Volume 4, Issue 3, 2026

Frontier in Medical & Health Research

ISSN: (e) 3007-1607 (p) 3007-1593

PLANT-BASED MEAT ALTERNATIVES: NUTRITIONAL QUALITY, PROCESSING TECHNOLOGIES, HEALTH IMPLICATIONS, AND FUTURE PERSPECTIVES

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DOI: https://doi.org/10.5281/zenodo.22763425

Keywords

Meat analogues; Nutritional quality; Extrusion technology; 3D food printing; Sustainability; Alternative proteins.

Article History

Received: 20 January 2026
Accepted: 05 March 2026
Published: 19 March 2026

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Abstract

The excessive meat consumption globally has increased the growing concerns regarding sustainability of environment, resource depletion, and the health-related issues, the prevalent issues lead to development of plant-based meat alternatives as replacements for traditional animal-derived meat products. Plant-based meat substitutes are formulated by means of plant-based proteins such as soy, wheat, rice, pea and legumes and are considered to replicate the sensory, nutritional, and functional properties of meat. This review highlights the insightful overview of the nutritional quality, processing technologies, health implications, and future prospects of PBMAs. In Nutritional perspective, there are several advantages possessed by meat alternative products from having lower levels of saturated fat, absence of cholesterol, and the presence of dietary fiber and other bioactive compounds. However, concerns remain highlighting the digestibility of proteins, essential amino-acids balance, and the bioavailability of micronutrients. The sensory and textural characteristics of PBMAs have significantly improving by utilization of recent advancements in processing technologies, including high-moisture extrusion, high-temperature conical shear cell processing, and three-dimensional (3D) food printing as they create fibrous like structures that shows similarities with animal muscle tissue. The potential health benefits of PBMAs include reducing the risks of cardiovascular and other heart related diseases, obesity, and metabolic disorders, while highlighting challenges related to ultra-processing, sodium content, additives, and food safety require further investigation. In addition, PBMAs offer environmental benefits through lower greenhouse gas emissions, reduced land requirements, and decreased water consumption compared with livestock production. Despite substantial progress, challenges related to consumer acceptance, product quality, cost, and regulatory frameworks persist. Future research should focus on enhancing nutritional value, sensory attributes, sustainability, and processing efficiency to support the broader adoption of PBMAs within sustainable food systems.

Introduction

The agriculture food system plays a pivotal role in ecological and human well-being. Contemporarily maladaptive food systems are significantly endangering population health and ecological integrity (European Commission 2020).

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ISSN: (e) 3007-1607 (p) 3007-1593

According to recent research and data evaluation it has been estimated that by 2050 planetary population is anticipated to reach 10 billion. Overpopulation will lead to depletion of natural resources so sustainable environmental practices are needed to be employed (Sridhar et al., 2023). In subsequent years demand for food commodities is envisaged to rise by nearly half. Correspondingly global requirement for animal origin food will increase about 70%. Existing food provisioning system is insufficiently developed to cope up with the forthcoming food challenges (Choudhury et al., 2020; Gastaldello et al., 2022). Food provisioning processes leads to drastic environmental changes. Agriculture based food products are driving one-third of human origin greenhouse gas emission. In distinction from this much more natural capital is required for production of livestock derived food products culminating in woodland clearance and reduction in species diversity. Overconsumption of meat can cause serious health implications due to presence of saturated fats, processed meat and higher cholesterol (Rust et al., 2020; Tso & Forde, 2021). Due to its elevated saturated lipid components and dietary cholesterol profile its hyper consumption can leads to the risk of cardiovascular diseases (Xazela et al., 2017).

The adoption towards the plant-based meat alternative is derived by the concept of sustainable diets has become a central factor in developing this innovative approach. According to the Food and Agriculture Organization (FAO), sustainable diets are dietary patterns that encourage human health and overall well-being and this approach is specifically leading the world to minimizing environmental impacts, preserving biodiversity, remaining culturally acceptable, and ensuring economic affordability. Livestock production contributes substantially to global greenhouse gas emissions, more water consumption, land use, and ultimately degradation of ecosystem. Replacing even a portion of animal meat with PBMAs can substantially reduce carbon emissions, conserve water resources, and improve land-use efficiency. Several life cycle assessment studies have demonstrated that PBMAs generally require significantly fewer natural resources and generate lower environmental footprints than traditional meat production. As governments, international organizations, and consumers increasingly prioritize climate change mitigation and sustainable food systems, PBMAs have emerged as an essential component of future sustainable diets (Poore & Nemecek, 2018; Willett et al., 2019). According to latest empirical analysis in the past 20 years worldwide demand for meat is elevated by 58%. Due to exponential population growth Plant Based Meat Alternatives have emerged as one promising alternative for competing the market equilibrium disturbance balance for the protein because it is not only the source of nutrients but is also the principal determinant behind eco system disruption. Plant based meat alternative have emerged as one of the promising strategies for reducing the human dependance on conventional livestock production. Plant based meat formulation is known with diverse nomenclature such as meat substitute, meat analogue, vegan substitutes and artificial meat (Sha and Xiong, 2020).

