children under five in low- and middle-income countries (LMICs), despite the fact that several effective strategies now exist to prevent them. This kind of malnutrition can have several immediate and long-term consequences on physical and mental well-being (Allen et al., 2006). Research evidence further supports the importance of reducing the burden of micronutrient malnutrition in children through such fortification methods. Population and context should be considered when selecting one or more appropriate interventions for programming (Tam et al., 2020).

Recent trends in plant-based fortified milk focus on mimicking the complex nutritional delivery and texture of the dairy matrix. Manufacturers are moving past basic calcium and vitamin D additions to use advanced nano-emulsions (Kaptan et al., 2024), protein blending (like pea and soy), and bioactive plant extracts to boost nutrient absorption and stability. Specialised calcium salts and liposomal delivery systems (Messersmith and Nguyen, 1998) are used to prevent mineral precipitation and improve bioavailability within the plant liquid matrix. This encapsulation shields the mineral from reactive counter-ions (such as phosphates or sulfates) in a liquid matrix, greatly enhancing stability, preventing lockout, and increasing cellular uptake and bioavailability (Erceg et al., 2022). Encapsulation stops mineral fallout or particle aggregation in complex liquid solutions, preserving a homogeneous suspension (Luo et al., 2025). It also protects payload integrity against shifts in pH, ionic strength, or temperature fluctuations common in complex liquid matrices (Yang et al., 2022).

Nanotechnology transforms plant-based and fortified milk alternatives by reducing particle sizes to the nanoscale (Altaf et al., 2026). This innovation significantly improves nutrient bioavailability, masks unappealing tastes of added minerals or plant extracts, and stabilises emulsions without altering texture (Biswas et al., 2022). Nano-emulsions disperse hydrophobic vitamins and minerals uniformly into aqueous plant bases (almond, soy, rice milk) for maximum absorption (Biswas et al., 2022). Research implicates the delivery of natural antioxidants, vitamins, and minerals (like iron and calcium) via nano-emulsions to prevent chalky textures or metallic aftertastes. Also, it optimises mucus penetration and controlled nutrient release during digestion (Liu et al., 2025). Finally, embedded antimicrobial nanocoatings and nanosensors enable monitoring of real-time spoilage and extend product shelf life (Ramani et al., 2024).

Using Pulsed Electric Fields (PEF) and ultrasonication together is an effective non-thermal method to kill spoilage microbes in plant-based milk (Wang et al., 2026). These techniques use short electrical pulses and sound waves to break cell walls without high heat, which keeps heat-sensitive vitamins like Vitamin C and B-complex intact. Sonication reduces particle size, which improves the physical stability and mouthfeel of the plant milk (Sotelo-Lara et al., 2024). Using both methods lowers the needed energy intensity, preventing local hot spots and fully protecting added nutrients (Ahmed et al., 2021). Another method, Ultra-High-Pressure Homogenization (UHPH), creates nano-emulsions that drastically improve physical stability and extend shelf life without heavy reliance on gums (Mengistu et al., 2025).

X. DISCUSSION

Changes in consumer preferences, culinary settings, labelling regulations, and demographics have all been cited as drivers of the shift in dairy consumption. Sales of plant-based milk rose by 20% in 2020, with yearly revenue growth that was twice as fast as that of dairy milk (Ramsing et al., 2023). In 2020, a projected 40% of families bought plant-based milk, accounting for 15% of retail milk sales. Almond, coconut, flaxseed, oat, rice, and soy milks are some of the most well-known commercial plant-based milk substitutes that have gained popularity in recent years. To be utilised in comparable applications, plant-based milk alternatives are usually made to resemble cow's milk in terms of appearance, texture, flavour, and shelf life (Rehal et al., 2025).

Regarding nutrition and health benefits, the PBMP offers a number of advantages. Additionally, their environmentally friendly operations cause less pollution. Protein, calcium, vitamins, and fibre are among the vital nutrients that PBMP are a good source of (Craig and Fresán, 2021). The bioactive components in PBMP include polyphenolic compounds, phytosterols, isoflavones, bioactive peptides, and saponins (Irondi et al., 2025). Additionally, people who are lactose intolerant can consume PBMP because it is said to be free of lactose and cholesterol. From a community nutrition and global malnutrition perspective, plant milk fortification adds essential vitamins and minerals — like calcium, vitamin D, vitamin B_{12}, and protein — to plant-based alternatives (such as soy, almond, or oat beverages). This process helps prevent micronutrient malnutrition and nutritional deficiencies in populations (Sonya Good et al., 2026).

