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Impact of Novel Food Processing Techniques on the Physicochemical, Dietary, Sensory, and Safety Characteristics of Plant-Based Non-dairy Drinks

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Abstract

Cow's milk (CM) is a staple in numerous diets due to its comprehensive nutritional profile, providing all essential nutrients required for human health. It is widely consumed as a beverage and incorporated into various culinary applications, including coffee, tea, milkshakes, and a broad range of dairy-based products such as ice cream, curd (or yogurt), cakes, and confections. Nevertheless, CM is not a good option for many people because of the reasons like lactose intolerance, allergies to milk proteins, metabolic diseases (for instance, galactosemia where the body cannot process galactose), and dietary restrictions due to different reasons like veganism, plant-based preferences, or religious and cultural practices that do not allow them to eat dairy products at all. Not only this, but also there have been many discussions on the possible health risks of dairy consumption, such as acne, high saturated fat intake, and cardiovascular disease. Plant-based Milk (PbM) alternatives have come up to satisfy the ever-increasing demand for Non-dairy substitutes that not only visually and texturally resemble CM but also have similar functional properties. These alternatives come with environmental benefits as well, among which is the eco-friendliness of the PbM production chain, and also the reduction of carbon emissions when compared to the dairy industry. However, the nutritional quality of PbM products is very often lower than that of the Plant-based Drinks (PbD) in terms of flavor, texture, and solubility, which makes it very difficult for these products to be accepted by a wider audience and be competitively positioned in the market. The most common method of microbial stability and shelf-life extension is thermal processing, while at the same time, high temperatures may lead to the loss of sensitive chemicals and may also raise specific unfavorable reactions, which result in the decrease of protein digestibility and amino acid bioavailability in Non-dairy PbD alternatives. To address these limitations, innovative non-thermal technologiessuch as high-pressure processing, pulsed electric fields, and ultrasoundare being explored for their potential to enhance product stability, nutrient retention, and sensory appeal without compromising safety. Even though the results from the preliminary stages were very encouraging, studies that were done on these

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new techniques and their effect on PbD are still very limited. So, research in the future should mainly focus on interdisciplinary cooperation to move forward with the development of PbM products that are suitable for health, nice to eat and drink, and different from each other according to the needs of the consumers.

Introduction

Over the past two decades, the consumption of Non-dairy plant-based drinks (PbD), commonly referred to as plant-based milk (PbM), has increased substantially. These beverages are typically derived from legumes (e.g., soybeans), cereal grains (e.g., rice), or nuts (e.g., walnuts), and their growing popularity is driven by nutritional and environmental concerns, lactose intolerance, and the rise of flexible dietary preferences despite ongoing challenges related to flavor and sensory appeal. According to Markets and Markets (Al-Yateem et al., 2023), the PbD market was projected to grow by 17% by 2022, reaching a valuation of approximately $18 billion. In addition, it is anticipated that the market share of non-dairy PbD products will amount to 6% of the overall market for dairy and dairy alternatives in 2027 (Kravets, 2021; Munekata et al., 2020). Not only replacing milk directly, but the production of PbD products is combining with such a variety of culinary applications. In general, these kinds of drinks are made by methods such as fermentation, grinding, and filtration, which take some plant materials and water, and then the remaining product consists of about 92% water.

The conventional use of the term "milk" for PbD alternatives is nutritionally ambiguous. While the general nutrition of PbD is typically less favorable than that of CM, some varieties like those from barley and soybeans stand out with relatively high protein content. PbD does not usually contain lactose and lower amounts of lipids compared to CM, but most preparations are supplemented with basic micronutrients, notably calcium and vitamin B12, to make them nutritionally more adequate. The primary sources of PbD are cereals (e.g., oats, quinoa), legumes (e.g., soybeans, peanuts), nuts (e.g., almonds, walnuts), seeds (e.g., flax, hemp), and pseudo-cereals (e.g., amaranth). Due to the functional characteristics being linked to the richness of bioactive constituents in these plant commodities, these have recently been identified as having potential for the production of new food applications. Bioactive constituents such as phytosterols, lignans, flavonoids, and phenolic acids influence the physicochemical behavior and interactions of food components. Anticancer activities, radiation protection, antimicrobial activity against pathogenic bacteria, lipid-lowering effect, and cardiovascular disease prevention are among many other significant health benefits that the plant polyphenols, incidentally great antioxidants (Sorrenti et al., 2023), provide.

