# ผลกระทบจากการแปรรูปขั้นสูงและสารเติมแต่งในผลิตภัณฑ์เนื้อจากพืชต่อสุขภาพหัวใจและหลอดเลือด

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**บทคัดย่อ**

ผลิตภัณฑ์เนื้อจากพืช ได้รับความนิยมเพิ่มขึ้นจากการเป็นผลิตภัณฑ์ทางเลือกแทนเนื้อสัตว์ หลายงานวิจัยกล่าวถึงข้อดีของผลิตภัณฑ์เนื้อจากพืชว่าสมีผลดีต่อระดับไขมันในเลือดหรือดัชนีมวลกายเมื่อเทียบกับเนื้อสัตว์ อย่างไรก็ตามความกังวลเกี่ยวกับกระบวนการแปรรูปขั้นสูงอาจส่งผลกระทบต่อสุขภาพ โดยเฉพาะอย่างยิ่ง โรคหัวใจและหลอดเลือด รวมถึงยังไม่มีการศึกษาหรือทบทวนวรรณกรรมที่เน้นวิเคราะห์ผลกระทบของวิธีการแปรรูปขั้นสูง และ การใช้สารเติมแต่งในผลิตภัณฑ์เนื้อจากพืชต่อสุขภาพหัวใจและหลอดเลือดโดยเฉพาะ ทั้งที่ผลิตภัณฑ์เนื้อจากพืชส่วนใหญ่จัดอยู่ในกลุ่มอาหารที่ผ่านการแปรรูปขั้นสูง โดยอาจลดทอนประโยชน์ที่คาดหวังไว้ วัตถุประสงค์ของการทบทวนนี้คือเพื่อรวบรวมและให้ข้อมูลผลกระทบของกระบวนการแปรรูปขั้นสูงในการผลิตภัณฑ์เนื้อจากพืชต่อสุขภาพหัวใจและหลอดเลือด เพื่อเป็นแนวทางในการพัฒนากระบวนการรวมถึงองค์ประกอบที่ปลอดภัยและเป็นธรรมชาติมากขึ้น เพื่อให้ส่วนผสมในผลิตภัณฑ์เนื้อจากพืช มีความปลอดภัยและป้องกันผลกระทบต่อสุขภาพตามมาได้ นอกจากนี้การศึกษาผลกระทบด้านสุขภาพในระยะยาวเป็นสิ่งสำคัญสำหรับการประเมินความเสี่ยงและประโยชน์ของผลิตภัณฑ์เนื้อจากพืช รวมถึงการพัฒนาสูตรที่มีคุณค่าทางโภชนาการสูง เช่น การลดโซเดียม และการเพิ่มธาตุเหล็ก วิตามินบี 12 และกรดไขมันโอเมก้า-3 เพื่อส่งเสริมสุขภาพหัวใจที่ดี

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# Impact of Ultra-Processing Methods and Food Additives in Plant-Based Meat Products on Cardiovascular Health

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## Abstract

Plant-based meat (PBM) products have gained popularity as an alternative to meat from animals. However, concerns about the ultra-processed and food additives of these products may an impact on health, especially those related to cardiovascular diseases (CVDs). Many studies have highlighted the benefits of PBM products in improving blood lipid levels or body mass index (BMI) compared to animal meat. However, concerns have been raised about the potential health impacts of advanced processing techniques, particularly regarding CVDs. Moreover, there is a lack of studies or reviews specifically analyzing the effects of advanced processing methods and additives in PBM products on cardiovascular health, even though most are classified as ultra-processed foods, which may diminish their expected health benefits. This review aims to provide information about the nutrients and non-nutrient composition, focusing on ultra-processing methods of PBM related to cardiovascular health. To suggest developing safety and dietary guidelines and preventing complications of health problems. Additionally, long-term health effects are necessary for evaluating the risks and benefits of PBM. In further study, the nutritionally optimized products will be formulated to be low in sodium and added with iron, vitamin B12, and omega-3 fatty acids to promote cardiovascular health.

**Keywords:** Plant-based meat products, Food additives, Ultra-processing, Cardiovascular health

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## Introduction

Plant-based meat (PBM) is an alternative meat made from plant-based ingredients intended to simulate the taste and texture of meat[1]. The global market for meat alternatives is projected to reach $8.1 billion by 2026, growing at a 7.8% compound annual growth rate from 2019 to 2026. This development is caused by increasing consumer attention to the health risks related to meat consumption and inadequate protein intake. The demand for PBM alternatives rises because more consumers follow healthier and more sustainable food choices[2]. The major components in PBM consist of proteins, fats, stabilizers, and flavoring agents, each contributing to the final texture, structure, and taste of the product. Focusing on protein sources includes legumes (soy, peas, and lentils), cereals (wheat, rice, and oats), oil seeds (hemp and sunflower), and algae, with soy and pea proteins being particularly valued for their ability to create a meat-like texture. Fats and oils, such as coconut oil, sunflower oil, and cocoa butter, provide the juiciness and mouthfeel of the PBM, while stabilizing agents, such as carrageenan, methylcellulose, and starch, provide proper consistency. Enhance flavor and appearance, including natural colorants (beetroot, lycopene, etc.) and taste enhancers (yeast extract, mushroom powder, and spices). These components are processed using technologies like extrusion, 3D printing, and shear cell processing to develop a fibrous texture that resembles standard meat, improving consumer acceptance[3]. Recent randomized controlled trials (RCTs) have suggested potential cardiometabolic benefits of PBM. For example, Bianchi et al. investigated 115 healthy adults to evaluate the effects of replacing meat with mycoprotein-based, vegetable-based, and pulse-based meat substitutes over 4 weeks and follow-up at 8 weeks in the UK. The results showed significant decreases in LDL-cholesterol (−0.16 mmol/L; 95% CI: −0.28 to −0.04; $p = 0.009$) and total cholesterol (−0.25 mmol/L; 95% CI: −0.38 to −0.12; $p < 0.001$), as well as moderately decreased body weight (−0.59 kg; 95% CI: −1.06 to −0.12; $p = 0.015$). However, there are no significant differences in body fat percentage[4]. Moreover, Crimarco et al. researched in the USA (the SWAP-MEAT trial) with 36 healthy adults (66.7% female) to compare the effects of PBM and animal-based meat over 8 weeks (intervention group replaced meat with PBM and the control group consumed two servings of meat per day). The results found that the PBM group significantly reduced LDL-cholesterol (−0.33 mmol/L; 95% CI: −0.48 to −0.18; $p < 0.001$), trimethylamine-N-oxide (TMAO; A gut microbiome metabolite linked to cardiovascular risk) (−3.74 μM; 95% CI: −6.75 to −0.74; p = 0.02), and body weight (−1.09 kg; 95% CI: −1.73 to −0.45; p = 0.001). Nevertheless, no significant effects were found for fasting glucose, insulin, or IGF-1 levels, suggesting that PBM may improve cholesterol and microbiome-related markers but not blood sugar control[5]. Furthermore, Crimarco et al. examined the impact of PBM on inflammatory biomarkers in a secondary analysis of the SWAP-MEAT trial. The analysis found that IL-7 (mean difference: −0.20 pg/mL; p = 0.043) and neurotrophin-3 levels (−0.27 pg/mL; p = 0.019) were significantly reduced in the PBM group, implying potential anti-inflammatory benefits. However, no significant changes were observed in other inflammatory markers, including IL-6, IL-18, TNF-α, IL-12β, IL-10, and TGF-β (all p > 0.05)[6]. However, these studies often focus on short-term benefits and compare PBM to red meat without isolating the effects of processing methods or food additives, which are key distinguishing features of PBM products.