PBMP is a superior substitute for animal-based milk because of its high unsaturated fat content and low saturated fat content (Röös et al., 2020). Compared to other PBMP types, soymilk is said to have a higher potassium concentration. Because of its many health-promoting properties, PBMP can be categorised as a nutraceutical or functional food (Aydar et al., 2020). Bioactive components in PBMP have been demonstrated to offer several significant health advantages, such as improving brain development and bolstering the immune system, reducing the risk of diabetes mellitus, atherosclerosis, coronary heart disease, neurodegenerative diseases like Alzheimer's disease, and preventing certain types of cancer (Veena and Nath, 2018).

Customers are becoming more inclined to buy plant-based milks due to their interest in sustainability as well as their concern for the environment and animal welfare. According to studies, consumers of dairy and plant-based milks concur that sustainability is crucial for the greater good (Nowson et al., 2025). Poorer digestibility, anti-nutritional factors, lower levels of important amino acids (particularly leucine), and deficiencies in other critical amino acids, like sulfur-containing amino acids, are some of the PBMP's disadvantages (Park et al., 2021). Because PBMP is highly susceptible to physical, chemical, and microbiological deterioration, more study may be done to produce immediate PBMP in powder form, which would have a longer shelf life while maintaining the mix of nutrients and bioactive substances. There are chances for research and innovation in a number of PBMP areas to strengthen, improve, and enhance.

The manufacturing techniques used to create plant-based milk alternatives should ideally result in a finished product that shares some structural and compositional characteristics of cow's milk. Since the fat globules and casein micelles give cow's milk its milky colour and creamy texture, its colloidal nature is very important in achieving its desired quality qualities (Scholarly community encyclopedia, 2026). Milk's flavour character is also significantly influenced by the carbohydrates and salts it contains. Therefore, colloidal fat and/or protein distributed in an aqueous solution comprising carbohydrates and salts is the characteristic composition of plant-based goods (Rachtan-Janicka et al., 2025). Therefore, one of the main areas of study and development is the creation of mimicked fat globules using plant-based substances and the breakdown of the inherent structures of some plant materials to release oil bodies or other colloidal particles. A homogenisation procedure is used to mix plant-based substances to create an emulsion. The type of ingredients and unit operations used have a significant impact on the stability and characteristics of this form of colloidal dispersion. This is another area that needs more research inputs.

To enhance the functional qualities of plant-based milk substitutes, a range of additional ingredients can be added. Many types of biopolymers with different molecular, physical, functional, and biological characteristics can be used as thickening agents (Yiu et al., 2023). These substances, which include minerals, vitamins, nutraceuticals, colours, flavours, or preservatives, improve the qualitative characteristics, nutritional profile, or safety of plant-based milk alternatives. To use a wide variety of additives, research on the components and their functions is necessary. Manufacturers must comprehend the key elements influencing the physical, functional, and sensory qualities that customers find appealing in plant-based milk substitutes, such as texture, appearance, and stability (Baranwal et al., 2022).

The possible chemical instability of any nutrients or nutraceuticals added to plant-based milk substitutes must also be taken into account. Many of these bioactive substances, such as ω-3 fatty acids, carotenoids, quercetin, resveratrol, and oil-soluble vitamins, are chemically labile molecules that break down over time (Pinto et al., 2016). Therefore, it is crucial to understand the reaction mechanisms involved and identify key factors affecting their degradation rate — such as pH, metal ions, temperature, oxygen, and light exposure. Based on this understanding, suitable strategies can be developed to prevent chemical degradation during storage of plant-based milk alternatives. Since plant-based milks play a significant role in making diets more affordable for financially constrained households, researching ways to reduce their cost should also be a fundamental part of this investigation.

XI. CONCLUSION

A significant development in food science, plant-based milk substitutes provide consumers all over the world with sustainable and health-conscious options. They contribute to increased nutritional diversity by offering a workable alternative for people with lactose intolerance, milk allergies, and plant-based diets. Their significance in the future of food systems is highlighted by their function in improving environmental sustainability by reducing greenhouse gas emissions and water consumption in comparison to traditional dairy production and by promoting public health. Technological developments in processing and fortification are resolving difficulties like sensory appeal and nutritional balance.

This review has comprehensively examined the sources, production methods, nutritional and nutraceutical qualities, sensory attributes, bioavailability, and biotechnological advances of plant-based milk products. The evidence presented demonstrates that PBMP offer significant potential as functional foods that can contribute to human health, environmental sustainability, and food security. However, challenges remain, including improving protein quality, addressing antinutrient concerns, enhancing sensory properties, and ensuring the stability of fortified nutrients. Future research should focus on developing improved processing technologies, optimizing fortification strategies, understanding the mechanisms of bioactive compound bioavailability, and conducting rigorous clinical studies to validate the health benefits of PBMP. As the plant-based milk market continues to grow, continued innovation in food science and biotechnology will be essential to meet consumer demands for nutritious, sustainable, and delicious plant-based alternatives.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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