PbD, as Non-dairy milk alternatives, have established a distinct position in the food industry due to their absence of lactose and cholesterol. Additionally, most PbD products are visually similar to milk from animals, boosting their consumer acceptance (Silva et al., 2020). They still have some specific sensory characteristics, kinetics of equilibrium, and nutrition of their own. The extracts of PbM alternatives are nothing but pureed and filtered homogenates of the plant matrices. They act as colloidal systems containing two phases, which are continuous aqueous and dispersed solid phases. The dispersed phase can have protein fractions, starch granules, insoluble plant solids, and cholesterol droplets, as indicated by Codina-Torrella et al. (2017).

Nguyen (2022) summarize and classify non-thermal processing methods that can be used for enhancing the sensory qualities, nutritional profile, and stability of plant-based beverages. Such methods are high-pressure processing (HPP), pulsed electric fields (PEF), and ultrasound. Kumar and Kumar (2020) have to report as references plant-based milks in their review regarding nutritional content, processing challenges, and potential health benefits. Consumer trends and market acceptance are also part of the discussion. Sethi et al. (2016) reviewed the various plant-based Drinks from nutritional composition to sensory characteristics and processing steps comprehensively in order to attract consumer acceptance and quality.

During the years 2010 to 2023, there was a massive increase in research activity on the topic, which was nicely illustrated in Fig. 1, which showed a significant

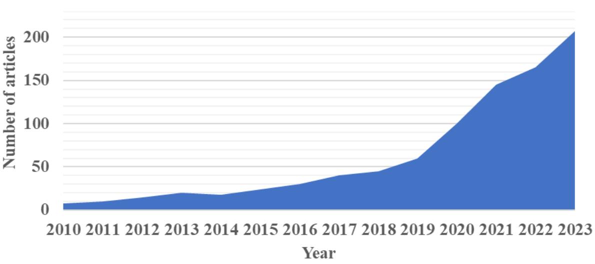

Fig. 1 Number of documents recovered from the Scopus repository
Source: Bocker & Silva (2022)

rise in the quantity of articles that the Scopus database located by searching with the term PbD. The PbM industry has to guarantee that the products are of high quality and safe for human consumption. Food and drinks are generally pasteurized for the purpose of extending their shelf life by reducing the number of spoilage and pathogenic germs and by inactivating the natural enzymes. Consequently, PbD products are processed to improve microbial stability, minimize perishability, and preserve desirable sensory properties for consumers (McClements & Grossmann, 2021; Short et al., 2021a). Traditionally, pasteurization has been achieved by thermal processing, and the main effect of this process is the inactivation of microorganisms and food matrix-bound enzymes.

Traditional pasteurization is a thermal processing method for which the primary purposes are the inactivation of microorganisms and enzymes. In general, milk is pasteurized at temperatures from 63°C to 72°C, although ultra-high temperature processing can go as high as 135°C for a few seconds. In contrast with other heat applications such as sterilization and prolonged heat treatment, PbD can be exposed to a broader temperature range (e.g., 55–125°C) that would affect their nutritional, sensory, and physicochemical properties. There is interest in mild-thermal and non-thermal processes, such as ultrasound, pulsed electric fields, and high-pressure processing, as alternatives to traditional heat treatment methods. Appropriate technologies in this regard have the potential for inactivating enzymes and microorganisms responsible for spoilage without undesirable food quality changes (Iorio et al., 2019a; Lu et al., 2019).

Consequently, various methods of pasteurization using advanced new technology have been developed to improve product quality, as the significance of PbD as an alternative to milk in the market for agricultural produce is growing, along with its nutritional and sensory attributes. There has been a growing interest in technologies such as intense ultrasound (IU), high-pressure processing, microwave energy, pulsed electric fields (PEF), ohmic heating, the use of cryogenic carbon dioxide, and ultraviolet (UV) light. This investigation looked into the vegetable matrices typically employed in PbD production and the modern techniques utilized in their processing. Moreover, it took a shot at the obstacles and the trends that are coming up in relation to this rapidly changing area of food innovation.

The dietary and biologically active profile of the most frequently consumed PbD

Because of the critical role that amino acids play in various physiological processes, it is advisable to assess the contents of both essential and non-essential amino acids in plant-based drinks (PbD) when they are considered as possible substitutes for dairy milk.