On the other hand, increasing concerns have been raised regarding PBM products being classified as processed or ultra-processed foods (UPFs), mainly due to food additives, stabilizers, and intensive processing methods. According to recent systematic reviews, many PBM formulations contain high levels of sodium, saturated fat, and added sugars, which are nutrients related to adverse health effects when consumed in excess. Additionally, the nutritional composition of PBM varies widely across products and may not offer the same health benefits as whole-food, plant-based diets[7]. Although most PBM products are under the UPF category, no comprehensive review has addressed how ultra-processing and food additives in PBM may influence cardiometabolic health. Therefore, based on clinical, experimental, and epidemiological evidence, this review critically evaluates the potential cardiovascular impacts of PBM on their processing methods and additive content.

## 1. Main ingredients in PBM

PBM are plants food products that directly replace animal-based meat, including poultry and seafood. They are also referred to as meat alternatives or analogs. Although plant protein isolates and textured vegetable protein are common ingredients in plant-based meats, they are not considered the final consumer product. The processing of PBM involves mixing plant proteins with fats, carbohydrates, and fiber, followed by processing techniques to replicate the texture and mouthfeel of animal meat[8]. Key components in plant-based meat include plant-based protein sources, mycoprotein, coloring agents, and flavor enhancers[9].

### *1.1 Plant-based protein source*

Proteins in PBM are derived from various plant sources, including legumes, cereals, pseudocereals, seeds, and nuts[10]. Legumes-based protein sources such as soybean, peas, chickpea, lupine, and lentils are excellent protein sources because different characteristics like foam stabilization and gel formation of the pulse crop and bean crop have been evaluated [9]. Peas can be utilized for different food product formulations to improve the human intake of protein[10]. Soy protein is incorporated into various products, such as plant-based sausages, chicken-like breast fillets, nuggets, and substitutes for sliced deli meats. Textured vegetable protein, produced from defatted soy flour after extracting soluble carbohydrates, is processed through spinning or extrusion methods to imitate the texture of meat muscle, enhancing its chewiness and fibrous quality[11]. Cereals, especially rice, contain four main protein types: albumin, globulin, glutelin (the dominant protein), and prolamin. It is highly digestible, hypoallergenic, and mainly found in rice bran (11–15% protein) compared to brown (7.1–8.3%) and milled rice (6.3–7.1%). While rice proteins have limited solubility, hydrolyzed forms improve functionality and are used in hypoallergenic formulas, sports nutrition, and gluten-free products[12]. Wheat protein consists of gluten, which includes gliadin and glutenin, providing structure and elasticity in baked goods. Wheat flour normally contains around 14% protein, but adding legumes such as faba bean flour can improve its nutritional quality. Replacing 30% of wheat flour with faba bean flour increased protein content from 11.6% to 16.5%, improving protein digestibility (up to 74%) when fermented faba bean flour was used. Additionally, fermentation improves amino acid composition, raises biological value, and decreases the glycemic index of wheat-based products[13]. Pseudocereal proteins such as amaranth, quinoa, and chia have gained attention as functional and nutritional alternatives. These proteins have a well-balanced amino acid composition, are rich in essential amino acids, and are highly digestible, making them valuable for human nutrition. They also show good emulsifying, foaming, and gelling properties, making them suitable for various food applications. Also, pseudo-cereal proteins are gluten-free, which is ideal for individuals with celiac disease or gluten intolerance[14]. Nut proteins, such as those found in baru almond, pequi almond, and cerrado cashew nut, are rich in essential amino acids and have good digestibility. Baru almond has the highest protein quality, with a protein digestibility-corrected amino acid score (PDCAAS) of 91%, while cerrado cashew nut and peanut have similar values (82%). These nuts also contain high amounts of lipids (40–50%), dietary fiber, and essential minerals like iron, zinc, and magnesium[15].

***1.2 Binding and texturizing agents***

Binders and texturizers enhance texture, stability, and water retention in PBM. Standard binders include methylcellulose, carrageenan, and modified starches, which provide gelling and thickening properties necessary for product cohesion and mouthfeel. Methylcellulose is particularly valued for its unique reversible thermal gelation, allowing it to form a firm texture when heated while maintaining juiciness. Further, plant-derived fibers such as citrus fiber, locust bean gum, and alginates are used to improve water-holding capacity, reduce cooking loss, and improve the general sensory characteristics of PBM. However, consumer demand for clean-label alternatives is causing research into more natural binding agents, such as protein-rich flours and minimally processed plant ingredients[16].

***1.3 Fat, oil, and oil substitutes***

Fats and oils are essential in PBM as juiciness, tenderness, and flavor release, mimicking the mouthfeel of meat. Plant-based fats such as coconut oil, palm oil, sunflower oil, and canola oil are selected based on their melting points to imitate the characteristics of animal fats. Emulsification processes, such as pre-emulsified fats and oleogels, help stabilize fat within the protein matrix, controlling oil leakage and ensuring a moist texture. Moreover, native plant oleosomes found in oilseeds, are gaining engagement due to their potential to replace synthetic emulsifiers. Some formulations also contain fat substitutes, such as konjac gels and inulin, to reduce fat content while preserving a desirable texture. However, excessive oil inclusion during extrusion-based structureing can affect fiber formation negatively by lowering shear forces, emphasizing the importance of balancing fat levels[16-17].

