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High-Moisture Extrusion in Plant-Based Meat: Challenges and Emerging Trends

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ABSTRACT

The global protein demand is predicted to double by 2050, driving the rise in the adaptation of plant-based meat alternatives (PBMAs), which replicate traditional meat textures while reducing environmental impact. This review examines challenges and opportunities in producing and adopting PBMAs, with a particular focus on high-moisture extrusion (HME) technology. Anisotropic structure control during HME remains a major challenge due to the varied physicochemical properties of plant proteins. Additionally, nutrient composition variability complicates standardization, which affects dietary adequacy and consumer acceptance, while understanding the effects of antinutrients on nutrient absorption is also crucial. The review further explores the nutritional profiles, health implications, environmental impacts, labelling practices, and marketing strategies of PBMAs, identifying research gaps. It highlights the need for cross-sector collaboration to advance sustainable plant-based diets. Eco-friendly plant protein production can be achieved through efficient agroecosystem management and dry fractionation, in contrast to water- and chemical-intensive wet extraction. Life cycle assessments consistently show a lower environmental footprint of plant-based diets versus meat-inclusive diets, although more comprehensive methodologies are required. Market challenges, including costs and consumer acceptance influenced by demographics and culture, remain key challenges. Policy interventions, such as carbon taxation, could reduce meat consumption, but socioeconomic impacts must be carefully considered. Reducing production costs and effectively communicating the sustainability benefits of PBMAs seem crucial for widespread adaptation. Advances in fermentation and genomic technologies hold promise for enhancing nutrient bioavailability sustainably. Ongoing evaluation of PBMA production processes is crucial to addressing nutritional variability, health impacts, and environmental concerns.

1 | Introduction

The worldwide food system is experiencing a profound transformation in response to the critical necessity to address environmental sustainability, public health, and ethical concerns associated with traditional animal agriculture. By 2050, it is anticipated that the world population will reach 9.7 billion, creating a surging need for sustainable protein alternatives (FAO 2017; Willett et al. 2019). Plant-based meat analogues aim to replicate the organoleptic and nutritional characteristics typically found in meat utilizing ingredients sourced from plants, offering potential solutions to some of the most critical global challenges (Asgar et al. 2010).

Environmental sustainability is a primary driver behind the acceptance of plant-based meat analogues. Conventional livestock farming significantly contributes to the emission of greenhouse gases, the clearance of forests, and the depletion of water resources (Steinfeld et al. 2006). On the other hand, plant-based meat alternatives generally require lower labor and energy inputs and use less land and water while emitting fewer greenhouse gases, making them a more sustainable option. Moreover, in an optimized continuous process, the desirable fibrous structure can be achieved without additives, further enhancing their environmental benefits (Ozturk et al. 2023; Poore and Nemecek 2018). However, the processing of plant-based meat, particularly through high-moisture extrusion (HME), which transforms plant proteins into fibrous structures by heating and pressurizing them to resemble the texture of animal meat, can be energy-intensive and may partially offset some of these environmental advantages (Dekkers et al. 2018).

These highlight the need for the precise optimization of HME process parameters and sourcing of ingredients to minimize the ecological footprint, while transparently communicating the environmental impact of plant-based meats. Comprehensive life cycle assessments (LCAs), particularly for HME, are essential to quantify these environmental advantages and guide improvements in production practices (Smetana et al. 2015).

Techniques such as HME, fermentation, and advanced protein processing are crucial in achieving the desired texture and flavor (Dekkers et al. 2018). However, these processes can be highly resource-intensive and expensive, raising concerns about their long-term sustainability and accessibility. Moreover, the reliance on highly processed ingredients may lead to skepticism about the health implications of these products (Asgar et al. 2010; van Vliet et al. 2021). Optimizing the HME process and selecting appropriate sources of plant-based protein remain key areas of research and innovation. There is a need for ongoing improvements in technology to reduce costs and improve the scalability of production without compromising sensory attributes.

From a nutritional perspective, plant-based meat alternatives offer both opportunities and challenges. Addressing potential deficiencies in amino acids, vitamins, and minerals, such as B12, iron, and zinc, and ensuring the bioavailability of these nutrients are vital concerns. Plant-based meat analogues may undergo fortification to provide essential nutrients similar to nutrients found in traditional meat (Sadler 2004; van Vliet et al. 2021). Additionally, some plant-based meats may contain high levels of sodium, artificial additives, and preservatives, which could adversely impact some of their health benefits. Conflicting evidence suggests the necessity for more research to draw decisive conclusions on these aspects (Kahleova et al. 2018).

Labelling and marketing are additional critical aspects impacting the adoption of plant-based meat analogues. Precise and transparent labelling is essential to educate consumers about the nutritional content and environmental impact of these products. Establishing regulatory frameworks and standardized labelling practices can assist in preventing misleading claims and building consumer trust (Bryant and Sanctorum 2021). However, there are concerns about the potential for greenwashing and the accuracy of environmental claims made by manufacturers. Stringent scrutiny from regulatory bodies and third-party verifications seems necessary to ensure the integrity of such claims. Strategic branding, targeted messaging, and educational initiatives seem essential to position these products as desirable and mainstream food preferences (Slade 2018). However, aggressive marketing strategies could obscure the fact that these are processed foods with some nutritional inadequacies, potentially misleading health-conscious consumers.

This review explores the technological, nutritional, gastrointestinal, environmental, labelling, and marketing aspects of plant-based meat analogues, with a focus on HME as a key production method, highlighting both the challenges and opportunities they offer. By addressing these challenges and incorporating critical comprehensive evaluations, plant-based meat analogues can contribute substantially to a sustainable and nutritious future, representing a promising opportunity to confront some of the global challenges associated with food production and consumption.