Essential amino acids (EAAs) are those that the human body cannot synthesize and must therefore be obtained through the diet. The nine EAAs include lysine, methionine, threonine, tryptophan, and valine. The following amino acids are not essential for human survival: alanine, arginine, aspartic acid, glutamic acid, glycine, proline, and serine. These amino acids can be produced by the body naturally.

PbD exhibits considerable variability in composition compared to CM. The nutritional content and sweetness levels in PbM alternatives vary significantly depending on the manufacturing process and ingredient formulation. Fig. 2 demonstrates the most common PbD products regarding dietary ingredients and characteristics.

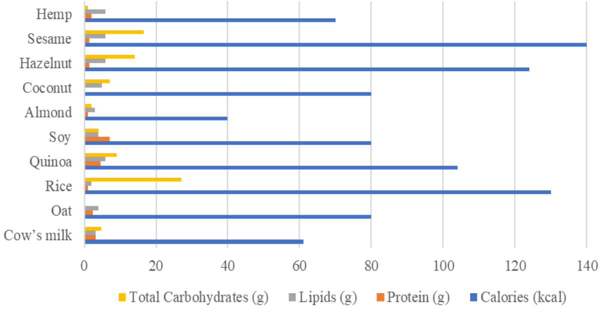

Fig. 2 Dietary and biologically active profile of the most consumed PbD
Source: Reyes-Jurado et al. (2023)

Nutritional content, functional properties, and important attributes of different types of milk are emphasized in Fig. 2, such as animal-derived milk (CM) and PbM alternatives.CM has moderate levels of calories, proteins, and fats, but the lack of some beneficial bioactive compounds is the major drawback. Milk, quinoa, and soy are all rich in proteins, but quinoa and soy are also rich in fats and minerals like manganese and phosphorus. Soy is, however, frequently associated with an undesired beany flavor, although it is well known for its health-promoting properties due to the presence of isoflavones and phytosterols (Pavalam & Kantor, 2023). (Alhendi et al., 2018) Among the various PbM types, almond and hazelnut milk, for instance, present low-calorie options, but at the same time, they can be allergenic, because almond milk contains amandin, which is one of the most common allergens. On the one hand, coconut and sesame milk are commonly credited for their specific functional benefits, like lactic acid, vitamin E, and lignans; however, on the other hand, sesame milk contains oxalates, which are considered antinutritional substances. The choice of alternative milk could be based on nutritional objectives, flavor acceptability, and possible allergenic or antinutritional factors (Sharma et al., 2024). The energy value of different plant drinks is quite variable according to their content.

The rice-based beverages have the highest energy content with an average of approximately 130 kcal mainly because they have large amounts of carbohy drates (Fig. 3). In the same vein, sesame, hazelnut, and coconut-based drinks also have high caloric contents varying from 100 to 130 kcal partly due to their high fat content. Soy and oat-based drinks have moderate energy contents, generally between 60–80 kcal, with soy milk being specially mentioned for its high protein content, more than caloric density. Hemp and almond drinks tend to be lower in calories, at about 30–50 kcal, since they contain more water and have relatively low-fat content. Cow's milk is about 60–65 kcal, which positions it with mid-range energy values. Different levels of calorific value indicate the different kinds of nutrition that can be obtained from the different plant sources. Rice, from the carbohydrates, is the most energizing choice, while soy is the most nourishing protein source, which gives balanced nutrition with moderate caloric density. Fig. 3: Caloric distribution across commonly consumed PbD and cow's milk.

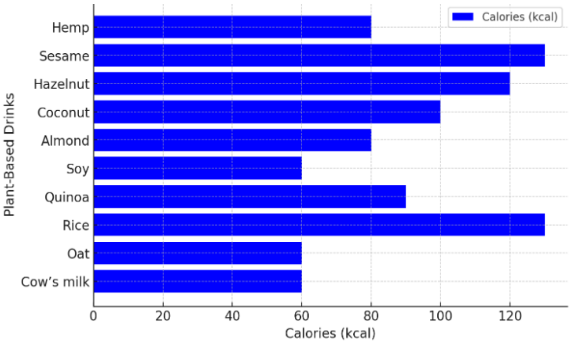

Fig. 3 Energy content of the various plant-based drinks
Source: Reyes-Jurado et al. (2023)

Furthermore, from a dietary standpoint, considering the emerging trend in several countries of decreasing CM consumption while increasing the intake of Non-dairy PbD, it is important to highlight that the nutritional value of these PbD differs significantly from that of CM. Replacing CM with Non-dairy PbD may result in lower intake of calcium, vitamin D, and other important micronutrients. The use of salt in particular formulations might lead to increased sodium consumption, as shown in Fig. 4.