Plant-based protein-based meat substitutes are designed in such a way that they closely resemble the conventional meat. As a consequence of sensory quality, chromatic property, nutrient profile, structural consistency, heterogeneity and costing they have stimulated strong consumer demand. Vegan meat contains a vast amount of macro and micro nutrients such as protein, iron, calcium, minerals and fatty acids (Ismail., 2020). Augmented awareness, technological advancements and sociocultural-economic transformations have revolutionized the mindset of people regarding meat consumption. Rising consumer awareness regarding health, environmental sustainability, and animal welfare has knowingly increased public interest in plant-based meat alternatives; however, widespread adoption towards this innovative concept still depends on improvements in sensory quality, affordability, and consumer acceptance. Novel meat analog formulations can be generated from multifarious sources. These sources entail soybean extracted from vegetal sources, millet, rice and wheat generated from cereal-based resources. Hemp and chia procured from seed matrices.

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Oleaginous derived walnuts and almonds. Legume derived lentils, beans and peas. More over microalgal and entomological resources also play a significant role in generation of novel meat substitutes (Oliver et al., 2022).

Despite the rapid commercialization and increasing scientific interest in plant-based meat alternatives, challenges remain regarding nutritional equivalence, processing technologies, sensory quality, consumer acceptance, and long-term health impacts. Therefore, this review comprehensively summarizes the nutritional composition, raw materials, processing technologies, physicochemical properties, health implications, environmental sustainability, regulatory aspects, current challenges, and future perspectives of PBMAs. By integrating recent advances in food science and technology, this review aims to provide a comprehensive understanding of the opportunities and limitations associated with next-generation plant-based meat products.

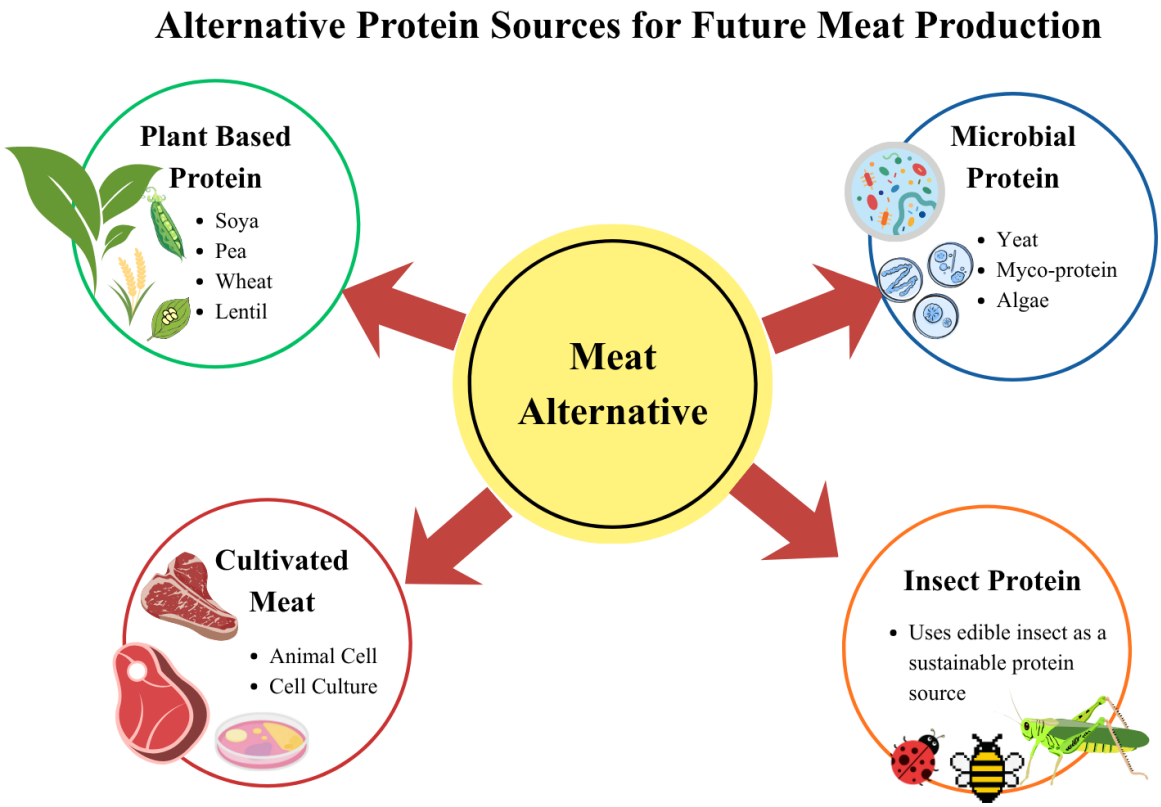


Figure 1: Protein Sources for production of plant-based meat alternatives

Lentils, oats, peas, wheat, rice and soybean are the major plant sources from where plant sourced protein-based meat alternatives are derived (Kyriakopoulou et al., 2021). There are four major classifications of non-conventional protein sources it includes Phyto-derived protein matrices, cell-cultured meat systems, microbial protein systems and arthropod based protein formulations (Sha and Xiong, 2020).