2 | HME

Several technologies have been introduced to imitate the texture of plant-based proteins to resemble whole animal muscle tissue. These technologies include extrusion, shear-induced structuring, three-dimensional printing, electrospinning, and freeze texturization. Among these, HME has emerged as the most effective technique for producing meat alternatives with a fibrous texture and sensory properties comparable to meat (Dekkers et al. 2018). Unlike low-moisture extrusion (< 40% moisture), which is suitable for producing plant-based nuggets, chunks, and strips (Sha and Xiong 2020), HME operates at > 50% moisture and creates structured products with a reduced environmental footprint (Dekkers et al. 2018).

Shear-induced structuring involves a shear cell designed like a rheometer to apply shear force. Control is convenient due to its simple geometry and two processing variables (temperature and shear rate). However, the processing time is relatively long (approximately 20 min) and the formation of fibrous texture relies on the velocity gradient (McClements and Grossmann 2022). 3D-printing technology is limited to thermoplastic materials, raises concerns about microbial growth due to prolonged processing, and requires adjustments because of additives used, which also complicate labelling (Ko et al. 2021; Sha and Xiong 2020). Electrospinning forms micro- and nano-scale fibers by establishing a strong electric field between the spinneret and the collection surface (Nieuwland et al. 2014). The method is still in its primary stage, with limited commercial applications (Miller et al. 2024). Freeze-structuring, involving freezing followed by freeze-drying or adding calcium chloride, depends heavily on the functional properties of plant proteins, making the process longer and labelling more complex (Chantanuson et al. 2022).

HME stands out for producing meat alternatives with high throughput and scalability, minimal energy and labor consumption, and no need for additives, making labeling simpler. This technology holds vast potential for various plant-sourced products and offers easy adaptability to accommodate changing parameters (Bamidele et al. 2023; Ozturk et al. 2023). The extrusion process involves multiple steps including protein denaturation, rearrangement, and texturizing (Liu and Hsieh 2007; Zhang et al. 2019) occurring at different stages within the extruder, as illustrated in Figure 1. The depolymerization of the native protein structure via the breaking down of hydrogen and

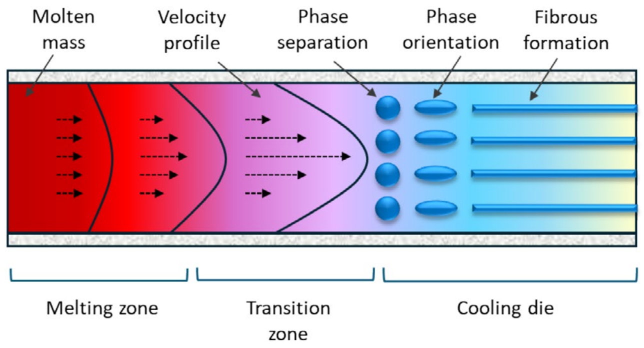

FIGURE 1 | Stages of high-moisture extrusion: Melting zone, transition zone, and cooling die.

ionic bonds accompanied by adsorbing water takes place in the first section of extrusion cooking. In the next section, the hot melt blend undergoes temperature and velocity gradients, transforming from sol to gel in a screw barrel. After passing through the die, the gel turns into a fibrous structure due to phase separation in biopolymer systems containing at least one protein. The cooling die creates a temperature gradient and velocity gradient, the latter being a result of laminar shear flow (Ubbink and Muhialdin 2022).

Thermodynamic incompatibility of polymers is the main reason for phase separation into a polysaccharide or secondary protein dispersed phase and a protein continuous phase (Tolstoguzov 2003, 1991). The shear rate leads to aligning separated phases in meat-like fibrous layers. Layer thickness is influenced by the proportion of shear rate to Cahn-Hilliard diffusivity (M'). If the ratio of temperature gradient (α) to Cohn-Hilliard diffusivity (M') is approximately 12, a fibrous structure would be created by the layered form with an orientation in the direction of flow. This is achieved in the middle part of the cooling die. In contrast, at a relatively high M', achieved when phase separation occurs rapidly at the start of the cooling die, the layers orient vertically. However, at the higher ratio of α: M' (≥ 100), two phases cannot be separated (Dekkers et al. 2018).

There are contradictions in the literature regarding the rheological properties of the two phases and whether they exhibit similar or different physicochemical characteristics (Grabowska et al. 2014; Osen et al. 2015; Schreuders et al. 2020). Variations in chemical composition and protein solubility due to natural protein denaturation and interactions with other components in raw materials (e.g., lipids and carbohydrates) can cause differences in the viscosity profile even for the same type of plant protein (Osen et al. 2015). Other extruder operational parameters, including shear rate, temperature, and moisture content, also significantly affect the rheological properties of the material. For instance, plant proteins exhibit gel-like properties and shear-thinning behavior during extrusion, but their responses in the nonlinear viscoelastic range vary considerably (Sui et al. 2024). These discrepancies can be attributed to differences in the physicochemical properties of the two phases and the specific processing conditions used, which vary between studies.

Plant proteins like peas, soy, and wheat have globular structures, which are swelled by absorbing water and forming phases. The water distribution between phases is related to protein concentration. The phase with more water absorption would be dilute, while another phase would be denser. In bi-continuous systems, both phases are dense and construct continuous phases (Clark et al. 1983; Fitzsimons et al. 2008; Shrinivas et al. 2009). Although polymer-blending law would be useful in the prediction of dispersed and continuous phases, this method has limitations in different protein concentrations (Kasapis and Tay 2009; Morris 1992).

According to Dekkers et al. (2018), in the blend of soy protein isolate (SPI) with wheat gluten (WG) in the ratio of 80:20, the SPI could absorb more water, so it had a higher viscous modulus compared to the WG phase. Therefore, SPI with a greater volume fraction would constitute the continuous phase, while WG would serve as the dispersed phase. Understanding different interactions in dense and dispersed phases with water and other ingredients, rheological behavior, and the complex hierarchical structure of biopolymers is essential to monitor and control the final properties of the product.

As the major aim of meat alternatives technology is providing food products with lower risks for the ecosystem, it can be supposed that both raw materials (plant-based ingredients) and HME support the goal. However, research on phase separation mechanisms responsible for creating anisotropic textures in meat alternatives during HME is underexplored, yet crucial for determining sensory attributes such as texture and mouthfeel. A deeper understanding of these mechanisms is essential for optimizing formulations and processing conditions, ensuring product quality, nutritional value, and cost efficiency. Investigating the structural and rheological behavior of biopolymers within dense and dispersed phases will enable better control over the physical and chemical properties of the final products.