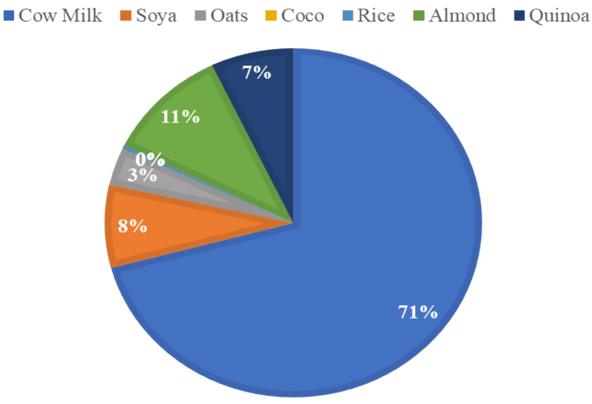

Fig. 4 Calcium levels (mg/250ml) in CM and PbM
Source: Silva et al. (2020)

Furthermore, from a health point of view, CM intake cannot be replaced with that of PbD due to its different nutritional content (Silva et al., 2020; Aydar et al., 2020). For this reason, such alternative foods, in the case of possible deficiencies of calcium and vitamin D, among other micronutrients, must be treated with care. Any nutritional deficiencies should be offset through a proper diet, especially when CM is not consumed for reasons involving allergy, intolerance, or other personal, religious, moral, or psychological factors.

Manufacturing stages in the design process of PbD

The dietary limitations of PbD can be addressed by fortifying them with essential nutrients. In addition, the drinks can be obtained from several plant matrices, which further increases their protein variety Sadulla (2024). The procedure, known as blending, increases the nutritional value of the final beverage because it can be prepared using more than one vegetable base, each with different dietary and physicochemical characteristics. The steps in the processing of PbD vary depending on the raw material. Despite this, the complete processing

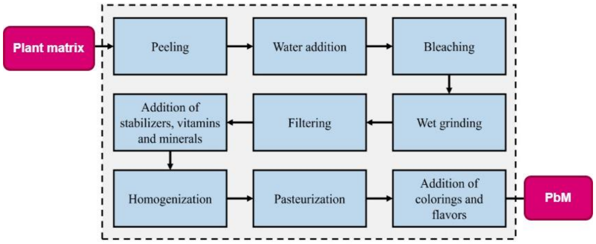

Fig. 5 Manufacturing stages in the design process of PbM
Source: Bocker and Silva (2022)

of different plant-based feedstocks to produce PbD involves similar unit operations. Thus, Fig. 5 presents a general structure of the processing chain to obtain PbD.

1. Selection of raw materials and pre-treatment

However, the unit operations for processing different plant-based raw materials to obtain PbD are similar. According to Rivera del Rio (2022), enzymatic therapies have the potential to enhance protein bioavailability.

2. Filtration and grinding

As noted by Mondor et al. (2012). particle size reduction and filtration technologies, including micro- and ultra-filtration, are significant factors in determining texture and stability.

3. Pasteurization and heat treatment

Sethi et al. (2016) recommended exploring how different pasteurization procedures affect the denaturation of proteins and amino acid retention. HPP and PEF are non-thermal alternatives that have demonstrated the ability to preserve nutritional and sensory qualities more effectively than conventional heat treatments. (Lu et al., 2019).

4. Stabilization and homogenization

One important consideration in the formulation of PbD is that emulsifiers and stabilizers often extend the shelf life and prevent phase separation, as stated by McClements & Grossmann (2021).

5. Fortification & packaging

More studies are required to establish whether micronutrients included at the time of fortification are retained and stable throughout storage (Short et al., 2021b).

Processing stages for PbD mainly depend on the physicochemical properties of the designated vegetable substrate, so that the production of soluble extract is at its best. The upfront processing of plant materials has the latter's characteristics as the independent variable. In a nutshell, nuts and seeds are undergoing de-shelling, whilst grains, muesli, and fruits receive hot water soaking followed by drying. Besides, raw materials can be subjected to heating or acid and base (peeling) treatment to improve emulsion stability, eliminate toxins, and get a higher yield.