## 2. Food additives in PBM

The purpose of adding additives in PBM is to enhance color stability, mimic natural meat appearance, and improve sensory attributes, along with common types and a list of frequently used additives, such as:

***2.1 Coloring agents***

Colors and their variations play an important role in determining the quality of alternative meat. Therefore, coloring ingredients are essential to their formulation[9]. One of the main challenges in PBM is imitating the red color of raw meat and its change during cooking. Traditional plant proteins like pea and soy often produce darker or less vibrant hues, affecting consumer appeal. Including air and structuring techniques can impact the visual properties of these substitutes, influencing their resemblance to meat[18]. Myoglobin, hemoglobin, and cytochromes determine the color of animal meat. Plant proteins naturally display beige, yellowish, or brown shades, challenging correct color replication. Various natural colorants can be used commercially in PBM. These colorants are classified into four categories: heme colorants derived from plants, non-heme plant-based colorants, reducing sugars, and microbial colorants[19].

#### *2.1.1 Heme colorants derived from plants*

Soy leghemoglobin (LegH) is a heme-containing protein from soy, and its applications in food, mainly in meat analogs, are produced using *Pichia pastoris*, safety evaluations, and its role as a flavoring and coloring agent in PBM. The potential of LegH is to replicate the taste, color, and nutritional benefits of meat, making it a useful component in sustainable food solutions. Safety studies of LegH confirm non-toxicity and low allergenic potential[20]. The limitations of LegH vary with pH, with reduced stability in highly acidic or alkaline environments, which may impact its use in diverse food formulations. Additionally, while its safety has been evaluated, concerns remain about consumer perception, regulatory approvals, and potential allergenicity due to residual Pichia pastoris proteins[21]. The FDA approved LegH as a color additive for use in uncooked ground beef analog products at levels up to 0.8% by weight. This approval permits manufacturers to use soy leghemoglobin to give plant-based meat alternatives a red, meat-like appearance before cooking. The decision of the FDA is based on scientific evaluations confirming its safety, including dietary exposure, toxicology, and allergenicity assessments[22].

#### *2.1.2 Non-heme plant-based colorants*

Plant-derived non-heme colorants are natural pigments that are extracted from plants. They play a crucial role in replicating the appearance of meat in PBM. These colorants are categorized into four main types[19]. First, heat-labile colorants, such as beet extract and anthocyanins in apples, mimic the red color of raw meat and fade to brown when cooked[16]. Next, Heat-stable colorants, including lycopene (from tomatoes), β-carotene (from carrots), and paprika extract, help maintain a reddish-pink color in processed meats like sausages and hams[23]. Next, yellow-brown colorants, such as turmeric and caramel colors, replicate the beige or golden hues found in poultry and pork products[19]. Finally, heat-induced browning colorants, like polyphenols from apple, tea, and potato extracts, develop a brown color upon heating, mimicking the Maillard reaction seen in cooked meat[24]. Despite their effectiveness, these pigments face challenges related to stability under heat, pH variations, and oxidation, which can affect the final product's appearance[25].

#### *2.1.3 Reducing sugars*

Reducing sugars plays a crucial role in the color development of PBM by participating in the Maillard reaction. This chemical process occurs when sugars react with amino acids under heat and form brown pigments[26]. This reaction is important for mimicking the natural browning effect in meat during cooking, enhancing the appearance and flavor of PBM [27]. This reaction not only enhances the cooked appearance of plant-based meats but also helps mask unwanted yellow tones that may arise from heat-degraded beet red extract[28]. This reaction improves the cooked appearance of PBM and helps hide unwanted yellow tones that may arise from heat-degraded beet red extract. Common reducing sugars used in PBM formulations include dextrose, maltose, lactose, xylose, galactose, mannose, and arabinose, which are used for this purpose and contribute to the characteristic browned and caramelized surface of cooked products like burgers and sausages[28-29].

### *2.2 Flavor enhancers*

PBM flavor development depends on various sources and techniques to imitate the umami, roasted, and savory notes in meat. The sources for developing PBM flavors include yeast extract, maillard reaction products, hydrolyzed vegetable protein, and fermentation-derived compounds[30]. First, yeast extract, a key natural flavor enhancer, is rich in glutamic acid and 5'-ribonucleotides, which amplify umami perception[31]. Next, in the Maillard reaction, volatile compounds such as 2-methyl-3-furanthiol, 2-furan methanethiol, and dimethyl disulfide are generated, lipid oxidation, and thiamine breakdown, contributing to meaty and roasted aromas[32]. Another source is hydrolyzed vegetable protein, which is produced via enzymatic or acid hydrolysis of soy, wheat, mung bean, rapeseed, and flaxseed. This process releases free amino acids, peptides, and sulfur-containing compounds, such as thiophenes and pyrazines, which enhance grilled and roasted flavors[33]. Besides, Maillard reaction products (MRPs) form when reducing sugars (e.g., xylose) react with amino acids (e.g., cysteine, glutamic acid) under heat, resulting in a rich, meaty, and brothy profile[34-35]. Finally, fermentation using *Bacillus subtilis* or *Lactobacillus* enhances complexity by breaking down proteins into peptides, nucleotides, and glutamic acid, supporting umami and kokumi characteristics[36]. These combined sources play a crucial role in mimicking the sensory attributes of animal-derived meat, enhancing both taste and consumer acceptance of PBM.

### *2.3 Food preservatives*

Food preservatives that prolong shelf life and assure food safety are used to prevent spoilage caused by physical, chemical, enzymatic, and microbial reactions. They are used to inhibit oxidation, microbial growth, and enzymatic reactions. Preservatives include natural or synthetic and must be selected depending on food type, pH, and other factors. They are classified into antimicrobial agents, antioxidants, and natural preservatives. First, antimicrobial agents such as organic acids (e.g., citric acid, sorbic acid) and parabens are commonly used to inhibit bacterial and fungal growth. Sulfur dioxide and sulfites also prevent spoilage in wine, dried fruits, and vegetables[37].

The systematic review discussed the potential risks and clinical applications of benzoate and sorbate salts, widely used as food preservatives. While these compounds are generally considered safe, concerns remain regarding their possible genotoxic and neurotoxic effects, including their role in mitochondrial damage, allergic reactions, and benzene formation in certain conditions[38].