The balance between protein aggregation and phase separation rates is also crucial. When these rates are similar, layered fibrous structures emerge. However, if aggregation outpaces separation, non-oriented gels form, and if separation dominates, layered structures develop. Particle size, influenced by heating and screw configuration, further affects these processes (Zhang et al. 2022). Viscosity ratios between the dispersed and continuous phases, which are affected by factors such as water distribution, ionic strength, and pH, are also critical. Fibrous shapes require a lower viscosity in the dispersed phase (Sui et al. 2024). Moreover, barrel temperatures must be carefully controlled, where temperatures below 120°C result in insufficient energy for protein reorganization, yielding dough-like textures. Conversely, temperatures above 160°C cause excessive aggregation that negatively impacts sensory attributes, resulting in rubbery textures and mouthfeel perception (Sui et al. 2024). Screw speed also affects shear and thermal treatment time, necessitating optimization with feed rate and material properties. Moisture content (40%–80%, with an optimal range of around 60%) plays an important role, acting as a plasticizer and solvent, influencing protein mobility, gelation, and product texture. If the moisture content is too low, it leads to increased viscosity and hardness, while excessive moisture content results in significant softening of the product. Cooling die design, including length-to-diameter ratio and temperature (20°C–80°C) also affects the final fibrous structure, with longer dies favoring laminar, pork-like textures, and shorter dies simulating chicken-like textures (Sui et al. 2024; Ubbink and Muhialdin 2022; Zhang et al. 2022). Overall, careful control of extrusion parameters, such as temperature, moisture content, screw speed, and feed composition, is essential for optimizing the rheological properties and achieving the desired sensory characteristics in plant-based meat products.

3 | Nutritional Aspects

While replicating the structural and sensorial aspects of traditional meat is crucial for plant-based meat analogues, the health perspective is even more vital. Meat proteins maintain a high biological value, complemented by considerable quantities of vital minerals (like zinc and iron) and vitamins (e.g., B complex), thereby enhancing the nutritional quality of meat-based products (Ishaq et al. 2022). Hence, the composition of meat analogues should be optimized through thoughtful selection of suitable plant-based sources of protein and control of main HME processing parameters to mimic the nutritional characteristics of conventional meat products.

One of the primary nutritional considerations is protein content and quality with balanced amino acid profiles to meet the dietary needs of consumers (Yu et al. 2023). Plant-based proteins are often lacking in specific essential amino acids, rendering them nutritionally insufficient. For instance, proteins sourced from grains tend to be deficient in lysine, threonine, and tryptophan, whereas legumes generally have insufficient amino acids containing sulfur, like cysteine and methionine (Langyan et al. 2021). Various plant-derived protein sources can be mixed to create a more balanced amino acid profile. For example, blending pea protein and rice protein in the right ratios can create a blend with an optimal balance of essential amino acids, adequately meeting human nutritional needs (Clark et al. 2022). Developing new plant protein varieties through breeding and biotechnology can also enhance their nutritional value. Moreover, the analogues can be enriched with essential micronutrients (e.g., iron, zinc, and vitamin B12) to address potential nutrient gaps commonly associated with plant-based diets.

Another nutritional concern regarding meat alternatives pertains to their high carbohydrate content alongside reduced protein levels. In examining plant-based meat alternatives available in Brazilian supermarkets, Lima et al. (2023) found notable nutritional discrepancies compared to conventional meat products (Lima et al. 2023). Among 59 analyzed products, soy appeared to be the primary protein source, and sunflower oil stood out as the predominant lipid source. Plant-based meat alternatives exhibited varied energy, carbohydrate, protein, and lipid profiles, with some exceeding recommended levels for carbohydrates and saturated fat. Only 49% and 23% of the plant-based meat alternatives satisfied the minimum protein and adhered to the maximum carbohydrate limits stipulated by legislation governing meat products, respectively (Lima et al. 2023). These findings emphasize the need for specific regulations for plant-based meat alternatives to ensure nutritional value and promote the expansion of the plant-based meat sector.

Costa-Catala et al. (2023) conducted a comparative analysis of plant-based meat analogues ($n = 100$) and their conventional meat counterparts ($n = 48$) available in the Spanish market. The nutrient composition of meat substitutes exhibited considerable variability, associated with the diverse array of plant-sourced ingredients utilized in the formulation. While some of the meat substitutes displayed a low protein content, others were fortified with cereals and legumes to enhance protein levels. In contrast to traditional meat items, plant-based alternatives generally contained reduced quantities of overall and saturated fats, ranging from 30% in burgers to below 15% in sausages, meatballs, and nuggets, and had greater fiber and starch content. The study concludes that plant-based alternatives cannot be regarded as nutritionally comparable replacements for traditional meat items because of considerable differences in protein levels and other nutritional factors (Costa-Catala et al. 2023).

Recent studies have concentrated on analyzing and enhancing the nutritional characteristics of plant-based alternatives to align with those of animal meat by adjusting macronutrient and micronutrient levels. However, the observed variability in protein levels and additional nutrients among meat alternatives highlights the difficulty in standardizing these products to match the nutritional profile of conventional meat. This inconsistency poses a challenge for consumers seeking a reliable alternative that meets their dietary needs. Additionally, the dependence on fortified ingredients to improve nutritional value introduces questions about the naturalness and processing of these products, potentially discouraging health-conscious consumers.