Afterward, the grinding process is carried out on the raw materials to decrease their particle size. The extraction of vegetable materials is also made easier and faster as the surface area of the ingredients in contact with the solvent is larger. The dry milling method is seldom adopted due to its being less energy efficient and also having a negative impact on the whitening process. The alternative to dry milling, which involves moistening the material, is a common practice in many processes that produce PbM substitutes. During the process of grinding, the temperature is also increased, but it is not considered a disadvantage since, on one hand, it helps grow the demand of the bleaching stage, while on the other, the demand for the processing time is also reduced. The microorganisms and the enzymes that were in the product are now significantly reduced by the bleaching process.

Bleeding, then followed by filtration, is used to obtain the water-soluble portion of the product. A common practice for prolonging the shelf life of the extract is the addition of antioxidants and stabilizers. The product may also be fortified with essential nutrients to increase its nutritional value. Homogenization improves the integrity of PbD by reducing the size of suspended particles without affecting either consistency or the composition of proteins. The final step in the preparation of PbD involves pasteurization. In most cases, ultra-pasteurization methods are employed as an efficient and fast means of making the product safe microbiologically and enzymatically.

Novel food processing techniques

New trends in procedures involving high-pressure analysis (HPA), pulsed electrical fields (PEF), and intense ultrasound (IU) are good alternatives to traditional heat treatments for stabilizing PbD.

1. HPA [HPP] (Fayaz et al., 2019)

HPA is a new non-thermal technology with pressures ranging from 150 to 1500 MPa. One of the disadvantages of HPP compared with traditional thermal processes is that it operates in batch mode. Conventional heat treatment is, in general, performed in continuous mode, allowing much higher throughputs to be processed in less time.

However, HPA [HPP] comes with numerous benefits in comparison with conventional pasteurization methods. Pressure acts on food in an isostatic, volumetric, and instantaneous manner and is evenly distributed throughout the product. This technique is still in use. Nonetheless, this treatment is more suitable for smaller batch sizes. The applied pressure makes it easier to carry out isothermal procedures, as a pressure increase of 150 MPa generally causes a temperature rise of about 4 to 8°C. In such conditions, proteins and enzymes are denatured, and microbial cell membranes are disrupted, thereby reducing microbial activity.

Moreover, HPA [HPP] alters the physical properties of microorganisms. The higher-pressure results in the fatty acids of the bacterial cell membrane being more and more comfortable in the membrane, which means the bacteria can pass through the membrane with even greater ease. This promotes ionic exchange fortification, which interrupts cellular functions and might lead to microbial lysis. The main action of HPA [HPP] is the inactivation of microorganisms. In addition to microbial control, HPA [HPP] contributes to the stabilization of food products and induces various physical effects on the components of the processed liquids. The breakdown, cavitation, turbulence, and pressure-induced stress associated with this method contribute to particle size reduction. Decreasing the size of particles improves the kinematic stability of the final product.

However, HPA [HPP] was not sufficient to maintain the homogeneity of a PbD prepared using soybeans. Therefore, the product underwent further heat treatment in order to enhance consistency. Heat accelerates the clumping of proteins during the process of thermal dehydration, which in turn affects the physical stability of the beverages. Hence, to assess the interaction of pressure, temperature, and processing time on the shelf-life of the product, treatments were given at 4, 108, and 180 MPa; 80 and 120°C; and periods of 10 and 35 min. The soy-based PbD treated at 180 MPa and 80°C for 35 min showed improved resistance to phase separation.

2. PEF (Suma et al., 2022)

PEF has been widely applied for the microbial and enzymatic inactivation of liquid foods, including PbD. This non-thermal technique operates typically at mild temperatures in the range of 35°C to 45°C, with low thermal damage to sensitive food components. In PEF processing, the food matrix is typically subjected to a high electric field for less than one minute. Such a field delivers steady pulses between 10 and 60 kV/cm to the product. This non-thermal method of treatment causes an osmotic potential that reduces the amount of microorganism's present (Iorio et al., 2019b). When this is done at certain levels, it results in the creation of holes in the structures of the microbial cells. The process whereby microbial cells become more permeable is known as electroporation. It ruptures the lipid membrane and hydrolyzes microbial proteins. Consequently, microbes are susceptible to external compounds that may permeate their structure, causing cell lysis.