Next, natural preservatives have gained awareness due to concerns about excessive synthetic additives. Essential oils from plants (thyme and oregano) and animal-derived compounds (lysozyme and lactoferrin) have antimicrobial properties. Bacterial-derived preservatives such as nisin and natamycin are widely utilized in dairy and meat products. Finally, antioxidants are vital in preventing food deterioration by inhibiting enzymatic browning and lipid oxidation. Synthetic antioxidants such as butylated hydroxyanisole (BHA), butylated hydroxytoluene (BHT), and natural alternatives such as tocopherols and rosemary extracts are used to maintain food quality [37].

## 3. Processing method

PBM is an ultra-processed food that undergoes various processing techniques to enhance its texture, flavor, and nutritional profile [39].

### *3.1 Protein extraction methods*

Protein extraction methods are essential for acquiring the increased purity and functionality of plant-based proteins. The main techniques include chemical, enzyme-assisted, and physical-assisted methods[39].

Chemical extraction leads to protein denaturation and raises environmental concerns due to solvent disposal[40]. Chemical extraction uses solvents such as water, alkalis, acids, and organic compounds. Water extraction uses sodium chloride, sodium dodecyl sulfonate, and non-ionic detergent in hot or freezing water. This method struggles to extract proteins with hydrophobic amino acids because of their low water solubility [41]. Alkaline extraction (pH= 9–12) uses NaOH or KOH and is widely operated in industrial protein extraction, as it increases protein solubility by breaking disulfide bonds, thereby improving extraction efficiency. Acid extraction changes the charge of proteins, keeping them away from their isoelectric point to enhance solubility[42-44]. Organic solvent extraction using ethanol, butanol, or acetone is especially effective for extracting lipid-binding proteins and those with nonpolar side chains[43].

Enzyme-assisted extraction (EAE) utilizes pectinase, cellulase, and protease to break down plant cell walls and release proteins, thereby increasing the yield of proteins[41-42]. Furthermore, combining EAE with other techniques, such as ultrasound and microwave processing, further boosts extraction efficiency[45].

Finally, physically assisted extraction methods that disrupt cell walls to facilitate protein release include high-pressure, pulsed electric fields, ultrasound-assisted extraction, and microwave-assisted extraction[45-46]. Ultrasound-assisted extraction, for instance, has been found to increase protein recovery rates significantly, making it a promising non-chemical approach to protein extraction[47].

### *3.2 Structuring and texturizing methods*

Structuring and texturizing methods are essential in the production of PBM because they help create a fibrous structure that mimics the texture of meat. Extrusion technology is one of the most widely used methods, where plant proteins are subjected to high temperature, pressure, and shear forces to form a meat-like texture. The extrusion method can be classified into two categories, including low moisture extrusion (<30% moisture) and high moisture extrusion (>50% moisture), with the latter being more effective in replicating whole muscle meat because of the formation of a tighter protein network[48]. Although extrusion is highly effective, it demands detailed regulation of temperature, screw speed, and moisture content, as these elements significantly impact the texture and sensory qualities of the product [49].

Next is 3D printing, an emerging technology that promotes the precise structuring of PBM by layering protein-based inks in a controlled manner[50]. This method authorizes customization of the shape, texture, and composition of PBM, making it a promising alternative for personalized nutrition and novel product development[51]. However, printable plant protein materials must possess good gelation and mechanical strength to ensure structural integrity, often requiring the addition of crosslinking agents or biopolymers[52]. Other advanced structuring techniques include electrospinning and wet spinning, which produce ultrafine protein fibers similar to muscle fibers, and shear cell technology, which aligns plant proteins into fibrous structures under controlled shear and heat conditions[53-54].

### *3.3 Functional enhancement methods*

Functional enhancement methods are proposed to improve the solubility, emulsification, gelation, and overall texture of PBM. First, fibrillation is a technique that applies mechanical shearing forces to break down plant proteins into smaller, more soluble units, enhancing their emulsifying and foaming properties[55]. Next, enzymatic hydrolysis is the process in which the protein structure breaks peptide bonds and improves solubility and emulsification, but excessive hydrolysis may produce bitter flavors, affecting sensory appeal[56-57]. pH-shifting treatment alters the charge distribution of proteins, influencing their three-dimensional structure and improving solubility and emulsification. Heat treatment also improves functional properties by modifying protein structure, but extreme heating may degrade essential nutrients and negatively affect sensory attributes[58]. Other strategies involve additives and microbial fermentation. The addition of food-grade auxiliaries like xanthan gum or galactosidase enhances protein stability, water absorption, and emulsification[33]. Microbial fermentation can modify protein structure and improve texture and flavor using bacteria such as lactic acid and yeast. For example, *Pichia pastoris* yeast produces soy leghemoglobin, which gives plant-based burgers a meat-like color and taste[59]. These enhancement methods play a crucial role in optimizing the functionality of plant proteins, ultimately improving the texture, mouthfeel, and acceptability of plant-based meat products.

**Table 1.** Nutritional and processing characteristics of PBM, animal meat, and whole plant foods

| Characteristic | PBM | Animal Meat | Whole Plant Foods |
|---|---|---|---|
| Processing Level | Ultra-processed; extensive industrial processing; often includes additives (flavorings, emulsifiers, preservatives)[61-62] | Minimally to moderately processed; usually fresh or frozen; few additives[63-64] | Minimally processed; whole foods, no additives[65-66] |
| Protein Content | Moderate; plant proteins with varying amino acid profiles; lower digestibility than animal proteins[60, 67] | High-quality complete proteins with all essential amino acids[60] | Moderate; incomplete proteins, but complementary in diverse diets[65] |
| Fat Profile | Lower total and saturated fat; uses plant oils (coconut, sunflower); variable PUFA content [63-64] | Higher total and saturated fat; rich in cholesterol and saturated fats[63-64] | Low total fat; predominantly unsaturated fats and fiber[65-66] |
| Micronutrients | Often fortified (iron, B12, zinc); minerals mostly non-heme form with lower bioavailability [63, 66, 68] | Rich in heme iron, B vitamins, zinc; higher bioavailability[68] | Rich in vitamins, minerals, antioxidants; no B12 naturally[65-66] |
| Sodium and Additives | Often high sodium content and multiple additives for flavor and texture[61-62] | Typically low sodium unless processed; few additives[63] | Naturally low sodium and free of additives[65] |
| Dietary Fiber | Higher fiber than meat, but lower than whole plants; some added fibers[63, 65] | None | High dietary fiber; whole intact plant cell walls[65] |
| Potential Health Impacts | Mixed: benefits from plant origin but concerns from additives, processing, and nutrient bioavailability [7, 61-62] | Associated with higher saturated fat intake and CVD risk; also provides bioavailable nutrients[60,64] | Generally associated with lower chronic disease risk; promotes gut health and reduced inflammation[7,65] |

## 4. Nutrient contents and concerns in PBM

The nutritional composition of PBM is influenced by the types of ingredients used and the processing methods applied[39]. PBM has been developed to offer an alternative to traditional meat, but their nutritional profiles differ significantly from animal-based products[60]. Table 1 summarizes the key differences between PBM, conventional animal meat, and whole plant foods to compare nutritional profiles and processing levels. This table highlights important distinctions in macronutrients, micronutrients, degree of processing, and potential health impacts, setting the stage for subsequent discussion on cardiovascular risk.