Though the lower levels of total and saturated fats in meat alternatives compared to traditional meat products may offer a healthier alternative, the higher fiber and complex carbohydrate content may interfere with mineral bioavailability and absorption through binding to minerals, potentially leading to mineral deficiency. These could also pose concerns for individuals following specific dietary guidelines and underscore the significance of taking into account the overall nutritional impact of meat alternatives beyond isolated micronutrient levels (Baye et al. 2017). Additionally, there has been a notable neglect in prioritizing the enhancement of the stability of these nutrients. Given the rigorous HME process involving high temperatures, pressures, and shear forces, investigating the encapsulation of micronutrients to improve their stability can be worthwhile (Amiri Rigi, Pillai, and Emmambux 2022). Encapsulation can enhance the stability of bioactive compounds by shielding them from environmental and processing stresses, as well as by improving their bioavailability (Amiri Rigi, Abbasi, and Emmambux 2022). Encapsulated nutrients can be incorporated either as dry ingredients or within moisture to increase nutrient stability during HME and enhance the nutritional profile of plant-based meat alternatives.

While meat alternatives offer a promising alternative to conventional meat, their nutritional variability and potential health implications necessitate further investigation and regulatory oversight to ensure dietary adequacy and consumer safety. Moreover, recent studies focused on the local markets could restrict the generalizability of the findings to other regions with various eating habits and preferences. Future research should focus on optimizing HME parameters and formulations for plant-based meat alternatives while considering their nutritional impact across diverse cultural contexts to enhance the applicability of findings.

4 | Gastrointestinal Health

Beyond the nutritional characteristics of plant-based meat alternatives, understanding the behavior of the nutritional components (e.g., digestibility and bioavailability) within the digestive system is essential (Lee et al. 2020). The nutritional quality of a protein mixture relies not only on its amino acid profile but also on how effectively the human gastrointestinal tract can break down the proteins and absorb the free amino acids into the bloodstream (Chardigny and Walrand 2016). The FAO established the Digestible Essential Amino Acid Score (DIAAS) in 2013, considering both the amino acid profile and small intestine digestibility (FAO 2013).

Plant proteins can contain natural antinutrients such as phytates, glucosinolates, tannins, isoflavones, saponins, and phenolic compounds, which can hinder the absorption and digestion of proteins and micronutrients. However, in small quantities, some antinutrients (e.g., phytates, saponins, and phenolic compounds) can offer health benefits. Techniques such as fermentation, soaking, heating, and advanced genomic technologies can balance enhancing the bioavailability of proteins and micronutrients while preserving these health benefits. HME may also reduce the levels of antinutritional factors in plant proteins, enhancing their digestibility and nutrient bioavailability (Popova and Mihaylova 2019).

Meat analogues undergo distinct processing steps in comparison to animal-derived meat products, each influencing the bioavailability of both macronutrients and micronutrients (Ishaq et al. 2022). HME induces structural changes in proteins through denaturation and aggregation. Extrusion can improve protein digestibility by altering protein structure, reducing β-sheet content, and increasing intermolecular aggregates. In soy protein, these effects are observed at temperatures above 120°C, screw speeds of 400 rpm, and high moisture content (Fu et al. 2024; Ribeiro et al. 2024). This process transforms proteins from spherical to fibrous forms, disrupts original bonds, and forms new cross-links, leading to increased proportions of shorter peptides in digesta, which can enhance absorption in the gastrointestinal tract (Wang et al. 2024). Additionally, various processing technologies, such as sonication, microwave, and enzymatic hydrolysis, can be applied to plant-based proteins to enhance their digestibility and bioavailability (Shaghaghian et al. 2022).

These modifications can affect protein hydrolysis during digestion, potentially altering amino acid release rates (Osen et al. 2015). Zhu et al. (2021) studied the digestion rates of beef and beef analogues employing an in vitro digestion simulation (Zhu et al. 2021). They found that dietary fibers in meat analogues slowed the rate of fat digestion in the small intestine. Plant proteins were digested more rapidly than meat proteins in the stomach but slower in the small intestine because of differences in protein variety and configuration. In a similar study, the behavior of plant protein isolates sourced from soybeans, lentils, garden peas, and grass peas was examined throughout the digestive process utilizing the Infogest in vitro digestion method (Santos-Hernández et al. 2020). Protein isolate obtained from soybean exhibited the highest percentage of insoluble nitrogen following digestion and released between 21% and 24% of overall nitrogen content as free amino acids throughout intestinal digestion. Pulse proteins withstood gastric digestion but were hydrolyzed into amino acids and peptides throughout digestion in the intestines, making them efficient sources of essential amino acids (Santos-Hernández et al. 2020).

Another investigation in this area analyzed the nutritional properties of plant-based meat alternatives compared with traditional meats by analyzing their chemical composition, peptide profiles, and bioactivity following in vitro gastrointestinal digestion. The peptides derived from plant-based meat analogues and those from beef and pork predominantly had molecular weights between 800 and 1500 Da. Principal component analysis demonstrated that the peptide compositions of beef and pork were significantly different from plant-based meat analogues but showed slight overlaps with chicken peptides. Common peptides among all groups were scarce. Furthermore, peptides derived from plant-based meat analogues had a higher percentage of peptides with high biological scores (33.3%–40.0%) compared to peptides derived from beef and pork (4.8%–20.8%) and were predicted to have superior antibacterial properties (Xing et al. 2022).

However, the relevant studies scope has been limited, focusing predominantly on amino acid and peptide profiles and bioactivity without thoroughly investigating other crucial nutritional aspects like vitamins and minerals. Moreover, the criteria for determining high biological scores of peptides may be impacted by specific in vitro conditions, potentially biasing the results. Though in vitro investigations provide valuable initial insights, they may not directly translate to the human body. Findings from in vitro studies often fail to replicate the complex physiological conditions of the human gastrointestinal tract, such as variations in pH, enzyme activity, and gut microbiota interactions.

Further in vivo investigation into the gastrointestinal fate of plant proteins seems necessary for a more comprehensive understanding of their digestibility behavior. Besides, the potential long-term health impacts of consuming plant-based meat analogues remain largely unknown. Investigating the effects of HME is also essential for optimizing plant-based meat product formulations, as the process can modify protein structures, influencing their functional properties, digestibility, and nutrient bioavailability. For instance, protein modification to achieve desired functionality can alter structural characteristics such as protein denaturation, formation of cross-links, and assembly. These can affect the vulnerability of proteins to hydrolysis by digestive enzymes, influencing the release rates of amino acids and polypeptides. Such changes lead to variations in the digestion rate for quickly digestible, gradually digestible, and non-digestible proteins, which are often not accounted for in vitro models (Kaur et al. 2022). Therefore, multidisciplinary approaches combining in vitro models, in vivo studies, and clinical trials are essential to bridge the knowledge gaps and ensure the development of meat alternatives with optimized gastrointestinal health effects.