Denaturation of enzymes by PEF treatment is through the breakage of protein structures. The changes in the structure of the enzymes, occurring after PEF application, have a negative impact on their catalytic activity. The impact of pulse frequency (120–650 Hz), bipolar pulse width (1–4 μs), and temperature (27°C) was examined on the inactivation of soy lipoxygenase by PEF treatment in soybean-based beverages (Glycine max). The highest inhibition rate of 88% was obtained at 500 Hz pulse frequency and 2.5 μs bipolar pulse width. Enzyme activity was significantly reduced under these conditions, which indicated that PEF processing can be a suitable alternative to conventional thermal treatments.

This novel method is not very effective in bacterial spore inactivation since the electrical pulses themselves are not sufficient to initiate spore germination. Additional treatments are thus commonly needed to induce the germination of endospores and their subsequent inactivation. These have included the addition of acidic ingredients, modification of water activity and pH, thermal energy, or the addition of antimicrobial agents like nisin. PEF treatment not only reduces microbial and enzymatic activity in food products but also maintains their nutritional value since it is a non-thermal approach. This has been seen in PbD manufactured from soya milk. Important nutrients were better retained in PEF-treated samples than in those treated by conventional pasteurization at 95°C for one minute. Both treatments were effective in ensuring the soy-based beverage was microbiologically stable.

3. IU (Bhargava et al., 2021)

Ultrasound is the designation of acoustic waves in the range of frequencies between approximately 30 kHz and 100 MHz. For food and beverage applications, ultrasonic techniques are usually classified by the frequency used: low-frequency ultrasound (20–150 kHz) and high-frequency ultrasound (150 kHz – 2 MHz). IU during the manufacturing process of PbD can allow for minimal nutritional loss and deactivation of natural enzymes. Besides, it decreases bacteria associated with spoilage and decomposition. Rheological changes might be induced by ultrasonic treatment. Promising results have been achieved by combining IU with heat or HPP to enhance microbial stability. This emerging technology relies on sound-induced physical phenomena; specifically, ultrasonic vibrations propagate through a fluid medium due to compressions and rarefactions.

Another consideration for future research is the effect of new processing methods on the bioavailability of beneficial compounds naturally occurring or added intentionally to PbD in order to create new functional beverages. Scientific experiments have corroborated that the phenolic compounds present in soymilk are taken up during the gastric-intestinal digestion and have the ability to scavenge the free radical species. Hence, it is likely that the marketing strategies can be heavily influenced by the products being, so to speak, "two birds with one stone": satisfying the extractions of food choice preferences and providing health benefits through bioactive compounds. For this reason, young consumers will be the leading target group for this marketing strategy. Thus, the ultrasound process is a step in the direction of particle size reduction, and simultaneously, it makes the product hydrophilic. Such an effect has been observed in the case of an almond drink, where the ultrasound therapy alters the physical characteristics of the beverage. The length of ultrasonic treatment has an influence on its physicochemical properties. The highest power was 110 W at 30 kHz for 0, 3, and 7 min. With the prolongation of the treatment time, the water-soluble solids were greater, the foaming capacity was improved, and the product's stability was higher. Moreover, the prolongation of the sonication duration led to a reduction in aggregate particle size and viscosity.

Consequently, the beverage prepared from nuts that have gone through ultrasonic processing was found to be more uniform, more resistant in terms of physical characteristics, and with a longer shelf-life. Besides that, IU has been chiefly the healthier method in the preservation of bioactive compounds, as it has less effect on rheological properties than the traditional heat treatment. The improved preservation is a result of the sudden pressure and temperature rise at the cavitation site, where microbubbles collapse within the medium. These conditions are conducive to the release and stabilization of heat-sensitive bioactive compounds without causing significant thermal degradation.

Consequently, during the application of ultrasound treatment, the overall temperature of the system does rise considerably. Nonetheless, this technique can support the pasteurization of the final product when combined with other mild treatments. Ultrasound-assisted processing induces minimal alterations to lipid characteristics and effectively reduces the microbial load in food products. Additionally, ultrasound leads to microbial cell membrane damage, where genetic material is more exposed, and microbial inactivation is enhanced.

In addition, the decline in enzymatic activity following ultrasound treatment is mainly caused by the formation of reactive oxygen species, which are formed in the medium as a result of sonolysis of water molecules. Acoustic cavitation facilitates the nano-process. Free radicals have a high level of reactivity and instability and will act with enzymatic proteins and form or donate electrons. As a result, enzymes undergo denaturation due to the disruption of their protein structures. Alternatively, free radicals may degrade ascorbic acid, accelerate lipid oxidation, and reduce the phenolic content of the product.