### *4.1 Proteins*

Many processing methods can modify protein structure, affecting the digestibility, solubility, and functional properties of PBM protein. While high-temperature processing can induce protein denaturation, it also assists in creating meat-like textures. Fermentation enhances amino acid composition and boosts protein bioavailability, making PBM more nutritionally comparable to animal proteins[67,69]. However, the report showed that PBM contain protein levels similar to meat, their amino acid profiles differ. PBM have higher concentrations of glutamic acid and cysteine but lower essential amino acid levels, including methionine, alanine, and glycine. Additionally, protein digestibility in PBM is commonly lower than in animal proteins, which could involve amino acid bioavailability[60].

### *4.2 Carbohydrates and dietary fiber*

PBM typically contains carbohydrates, as many formulations include plant-based starches, fibers, and other carbohydrate-rich ingredients[63]. A nutritional advantage of PBM is higher fiber content, while animal meat naturally has lower dietary fiber[63,65]. Many plant-based products incorporate whole food ingredients such as beans, lentils, and grains, increasing fiber levels and promoting better digestion and gut function[65].

Carbohydrates and dietary fiber are significant in PBM, contributing to texture, stability, and nutritional value. Starches, generally derived from sources such as corn and wheat, impact the structure and mouthfeel of the product. At the same time, advanced processing techniques can modify starch properties, affecting digestibility and absorption. Dietary fiber, both soluble and insoluble, is often added to improve gut microbiota and the texture of meat analogs. Fibers from chicory and oats sources have increased firmness, elasticity, and water retention in PBM[70-71]. Despite these benefits, the ultra-processing methods used in PBM may reduce the natural fiber content of plant-based ingredients, potentially limiting their overall nutritional advantages[72].

### *4.3 Fat content and lipids*

Lipids and fat are key components in animal meat, providing mouthfeel and juiciness. PBM usually contains sunflower, coconut oils, and rapeseed to enhance flavor, texture, juiciness, and nutritional balance. Lipids interact with carbohydrates and proteins during the processing methods, affecting the consistency and sensory attributes of the final products. High-temperature processing steps can initiate lipid oxidation, affecting flavor and stability. However, the addition of antioxidants and emulsifiers can maintain product quality and extend shelf life[73-75].

The health benefit of PBM is generally lower total and saturated fat content than animal meat [64]. To replicate the texture and juiciness of animal meat, PBM often uses vegetable oils (coconut, sunflower, or canola oil). Some formulations add saturated fats, such as coconut oil, to better mimic the mouthfeel of animal meat. However, PBM still tends to have lower saturated fat levels than animal meat products. Additionally, including polyunsaturated fatty acids (PUFAs), especially omega-3 and omega-6, may deliver further health benefits compared to meat, which generally contains higher amounts of saturated fat[63].

Despite these benefits, some PBM may contain higher sodium and added sugar levels, which could neutralize health benefits, particularly cardiovascular health. Thus, while PBM offers a healthier lipid profile, attentive formulation is necessary to maximize nutritional value[76].

### *4.4 Vitamins, minerals, and moisture content*

The essential nutrient groups in PBM, including vitamins, minerals, and moisture content, affect the nutritional value and sensory properties. Compared to animal meat, PBM frequently demands fortification with micronutrients lacking in plant-based diets, such as iron, zinc, and vitamin B12. The moisture content is used to specify the juiciness and texture of PBM. In high-moisture formulations that provide a more natural meat-like experience. However, some heat-sensitive vitamins degrade during ultra-processing production. The selection of ingredients and processing conditions is essential to ensure optimal nutrient retention while maintaining desirable texture and flavor[77-79]. PBM differs significantly from animal meat. Although PBM may contain iron and zinc, these minerals are mostly in non-heme forms, which are less bioavailable due to plant-based antinutrients such as phytates[68,80]. Also, PBM lacks vitamin B12, a required nutrient for nerve function and red blood cell production, so some products are fortified with synthetic B12 to compensate[77]. Moreover, like other B vitamins, PBM usually has lower B vitamins (niacin, riboflavin, and B6) and essential fatty acids, especially DHA and EPA, naturally abundant in animal meat and fish[76]. PBM fortification with essential vitamins and minerals such as iron, calcium, vitamin D, and B12[63,77]. The most concern is the high sodium content, preservatives, and flavor enhancers are added to improve taste and shelf life. Elevated sodium and preservative intake correlate to cardiovascular risks[66]. PBM can serve as a valuable alternative to meat, and consumers must carefully select products and plan their diets to ensure balanced nutrient intake and mitigate potential health concerns.

### *4.5 Ultra-processing and nutrient composition*

UPFs are extensively industrially processed and typically include additives such as preservatives, artificial colors, and sweeteners. Examples include snacks, soft drinks, instant noodles, and frozen-ready meals. These foods are often designed for convenience and palatability but tend to lose essential nutrients during production. UPF consumption has been associated with higher caloric intake and increased risk of chronic diseases such as obesity, type 2 diabetes, and CVDs[62]. According to Metz et al. [61], 88% of PBM products were classified as ultra-processed compared to 52% of meat products ($p < 0.001$), and PBM contained over three times the number of additives on average. PBM contained significantly more flavorings, color additives, and non-culinary ingredients. Nutritionally, PBM had lower fat, saturated fat, and protein content but higher levels of carbohydrates, sugar, fiber, and salt. Although PBM offers some benefits, such as higher fiber and lower saturated fat, their categorization as UPFs raises concerns. The high degree of processing and additive use may undermine their perceived health benefits. Thus, reformulating PBM to reduce additives and sodium content could improve their nutritional profile. Moreover, in the long term, choosing whole-food, minimally processed, plant-based alternatives may offer better health outcomes for consumers. The various characteristics of ultra-processing techni-ques used in PBM production indicate that their impact on nutritional quality and potential health risks can vary considerably. Table 2 summarizes the standard processing methods, including extrusion, thermal processing, high-pressure processing, and emerging technologies such as 3D printing, along with their specific effects on nutrient retention, formation of harmful compounds like AGEs, and implications for cardiovascular health. Recognizing the unique characteristics and consequences of each method is essential for accurately assessing the health profiles of PBM products.