5 | Environmental Sustainability

While it is apparent that plant protein production has a smaller environmental footprint compared to animal meat, the sustainability of the process depends on how the agroecosystem is managed and the methods used for post-harvest processing. Regarding the sustainability of meat alternatives, research findings indicate that products requiring minimal processing, such as those made from whole or minimally modified plant ingredients without extensive fractionation or additives, tend to have a smaller environmental impact (Macdiarmid 2022). However, meat alternatives require extensive processing or significant energy from technology, which can lead to a larger environmental footprint. Ingredients utilized in producing meat analogues may further contribute to negative environmental impacts. For instance, palm oil, often used to enhance the texture, is known for its extensive environmental impact (Macdiarmid 2022). Highly processed plant-based meat alternatives can still have a notable environmental impact or be less sustainable due to energy-intensive production, reliance on resource-heavy crops like soy, and excessive packaging (Bunge et al. 2022; Rust et al. 2020). Hoolohan et al. (2013) found that removing packaging, air transportation of food, and food waste in the food industry reduces greenhouse gases (GHGs) by 12%, 5%, and 3%, respectively, while replacing meat with plant-based meat alternatives leads to a 35% reduction of GHGs (Hoolohan et al. 2013). While plant-based diets are generally more sustainable, prioritizing minimally processed ingredients reduces biodiversity loss, deforestation, and resource depletion, maximizing environmental benefits (Bunge et al. 2022; Macdiarmid 2022).

The traditional method for extracting plant protein ingredients from legumes, such as peas and beans (rich in starch) and soy and lupine (rich in oil), is wet extraction. This wet extraction process demands notable amounts of water and chemicals, such as acidifiers and neutralizers. For example, producing protein isolate derived from lupine legumes requires over 80 kg of water, 22.4 kg of hexane solvent, and 40 g each of NaOH and HCl per kilogram of the isolate (Berghout et al. 2015). Dry fractionation, on the other hand, is a sustainable, energy-efficient, and resource-preserving technique for obtaining protein-rich components isolated from legumes using milling and air classification. This process, which is free from water and chemicals while preserving protein functionality, is ideal for organic food production without the need for E-number labelling (Schutyser et al. 2015). Even though dry fractionation results in lower protein enrichment compared to wet extraction, high purity is often unnecessary for many food applications. For instance, soy protein concentrate, which has about 70% protein content, is often preferred over SPI with 90% protein for many applications because it retains more of the natural components, such as carbohydrates. These components can improve the functional characteristics of the end product during HME and enhance texture, moisture retention, and overall sensory qualities (Kyriakopoulou et al. 2021). Plant protein isolate extracted by wet procedure results in a more compact texture after HME, whereas concentrate obtained from the dry method yields a spongier texture as a result of its more porous structure (Miller et al. 2024). The porous texture contributes to a juicier mouthfeel in meat alternatives (Zhu et al. 2021). Additionally, the presence of water-binding fibers can enhance gelling properties, beneficial for some plant-based meat analogues. However, despite the promise of dry fractionation to create efficient, integrated processes using the whole legume, the variability in fraction composition requires careful management (Schutyser et al. 2015).

Plant-based extrusion production of meat alternatives shows notable economic differences among protein sources. However, existing studies have not reported specific input cost figures for soy, pea, or wheat (Baune et al. 2022). The relevant literature indicated that soy and wheat benefit from global market presence and established supply chains, whereas pea protein extrusion could offer cost reductions through more flexible ingredient formulations (Onwulata and Mcaloon 2011). Zhong et al. (2023) have identified the optimal formulation for a plant-based beef patty, with a raw material cost of approximately $3.54 per serving, while distribution and storage expenses were estimated at $0.41 per unit of production. Additionally, the ideal market size for plant-based meat alternatives was calculated to represent 0.083% of the total meat market, which consumed 84.6 million kg of meat alternatives annually in 2021 (Zhong et al. 2023).

A recent study by Jarunglumlert et al. (2023) carried out a techno-economic analysis of plant-based meat production from soy protein through the freeze-alignment method. Their research provided valuable insights into the cost structure of PBM production, showing that raw material and labor costs together represented over half of the total production cost, with raw materials accounting for 32.09% and labor for 23.53%. Despite these significant costs, the study suggested that PBM production is economically viable, with positive financial indicators such as net present value (NPV) and internal rate of return (IRR). This finding is particularly relevant for assessing the economic sustainability of PBMs against traditional meats. Though high moisture extrusion was not directly examined, this study offered a comparable economic perspective for PBM production and highlighted strategies that could reduce costs across various production methods.

While LCAs reveal that vegetarian and vegan diets have substantially lower environmental impacts compared with diets including red meat, future research should consider incorporating comprehensive LCA methodologies to evaluate the sustainability of the entire process. Figure 2 demonstrates an example of a comprehensive LCA for commonly known meat substitutes, detailing the various stages from raw material sourcing to end-of-life disposal.

This contains an analysis of inputs and outputs at each phase, highlighting the environmental impacts and resource utilization associated with each stage. LCAs can compare plant-based proteins with animal-based proteins by evaluating elements like resource use, carbon footprint, nutrient pollution, biodiversity influence, and waste production throughout the life cycle (González et al. 2020). However, the results can vary based on the specific variety of plant-based protein, the agricultural practices employed, and the geographical location of production. Thus, while LCAs provide valuable insights, they should be part of a broader set of tools and considerations required to fully understand and optimize the sustainability of food production.