In addition, ultrasound shows a higher energy efficiency than that of the classical heat treatments. This superior performance is associated with the shorter duration of the ultrasonic treatment, which is the primary processing method. Besides that, ultrasonics is a technology that can be easily applied and allows volumetric heating with the least possible damage to the heat-sensitive components of the product.

Anti-nutrition factors in plant-based materials for PbD

The various plant-origin antinutritional factors of rice, almond, soy, and oat beverages not only reduce the bioavailability of minerals but also cause poor protein digestibility and impaired general nutrient absorption. Soy, almonds, and oats are notable sources of phytates, which bind to minerals and reduce their absorption. Similarly, tannins found in nuts and legumes inhibit iron absorption and interfere with protein digestion. Soybeans and other legumes have been found to possess trypsin inhibitors that again block the actions of digestive enzymes such as trypsin, thus impairing protein uptake. Furthermore, lectins, which are abundant in grains and legumes, can impede intestinal absorption and cause gastrointestinal discomfort. Oxalates in leafy greens and nuts create insoluble complexes with calcium and thus reduce its bioavailability. Despite the fact that these substances cause nutrient loss, soaking, fermenting, enzyme hydrolysis, sprouting, and heating can practically eliminate them. The treatments not only keep the plant-based drinks more digestible but also increase their nutritional value. Processing methods should therefore be optimized for enhancing the bioavailability of major nutrients in PbD preparations.

Novel processing effects on antinutritional components in comparison to conventional heatprocessing

To reduce antinutritional factors (ANFs) while preserving the nutritional quality in plant-based beverages (PbD), novel processing techniques like high-pressure processing (HPP), pulsed electric fields (PEF), and ultrasound (IU) offer substantial advantages over conventional thermal treatments.

1. Phytates

Phytate-reducing heat treatments like pasteurization and sterilization are not very effective in reducing phytates because of the high heat and lengthy processing involved, which also destroys other nutrients. Phytate degradation is better increased by HPP and enzymatic-assisted ultrasonic processing, which preserves heat-sensitive vitamins and other constituents.

2. Trypsin Inhibitors

Conventional heat treatments are very effective in killing the trypsin inhibitors present in soy-based drinks. However, with these techniques, the risk of denaturation of proteins and loss of essential amino acids does exist. On the other hand, PEF and HPP can inactivate trypsin inhibitors to a large extent without significantly altering the protein structure, thus making the functional proteins and digestibility intact.

3. Tannins

Heat processing is an effective method to reduce the quantity of tannin; however, when the thermal treatment is excessive, it can negatively affect PbD's nutritional and sensory properties. In contrast, ultrasound-assisted extraction (UAE) and high-pressure homogenization (HPH) have been shown to be more effective in lowering tannins without eliminating antioxidant activity, thus improving flavor and stability of the product.

4. Lectins

Lectins can be destroyed through proper heat treatment; too much heat, however, can easily destroy the nutrients that are sensitive to heat. In order to efficiently inactivate lectins with minimal nutrient loss, a combination of mild heat, enzymatic hydrolysis, and HPP is commonly employed.

5. Oxalates

The heat treatment of the raw material decreases the oxalate level, but it can also cause an undesirable change in the texture and flavor of the resulting plant-based product. There is a great deal of potential for ultrasound and fermentation processing to reduce the oxalates while at the same time improving the bioavailability of the related minerals.

New processing techniques are more precise and efficient in ANF reduction than traditional heat treatments, and at the same time, nutritional quality is not affected. The new technologies take the place of the standard thermal methods, for they bring to the surface the bioactive aspects while on the other hand increasing protein digestibility and mineral bioavailability.