**Table 2.** Summarizes common ultra-processing methods used in PBM production and their respective potential impacts on nutrient quality and cardiovascular health.

| Processing Type | Description | Health Implications |
|---|---|---|
| High-Temperature Extrusion[81-83] | Continuous cooking under high pressure and shear forces | Alters protein structure, reduces heat-sensitive nutrients (e.g., vitamins), promotes formation of advanced glycation end-products (AGEs) associated with oxidative stress and endothelial dysfunction |
| Thermal Processing[82-83] | Application of dry or moist heat at high temperatures | Increases AGEs, induces lipid oxidation affecting flavor and stability, reduces vitamin content |
| High-Pressure Processing (HPP)[84] | Non-thermal sterilization using 400–600 MPa pressure | Preserves heat-sensitive nutrients better, minimizes AGE formation, maintains protein digestibility |
| 3D Printing / Shear-Cell Technology[85-86] | Techniques using mechanical shear or additive manufacturing for structure | Emerging technologies with potential to preserve nutrient profiles due to lower heat exposure |

## 5. Ultra-process methods and additives in PBM affecting cardiovascular health

Although PBM is a healthier alternative to red meat, excessive ultra-processing methods decline its health benefits (Table 3). The study uses data from the French NutriNet-Santé cohort among 106,000 adults and found that nitrites from food additives, especially sodium nitrite, related to a higher risk of hypertension. However, no significant association was found between natural sources of nitrites or nitrates and CVDs[87].

In 2024, The UK Biobank cohort study by Rauber et al. investigated the effect of plant-sourced foods, classified by processing levels, on CVD risk. The results showed that a higher dietary contribution of plant-sourced non-UPF decreased a 7% risk of incident CVD and a 13% risk of CVD mortality per 10% increase in consumption. Conversely, an excessive intake of plant-sourced UPF was associated with a 5% increased risk of CVD and a 12% higher mortality rate per 10% increase. Moreover, the study also found that replacing plant-sourced UPF with plant-sourced non-UPF resulted in a 7% lower risk of CVD incidence and a 15% lower risk of CVD-cause mortality. So, it is important to prioritize minimally processed plant-based foods over their ultra-processed counterparts for improved cardiovascular health[88].

The systematic review and meta-analysis showed the association between ultra-processed food consumption and the risk of developing diabetes, hypertension, dyslipidemia, and obesity. In twenty-five prospective cohort studies, the analysis found a consistently positive association between high ultra-processed food intake

**Table 3.** Summary the effects of ultra-processing method or additive on cardiovascular health in PBM

| Study (Year) | Population / Study Design | Objective | Key Cardiovascular Findings |
|---|---|---|---|
| Srour et al. 2019[93] | 105,159 French adults (cohort study) | To assess UPF intake and CVD risk | Every 10% increase in UPF intake → 12% ↑ CVD risk, 13% ↑ heart disease, 11% ↑ stroke |
| Srour et al. 2022[87] | 106,288 French adults | To study nitrites/nitrates and risk of hypertension/CVD | Sodium nitrite (E250) → 19% ↑ hypertension risk; no significant link to CVD from other sources |
| Bonaccio et al. 2022[94] | 1,171 Italians with existing CVD | To study UPF and mortality in heart patients | High UPF intake → 38% ↑ all-cause death, 65% ↑ CVD death; effect remained after adjusting for diet quality |
| Liu et al. 2023[91] | 50 lab mice | To test effects of processed plant/red meat on health | Ultra-processed plant/red meat → increased LDL, TC, and signs of dyslipidemia compared to control |
| Sellem et al. 2023[92] | 95,442 French adults | To assess food additives (emulsifiers) and CVD risk | Additives like E460–E468, E471–472, and E339 linked to small but significant ↑ CVD and heart disease risk |
| Vitale et al. 2024[89] | Meta-analysis (25 studies) | To assess UPF and risk factors like diabetes, BP, cholesterol | High UPF intake → ↑ risk of diabetes (37%), hypertension (32%), high triglycerides (47%), low HDL (43%) |
| Lane et al. 2024[95] | Umbrella review (45 meta-analyses, 9.8M people) | To summarize evidence on UPF and health | Strong evidence: ↑ CVD death (50%), ↑ heart disease death (66%); moderate evidence for ↑ hypertension |
| Rauber et al. 2024[88] | 118,397 UK adults | To compare plant-based UPF vs unprocessed foods | Plant-based non-UPF → 7% ↓ CVD risk; Plant-based UPF → 5% ↑ CVD risk and 12% ↑ CVD death |

and increased risks of diabetes (37%), hypertension (32%), hypertriglyceridemia (47%), low HDL cholesterol (43%), and obesity (32%). The result showed a strong association between ultra-processed food intake and adverse health outcomes. The quality of evidence was rated as low to moderate, emphasizing the need for cautious interpretation and more standardized research approaches[89]. Moreover, the systematic review reported the relationship between consuming processed and ultra-processed foods and arterial hypertension in adults and older adults. The results showed a strong association between high consumption of ultra-processed foods, which are energy-dense and rich in salt, sugar, and unhealthy fats, and increased blood pressure or hypertension significantly contribute to cardiovascular risks[90]. Ultra-processed PBM decreased microbiota diversity and increased markers associated with gut inflammation. For example, the study investigated the effects of different processing degrees of PBM on inflammation and gut microbiota biomarkers in mice. Plant-based dietary patterns increased both the diversity and abundance of the gut microbiota compared to red meat diets. However, microbiota diversity in the ultra-processed plant-based meat group was lower than in the processed plant-based meat group, and ultra-processed plant-based meat group had a higher Firmicutes to Bacteroidetes (F/B) ratio, possibly due to the more significant number of additives in the ultra-processed food. The comparison between processed and ultra-processed PBM with processed and ultra-processed red meat. The results showed that mice consuming ultra-processed PBM and ultra-processed red meat exhibited significant weight gain, increased epididymal fat, and liver inflammation. Moreover, blood biomarkers revealed that ultra-processed PBM and ultra-processed red meat groups had elevated triglycerides (TG), total cholesterol (TC), and low-density lipoprotein (LDL-C), indicating dyslipidemia. Additionally, alanine aminotransferase (ALT) and aspartate aminotransferase (AST) were significantly higher in the ultra-processed PBM and ultra-processed red meat groups, suggesting liver damage[91].