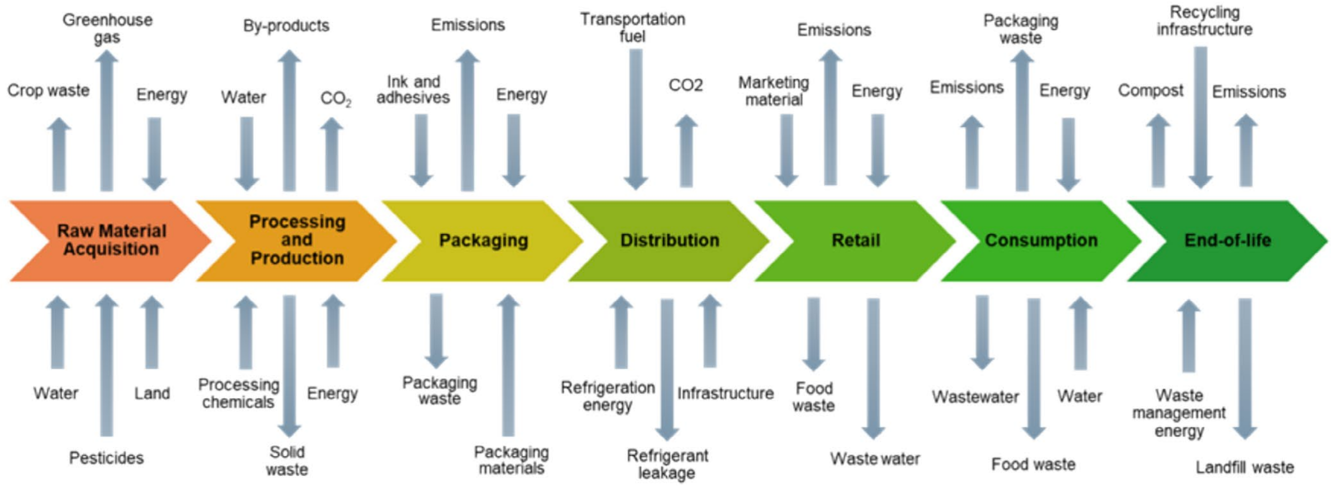

FIGURE 2 | Life cycle assessment of meat alternatives analyzing of inputs and outputs at each phase.

LCA has been used to study the environmental impacts of substituting ground beef with a new plant-based protein in the American diet (Goldstein et al. 2017). The research revealed that vegetarian and vegan diets substantially decreased water consumption, land use, and GHGs relative to the typical US diet. Replacing 10%–50% of beef patties with plant-based burgers (PBB) offered significant environmental benefits. Nonetheless, if not carefully managed, the production of PBBs could exert additional land-use pressures on biodiversity hotspots.

Similarly, the Centre for Sustainable Systems at the University of Michigan performed a comprehensive LCA of the Beyond Burger, comparing its environmental impact to that of conventional US beef production. This study analyzed energy consumption, water use, land occupation, and GHGs. The results revealed that the Beyond Burger had over 99% lower water scarcity impact, required 93% less land, released 90% lower GHGs, and used 46% less energy compared with a 4-oz serving of American beef. Key factors contributing to the environmental footprint of the Beyond Burger included its ingredients, such as pea protein, canola oil, and coconut oil, as well as its packaging (Heller and Gregory 2018).

However, these studies mainly concentrated on carbon emissions, water consumption, energy usage, and land occupation, overlooking other crucial impact categories like biodiversity, soil health, eutrophication, and acidification. The assessments may lack consideration of regional variations and long-term environmental effects and do not deeply explore the environmental impacts of sourcing components like pea protein and canola oil, particularly concerning their agricultural practices and regional effects. Further, the comparative baseline could be expanded to incorporate a wider variety of protein sources for a more thorough investigation.

6 | Labelling Requirements

The label assigned to food can significantly impact its appeal, influencing its acceptance (Wolfson and Oshinsky 1996). Labels and certifications serve as a means for producers and consumers to exchange and convey information. Labelling is necessary when consumers cannot identify the credence attributes they seek, such as greenhouse gas emissions, through the appearance, taste, or smell of the products (van Amstel et al. 2008). The impact of labelling information can vary. For example, organic labels on food have paradoxical effects on consumers, symbolizing healthiness while sometimes acting as a hindrance to willingness to purchase (Schuldt and Hannahan 2013). According to Kunst and Hohle (2016) findings, labelling of "beef" or "pork" products with terms like "cow" or "pig" increased both empathy and aversion, reducing the desire to eat meat and increasing interest in plant-based products (Kunst and Hohle 2016).

Fulfilling the United Nations Sustainable Development Goals (SDGs) would be achieved by introducing more sustainable food products. The pillars of sustainability are environmental, social, and economic facets (Adesogan et al. 2020; Resare Sahlin et al. 2020). Findings of recent studies indicated that the primary concern for consumers regarding sustainable food was its environmental impact. The results showed that consumers were more concerned about the carbon footprint, but there was less attention given to nitrogen emissions during the production phase (Annunziata and Scarpato 2014; Macdiarmid, Douglas, and Campbell, 2016; Van Loo et al. 2014).

In a study conducted by Turnes et al. (2023), consumers were 3.6 times more likely to reduce their intake of animal protein due to its adverse health effects. Given that GHG is 57 times higher in beef than in tofu, and 4 times higher than in chicken, consumers were 4 times more likely to decrease meat consumption due to environmental concerns (Turnes et al. 2023). In addition, consumers might not consider the source used for the production or usage of pesticides (Shao et al. 2017). Hence, clear and authentic labelling is essential to ensure consumers are adequately educated regarding the environmental advantages of extruded meat analogues compared to traditional meat. Misleading labels can result in confusion and potentially undermine the perceived benefits of meat analogues. Grunert et al. (2014) found that consumers can only recognize sustainable labels which are self-explanatory. Ensuring transparency in labelling can help consumers make more sustainable choices, aligning with the SDGs by promoting eco-friendly food alternatives. The pillars of sustainability have been the foundation for various voluntary sustainability standards such as Fair Trade, particularly within the food industry (Manning et al. 2012; Reinecke et al. 2012). The pillars of sustainability not only interrelate with each other but also have synergistic effects as social or environmental attributes lead to economic advantage (Janßen and Langen 2017).