Table 1 Effects of Novel Food Processing (HPP, PEF, and IU) on PbD

Processing method	Physicochemical effects	Dietary & Nutritional impact	Sensory characteristics	Safety & Microbial stability
High-Pressure processing (HPP)	- Modifies protein structure, improving solubility and stability - It decreases phase separation, thus and consequently enhances homogeneity. - Increases viscosity and alters rheological properties	- Reduces antinutritional factors (e.g., trypsin inhibitors, phytates) - Preserves vitamins and bioactive compounds better than thermal methods - It makes proteins more digestible	- Retains natural color, taste, and texture more effectively than heat treatments - Enhances sensory texture (mouthfeel) and reduces grittiness	- Inactivates bacteria, yeasts, and molds by disrupting cell membranes. - Not effective against bacterial spores; may need to be combined with other treatments.
Pulsed electric fields (PEF)	- Minimal effect on chemical composition and pH - Reduces particle size, improving colloidal stability - Limits phase separation, improving emulsion stability	- Maintains protein functionality and lipid integrity - Preserves heat-sensitive vitamins and antioxidants - Decreases enzyme activity (e.g., lipoxygenase in soy-based drinks)	- Preserves original flavor and aroma by avoiding thermal degradation - It keeps the original texture and viscosity	- Inactivates microorganisms via electroporation - Ineffective against bacterial spores - It needs to be combined with other methods for a complete microbial safety claim.
Ultrasound (IU)	- Enhances solubility and dispersion of ingredients - Reduces particle size, enhances texture and stability - Alters surface tension and viscosity.	- Retains high levels of polyphenols, antioxidants, and vitamins - Reduces enzyme activity and antinutritional factors - Improves nutrient bioavailability	- Enhances creaminess and reduces sedimentation - Maintains fresh taste and color compared to heat treatment	- Disrupts microbial cell membranes, enhancing safety - May generate free radicals requiring control to avoid oxidative degradation

Compared to traditional heat processing methods, HPA, PEF, and IU boost microbiological stability, maintain sensory characteristics, and keep the nutrients intact without making undesirable chemical changes in PbD, as shown in Table 1 (Balasubramaniam et al., 2015).

Challenges and suggestions for subsequent research

The use of advanced food processing methods, such as HPP, PEF, and IU, for the preservation of PbD offers many advantages over traditional heat treatments. Nevertheless, the merging of such cutting-edge technologies with thermal processing is still a significant hurdle for the PbD industry, which is why they are not implemented yet. To address this, further efforts are needed to explore scale-up possibilities, as many of these technologies are currently limited to laboratory-scale applications. It is critical to specify processing conditions under continuous systems with high flow rates, in particular for the HPP technology.

Another important consideration for future research is the impact of novel processing methods on the bioavailability of beneficial compounds naturally present or intentionally added to PbD to develop new functional beverages. Scientific studies have shown that phenolic compounds in soymilk may be absorbed during digestion and exhibit antioxidant properties. This implies that marketing efforts may be supplemented by framing such products as having dual values: resolving individual diet considerations (e.g., lactose- and cholesterol-free) and offering health benefits in addition to that through bioactive compounds. Such an appeal is directly appealing to young consumers. Therefore, both technological and consumer research should focus on this demographic to support the development of new products, the adoption of novel technologies, and the definition of this emerging niche within the food industry.

Conclusion

The amount and quality of plant-based drinks (PbD) have been remarkably improved because of the new methods of processing, such as high-pressure processing (HPP), pulsed electric fields (PEF), and ultrasound (IU). These methods provide effective microbial deactivation, enzyme control, and product protection with less loss of essential nutrients and flavor qualities compared to conventional heat treatments.

The impact of these techniques is drastic regarding the ANFs reduction, where the likes of tannins, phytates, trypsin inhibitors, and lectins are entirely eliminated, thus, the nutritional profile of PbD is augmented with an increase in both the protein digestibility and mineral bioavailability. The distinction between the traditional thermal processing and HPP, PEF, and IU lies in the fact that the latter not only annihilates sensitive vitamins, antioxidants, and bioactive compounds but also plays a role in the preservation of these beneficial components.

These technologies have been the primary source of providing nutrition, improving stability, and prolonging shelf life, as well as better sensory properties. HPP and IU, in particular, contribute to better texture, phase stability, and homogeneity, which in turn lead to better consistency and consumer acceptance. PEF very effectively retains the functional properties of proteins and lipids, thereby causing only slight alterations to taste and texture. Moreover, by reducing the thermal load and processing time, these methods result in greater energy efficiency and also support a more sustainable production practice. Thus, they become the preferred option for large-scale production of PbD, matching the demand of consumers for healthy, natural, and minimally processed drinks.

To conclude, the utilization of new processing technologies in PbD has a remarkable impact as the quality of nutrition, sensory, and energy efficiency has been uplifted to a great degree, whereas the safety and stability have not been affected at all. Besides, the research openings that come after this will only serve to further elaborate on the PbD formulations and thus to provide a better and more sophisticated way to cope with the demands of the health-conscious and sustainability-driven consumers who are constantly changing.

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