According to the prospective cohort study by Sellem et al. in 2023, food additive intake such as emulsifiers followed 95,442 French adults for a median of 7.4 years to evaluate the link between food additive emulsifier intake and CVD risk. Higher intake of celluloses (E460-E468) was associated with a higher risk of CVD (HR 1.05, 95% CI 1.02-1.09, P=0.003) and coronary heart disease (CHD) (HR 1.07, 95% CI 1.02-1.12, P=0.004). Specifically, E460 and E466 showed positive links to these risks. Likewise, higher consumption of total monoglycerides (E471) and diglycerides of fatty acids (E472) was associated with higher risks of CVD (HR 1.07, 95% CI 1.04-1.11, P<0.001), CHD (HR 1.08, 95% CI 1.03-1.14, P=0.001), and cerebrovascular disease (HR 1.07, 95% CI 1.01-1.13, P=0.02). E472b and E472c were associated with increased CVD risks within this group. Higher intake of trisodium phosphate (E339) was correlated to an increased risk of CHD (HR 1.06, 95% CI 1.00-1.12, P=0.03). This analysis suggests that these widely used emulsifiers in industrial foods may be associated with a higher risk of CVD [92].

The differences observed across studies about the impact of PBM on LDL-C and cardiovascular health outcomes may be attributed to several methodological and compositional factors. The degree of food processing involved in the PBM products is a primary reason for inconsistency. Studies demonstrating the advantageous effects of PBM on LDL-C levels often involved minimally processed plant-based foods, which are naturally higher in dietary fiber, phytonutrients, and beneficial fatty acid profiles. In contrast, studies reporting invalid or adverse effects frequently examined ultra-processed PBM products, which tend to contain elevated sodium levels, saturated fats, food additives, and emulsifiers. These components, particularly certain emulsifiers (e.g., E460–E468, E471–E472) and nitrite preservatives, have been independently associated with increased risks of CVDs, including hypertension and dyslipidemia. Furthermore, animal studies indicate that ultra-processed PBM may negatively affect gut microbiota diversity and promote inflammatory responses, which are known to contribute to metabolic disturbances and elevated LDL-C levels. Divergences in study populations, durations of follow-up, and outcome measures also contribute to the heterogeneity of findings. These considerations emphasize the importance of contrasting between the nutritional quality of minimally processed and ultra-processed PBM. The cardiovascular benefits of plant-based diets are more likely to be realized when emphasizing whole, less-processed plant-based options rather than highly processed meat substitutes.

**6. How nutrient composition, additives, and processing in PBM are related to cardiovascular risk**

PBM products are considered healthier alternatives to animal-based meats. However, the nutritional benefits of PBM depend not only on their plant origin but also on their overall nutrient composition, the inclusion of food additives, and the degree of industrial processing. These related factors can influence cardiovascular health through multiple biological pathways. From a nutritional viewpoint, PBM products typically contain adequate protein levels. However, their amino acid profiles, especially essential amino acids, are often incomplete and may exhibit lower digestibility than animal proteins. Moreover, PBM products frequently contain high sodium levels due to added flavoring agents, preservatives, and texturizers, which are associated with increased blood pressure and are a well-established risk factor for CVDs. While many products reduce saturated fat relative to red meat, others use plant-based saturated fats such as coconut oil, which may negatively affect lipid profiles by increasing LDL cholesterol. RCTs have shown that replacing polyunsaturated fat with saturated fat, such as coconut oil, increases LDL cholesterol by approximately 10–15% (mean difference 0.30 mmol/L; 95% CI: 0.20–0.40; $p < 0.001$)[96]. In addition, using food additives such as emulsifiers (e.g., E471, E472) and phosphates (e.g., E339) raises concerns. Emulsifiers have been shown to disrupt gut microbiota and increase intestinal permeability, which may trigger low-grade inflammation and promote atherosclerosis. Emulsifiers such as mono- and diglycerides of fatty acids (e.g., E471, E472) are commonly used in PBM to stabilize emulsions, improve texture, and prevent ingredient separation. E471 refers to mono- and diglycerides derived from glycerol and natural fatty acids found in many ice creams and, frozen yogurts, guar gum[97], while E472 includes various esters of mono- and diglycerides with acetic, lactic, citric, or tartaric acid[98]. These compounds are widely used in processed foods, including margarine, baked goods, and plant-based products. Phosphates, such as sodium phosphate (E339), are stabilizers and water-retaining agents. Although generally recognized as safe (GRAS), EFSA has set the acceptable daily intake (ADI) for total phosphate at 40 mg/kg body weight/day. At the same time, no ADI is established for mono- and diglycerides, though caution is advised (EFSA, 2019)[99]. Emulsifiers have been shown to disrupt gut microbiota and increase intestinal permeability, which may trigger low-grade inflammation and promote atherosclerosis. For example, Emulsifiers (e.g., carboxymethylcellulose, polysorbate 80), artificial sweeteners (e.g., sucralose, saccharin), and certain food colorants can disrupt the gut microbiota, contributing to gut dysbiosis. These additives reduce beneficial bacteria like *Faecalibacterium prausnitzii*, *Bifidobac*terium spp., and *Akkermansia muciniphila*. At the same time, they promote the growth of potentially harmful microbes such as *Escherichia coli*, *Bilophila wadsworthia*, and *Proteobacteria*. This microbial imbalance is associated with increased intestinal permeability and chronic inflammation. As a result, these food additives are considered key environmental factors that may contribute to developing inflammation[100]. These changes also reduced short-chain fatty acid (SCFA) production, particularly butyrate, which is key in maintaining gut barrier integrity and modulating systemic inflammation. As reflected in elevated inflammatory biomarkers, sodium, emulsifiers, and phosphates may also induce low-grade systemic inflammation. In the Nutri-Net-Santé cohort study, higher UPF intake was associated with increased hs-CRP levels ($\beta = 0.08$; 95% CI: 0.04–0.12; $p < 0.001$), indicating a systemic inflammatory response[89]. The processing methods used to manufacture PBM, especially high-temperature extrusion, can reduce the bioavailability of heat-sensitive nutrients and change protein structures. Ultra-processing also tends to increase the dependence on additives to restore sensory properties and shelf stability, potentially compounding cardiovascular risks. Also, high-temperature extrusion may promote Maillard reactions between reducing sugars and amino groups in proteins, leading to advanced glycation end-products (AGEs). These compounds are related to oxidative stress and vascular damage by interacting with the receptor for AGEs (RAGE), stimulating reactive oxygen species (ROS) production and pro-inflammatory cytokines. Elevated dietary AGE intake has been associated with reduced nitric oxide bioavailability, endothelial dysfunction, and increased arterial stiffness mechanisms that are directly implicated in atherosclerosis and cardiovascular disease development. Studies have reported that ultra-processed foods, particularly those subjected to dry-heat cooking methods such as extrusion, contain substantially higher levels of AGEs than minimally processed foods[82-83].