Labels play a pivotal role in encouraging consumers to choose a plant-based food, as they provide information during shopping, reducing decision-making time (Grunert 2011; Horne 2009) and increasing attitudes toward consumption (Gorton et al. 2021). Habitual behavior is a significant stimulating factor for eating meat, as consumers often select products based on their established habits (Zur and Klöckner 2014), but changing habits can encourage the selection of meat alternatives. Weinstein (1988) showed that the prerequisite for adopting new habits is consumer awareness of the advantage of action on society and themselves (Weinstein 1988), which can be feasible by labelling. Consumers have a rational decision-making reaction to sustainable labels, so they buy sustainable products when the perceived advantages exceed the costs. Consumer confidence in the reliability and accuracy of the information provided on the labels is indispensable for encouraging them to choose sustainable products (Sirieix et al. 2013).

According to the grounded cognition theory of desire, food-related cues such as sensory attributes, hedonic qualities, and contextual factors initiate cognitive simulations of eating that food (Papies, Barsalou, and Rusz 2020; Papies, Johannes, et al. 2020). These mental simulations create positive experiences in the mind, which in turn enhance the appeal of the food and its desirability. Carlsson et al. (2022) scored six features based on their importance in choosing meat substitutes: label (6.2), taste (6), price (5.9), visibility in supermarkets (5.7), supplying at restaurants (5.2), and taxing (3.8). Response to labels depended on previous experiences, and for those unfamiliar with plant-based products, taste was a considerable attribute. Notably, labels containing information about animal care ranked as very important, followed by antibiotic use and health, whereas climate impact and price were considered unimportant by respondents in this particular research. Additionally, more than half of respondents claimed that they could not find the required information to make a purchasing decision (Carlsson et al. 2022).

Familiar meat-related labels (e.g., steak, nuggets, meatballs) can help conceptualize meat-like sensory attributes compared to neutral words (e.g., slice, bites, pieces). However, plant-based products, such as vegetarian burgers, nuggets, and meatballs, face labeling restrictions. For instance, in 2024, the government of France prohibited the utilization of meat-based labels for these products, addressing concerns about potential consumer confusion (Southey 2024). In contrast, the European Parliament supported the use of meat-based terms for labeling plant-based items (European Parliament and Council of the European Union 2002, 2011).

Papies, Johannes, et al. (2020) found that plant-based foods with labels associated with taste, mouthfeel, and other sensorial characteristics enhanced the attractiveness of these products, especially to the omnivorous. Therefore, simulation-based descriptions can increase willingness to buy meat substitutes compared to just listing ingredients (Collier et al. 2021). Collier et al. (2021) found that simulation-based labels were effective in changing the habitual behavior of those who like meat and in reducing their aversion to plant-based foods. Offering plant-based meat products in smaller quantities may also encourage trial and repeat purchases, which can drive demand and expand their availability in the market (Funder and Ozer 2019).

The grounded cognition theory of desire can be applied to labelling plant-based meat alternatives, as their environmentally friendly impact and health benefits may influence consumer perception and preference. According to some research, health-focused labels decrease the desire for food and may adversely affect people, causing them to worry (Liem et al. 2012; Turnwald et al. 2017). Specifying words such as taste or context that are indicative of a unique rewarding feature of the alternative ingredients on the label of plant-based products could make them more appealing and engaging for consumers.

However, the grounded cognition theory of desire is debatable due to the various desires, cultures, ages, and even genders of consumers. For example, some people prefer choosing food based on their previous pleasurable experiences, while ethical opinions may be preferable for others. Therefore, it seems that simulation labels need to be designed with different stimulating representations tailored to consumer preferences, which are extremely heterogeneous. Furthermore, there is the question of whether such labeling strategies might oversimplify consumer behavior and fail to address deeper, more complex motivations behind plant-based food choices. It can be argued that relying too heavily on sensory and contextual cues could overlook the essence of educating consumers about the broader environmental and ethical consequences of their dietary decisions, thus limiting the potential for long-term behavioral transformation.

7 | Marketing Strategies

Meat consumption is linked to economic growth (Fiala 2008) and worldwide consumption of animal flesh is predicted to soar about 75%–80% by 2050 (Wellesley et al. 2015). Given the rising meat consumption, it would be extremely challenging to meet the goals of the UN Paris Agreement of keeping the global warming trend below 2°C. Reducing meat consumption is essential to attain UN Sustainable Development Objective 2 (eliminating hunger and malnutrition) and Goal 13 (immediate measures to address climate change). Sustainability standards open opportunities in appropriate markets for sustainable products. The increasing sales of organic and Fair Trade food products underscore the need to understand the impact of sustainability on purchase decisions and consumer preferences (Shao et al. 2017). Some policymakers and market-based levers suggest carbon taxation as an effective strategy for diminishing meat intake (Cuevas and Haines 2016). The recommendation is due to the higher carbon footprint of animal-derived foods compared to plant-based alternatives, which could result in higher prices of animal-based food. Therefore, taxing animal products could potentially have a win-win impact on human well-being and the mitigation of GHG, especially in high-and middle-income countries (Springmann et al. 2017). However, taxation could have adverse consequences on the nutrition of the low-income population (Springmann et al. 2017).

Decreasing the market price of meat alternatives can be a viable strategy for supporting the environment and human health at all income levels (Joshi and Kumar 2016). However, the total market share of meat alternatives is small (Mintel 2013) because of their higher price compared to meat products. This suggests a significant barrier to their adoption that requires addressing through economic and educational measures. There have been contradictory opinions on the economic facet, as some consumers believe that they would pay an extra cost for plant-based meat substitutes, while others argue that sustainable products should be affordable (de Garcez Oliveira Padilha et al. 2021).

In nations with low social acceptability for meat alternatives, the substitution effect would be negligible even if their price decreased by 75% (Ritchie et al. 2018). According to research findings by Slade (2018) using a mixed logit model conducted in Canada, the distribution of sales between traditional beef burgers, high-moisture extruded PBB, and lab-grown burgers would be 65%, 21%, and 11%, respectively, if their price remained constant at $4 (Slade 2018). A similar study investigated US consumer willingness to pay (WTP) and found that 31% of American consumers are certain and 34% are likely to buy lab-grown meat. Although 65% of US consumers are open to trying new foods, just one-third of them eat these products regularly (Wilks and Phillips 2017). Evaluation of WTP values for different meat products in another study showed that WTP was the highest (72%) for farm-raised beef compared to lab-grown meat with the lowest WTP (5%) (Van Loo et al. 2020).

In the USA, China, and India, the percentages of consumers with the highest WTP for plant-based meat substitutes were 32.9%, 62.4%, and 62.8%, respectively; those with moderate WTP were 41.8%, 33.2%, and 31.7%, respectively; and those with no WTP were 25.3%, 4.4%, and 5.5%, respectively (Bryant et al. 2019). The key motivations for purchasing plant-based meat alternatives included attraction, enthusiasm, and minimal aversion in the USA; nutritiousness, attractiveness, flavor, and eco-friendliness in China, and sustainability, excitement, essentiality, and quality in India. Providing sustainability information enhanced WTP for plant-based alternatives, whereas technology information had the opposite effect (Bryant et al. 2019). This highlights the essence of effective communication strategies tailored to consumer values. Presenting sustainability information can stimulate new consumers toward PBB without necessarily reducing the beef market share.

Research on demographic aspects indicated that vegetarian, more highly educated, and young consumers frequently preferred non-beef alternatives. However, it has been suggested that the current demand for plant-based meat substitutes is driven by novelty, which may gradually wane. Some well-known fast food chains, like Burger King, experienced initial sales growth when introducing PBB, followed by a decline in sales (Times 2020). According to the International Food Information Council (2020), it is projected that about 50% of US consumers will try plant-based meat substitutes in the foreseeable future. Economists have identified a positive relationship between income and meat consumption in countries such as China and Brazil as higher income levels are associated with higher meat consumption. Additionally, there is a debate on the attractiveness of plant-based meat substitutes in developing countries because of their low income and low protein intake (Kearney 2010). Placing meat substitutes in central positions on supermarket shelves can increase their visibility and accessibility. By designing appealing labels and marketing strategies, plant-based products can become mainstream within the food sector (Wunsch 2022).

The market share of European plant-based meat is predicted to exceed 3 billion US dollars by 2028. Germany and the United Kingdom, with sales of about 643 and 530 million euros, respectively, have dominated the markets for plant-based meat alternatives in European countries. These two countries have accounted for more than half of the market share of plant-based meat alternatives in Europe. Scandinavian countries have spent the most on plant-based meat alternatives per capita among European countries. Per capita consumption of meat alternatives in the European Union was calculated at a quarter of a kilogram in 2023 and is predicted to reach 0.4 kg by 2028 (Wunsch 2022). Political views can significantly influence WTP for plant-based meat substitutes. In the USA and India, more liberal citizens had a higher WTP because they placed a high emphasis on universalism and benevolence and less emphasis on conformity and tradition (de Garcez Oliveira Padilha et al. 2021).

While the presented studies and strategies provide valuable insights into reducing meat consumption and promoting plant-based alternatives, several limitations still need to be addressed. Firstly, the reliance on economic incentives such as carbon taxation can raise ethical concerns regarding its impact on low-income populations, potentially worsening nutritional disparities rather than alleviating them. Further, while the novelty and initial excitement surrounding plant-based meat products can drive temporary sales growth, the long-term sustainability of this demand remains questionable. Recent studies often overlooked the cultural and social factors that significantly impact dietary habits, especially in developing countries where plant-based alternatives might not be culturally acceptable or economically feasible. Additionally, the market research is mainly focused on higher income countries, leaving a gap in understanding the behaviors and preferences of consumers in lower-income regions.

The influence of brand recognition and effective marketing strategies on consumer willingness to pay for meat alternatives recommends that public perception and misinformation can heavily affect market dynamics, necessitating a more nuanced strategy for consumer education. Lastly, while political views are shown to influence consumer behavior, this relationship might oversimplify the complex interplay of values, habits, and economic capacities across different demographics. Future studies should strive to fill these gaps and offer a more holistic understanding of the challenges and opportunities in marketing strategies as we transition toward a more sustainable food production.

8 | Conclusion

The escalating global demand for protein underscores the importance of plant-based meat alternatives. Transitioning to plant-based proteins aligns with key UN Sustainable Development

Goals (SDGs), including SDG2 (zero hunger and malnutrition) and SDG13 (urgent action to combat climate change). Moreover, the shift toward plant-based alternatives supports animal welfare by reducing reliance on slaughter and antibiotics, positively impacting the socio-cultural and health pillar of sustainability. Effective transformation of plant protein into the anisotropic texture of meat products requires a meticulous selection of raw materials, pretreatment techniques, formulations, and processing technologies. Choices in these areas should be guided by consumer preferences, as informed by the grounded cognition theory of desire and principles of sustainability. Addressing economic considerations and reducing the market price of plant-based meat substitutes may be a more viable strategy compared to meat taxation policy, encouraging greater consumer adaptation. Labels should concentrate on the environmental pillar of sustainability, as this pillar seems to be the primary stimulating factor for consumers compared to health and ingredient concerns. LCA have demonstrated that replacing animal proteins with plant-based alternatives can result in more sustainable products with reduced environmental impact. However, the overall sustainability of plant-based meat alternatives remains disputable due to varying water and land use, energy consumption during processing, and pricing dynamics. Future research should focus on optimizing the sustainability of plant-based meat production by improving agricultural practices, enhancing processing efficiencies, and developing comprehensive LCA methodologies. Additionally, interdisciplinary research integrating consumer behavior, nutritional perspectives, market dynamics, and technological innovation is essential to ensure the scalability and wider societal acceptance of plant-based meat alternatives.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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