Overall, the combined influence of nutrient imbalance, additive exposure, and intensive processing may damage the intended health benefits of PBM. A comprehensive evaluation of PBM should thus consider its plant-based label and the underlying formulation and processing factors contributing to cardiovascular health outcomes. To synthesize the associations between PBM composition, ultra-processing, and potential cardio-metabolic risk, a conceptual diagram is presented in Figure 1. Ultra-processing methods and food additives commonly used in PBM products may contribute to adverse cardiovascular and metabolic outcomes. The figure summarizes pathways involving sodium, saturated fat, emulsifiers, phosphates, and flavor enhancers relating to increased blood pressure, lipid dysregulation, systemic inflammation, and gut microbiota imbalance. This figure emphasizes the potential health risks associated with the ultra-processed nature of many PBM formulations despite their plant-based origin.

## Future directions

The future direction of PBM is based on the production of safe and more natural food additives through regulatory and policy improvements to make sure that all ingredients meet the safety standards as well as maintain the quality of PBM products. Consumers should be encouraged to select PBM products with low sodium and minimal additives, preferably those fortified with bioavailable nutrients such as vitamin B12 and iron to support cardiovascular health. Manufacturers are urged to reformulate products by reducing harmful additives like emulsifiers and phosphates and adopting gentler processing techniques, such as high-pressure processing, to preserve nutrient quality and minimize the formation of harmful compounds.

Moreover, health impact studies are important to assess the long-term effects of PBM consumption, especially regarding cardiovascular health related to inflammation, homeostasis of the gut microbiome, and metabolic outcomes. Regulatory agencies should develop clean labeling guidelines and biotechnological emulsifiers that disclose the degree of processing and additive content to help consumers make informed choices. Additionally, public health policies promoting whole-food, minimally processed plant-based diets alongside restrictions on ultra-processed food consumption could reduce cardiovascular disease risk. Continued research on the long-term health effects of PBM consumption, especially regarding inflammation, gut microbiome homeostasis, and metabolic outcomes, remains essential. This review is one part of the information that guides the reformulation of PBM to normalize nutritional content and composition by reducing harmful additives, improving essential nutrients such as vitamin B12 and iron, and lowering ultra-processing. Furthermore, combining the research into dietary guidelines will help consumers make knowledgeable choices, encouraging a balanced diet that combines PBM with plant-based foods for better overall health.

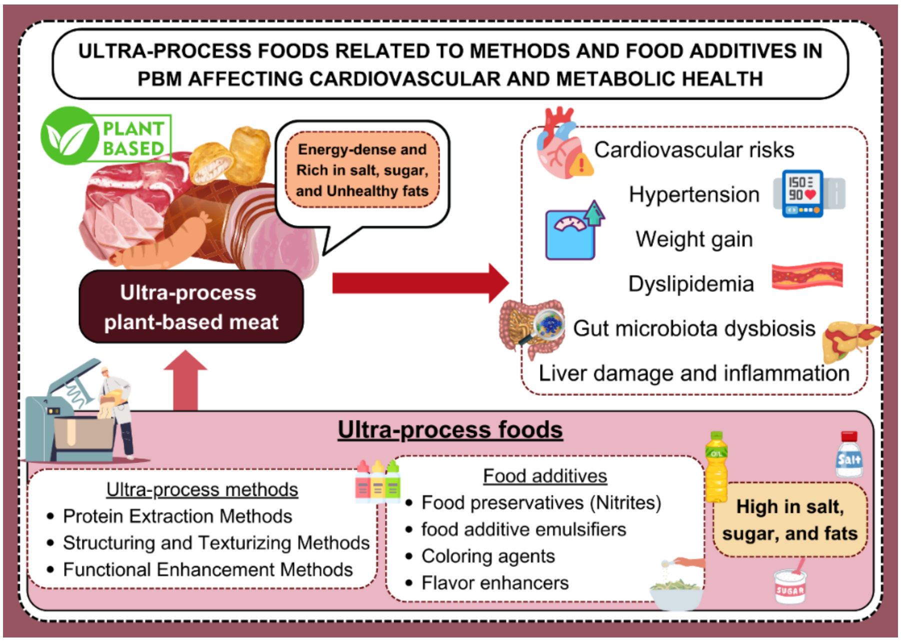


**Figure 1.** Ultra-process foods related to methods and Food additives in PBM affecting cardiovascular and metabolic health

## Conclusion

PBM has become an option for animal-based meat. However, their nutrient composition through ultra-processing methods and the potential effects of food additives on cardiovascular health must be a focus. Although PBM can provide positive benefits such as lower saturated fat and cholesterol than animal-based meat, there are still problems and concerns regarding food additives, ultra-processing, and variations in nutrient content. Comprehensive health impacts are important for evaluating the long-term effects of PBM consumption on cardio-vascular health related to cholesterol levels, blood pressure, and inflammatory markers. Moreover, nutritional value optimization, such as adding bioavailable iron, vitamin B12, and omega-3 fatty acids, can improve the role of PBM in supporting cardiovascular health. In the future, regulatory and policy improvements are essential to confirm the safety and quality of PBM by encouraging the use of natural additives and decreasing excessive sodium and unhealthy fats. Furthermore, according to the scientific findings in dietary guidelines, consumers can be inspired to balance PBM with a whole plant-based diet to improve health benefits and reduce risks of CVDs.

## Conflict of interest

The authors declare that there is no conflict of interest.

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