Relationship Between Skeletal Muscle Structure and Sensory Attributes of Meat

On micromorphological examination it has been evidenced that farm derived meat has complex structural framework because of systematically arranged subcomponents present within it. These hierarchically arranged components are muscle fibers, myofibrils, sarcomeres, thick and thin myofilaments such as actin and myosin. Pattern of distribution and structure of these micro

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components determines multidimensional structural and sensory properties. An oxygen carrying protein myoglobin gives meat its characteristic red pigmentation. Myofibrillar units and connective tissue matrix are continuously arranged in a regular order which governs mastication properties and textural softness. Thick and thin myofilament augment juiciness and moisture retention through their aqueous retention capability. Throughout thermal processing gustatory and olfactory properties of meat are enhanced due to mutual interactions among fats, proteins and flavor progenitor molecules. In contrast plant-based meat alternatives lack such organized structural composition therefore some structural associated meat properties are not embodied in them (Moss et al., 2023). There is a huge difference between the morphological and physicochemical organization of animal and plant-based meat. Plant derived meat lacks many essential amino acids as well certain proteins like actin and filament, certain pigments are absent along with other structural components that are present in animal sourced meat. Due to the absence of these key constituents' plant-based meat alternatives have still not achieved the structural and chemical makeup like real meat there is a huge difference in taste and aroma of plant derived meat substitutes.

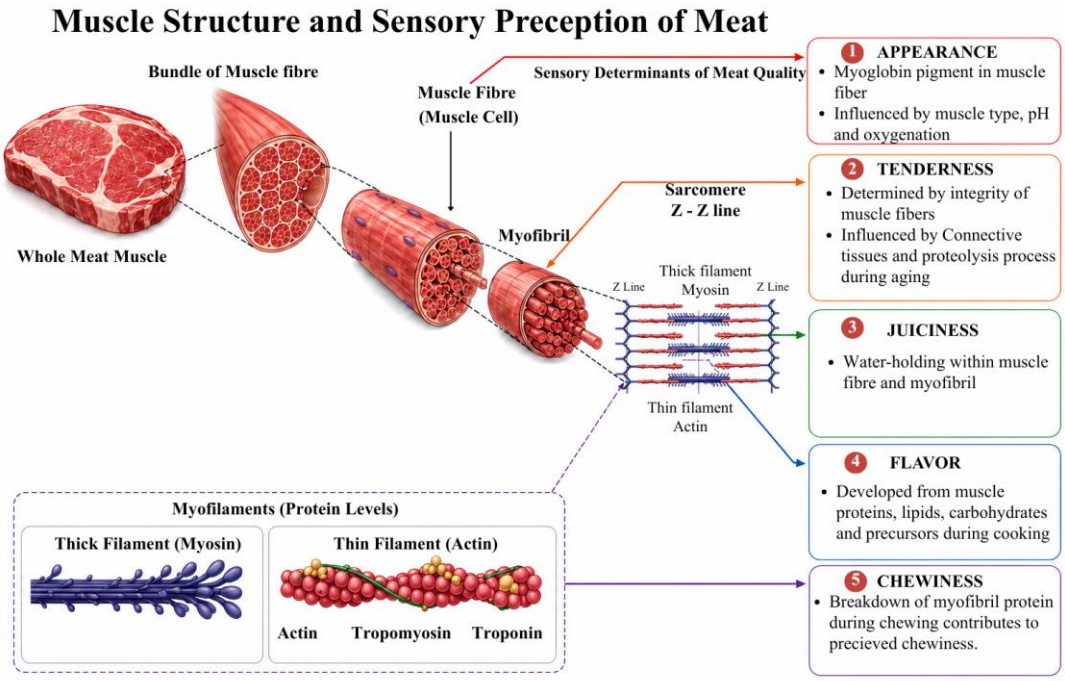


Figure 2: Schematic Diagram showing muscle structure and sensory attributes of Meat

Current investigations have revealed that textural properties and flavor perception are the parameters on the base of which people evaluate the quality of the product and by enhancing these indicators consumer acceptance for the plant-based meat products can be enhanced. To increase the market receptiveness of the meat alternatives more working in needed to be done on sensory properties because people can easily determine distinctions between plant and animal- based meat. To achieve original meat like properties in plant-based meat scientists are implementing contemporary processing strategies encompassing 3D food printing, electrospinning, moisture extrusion and shear-cell technology. For achieving fibrous protein like structure as in animal meat 3D food printing technique has been vastly employed. To enhance the quality of plant driven meat to improve olfactory properties flavors are added. To increase tenderness fats are added, artificial coloring agents are used to give characteristic color to the meat (Appiani et al., 2023). To optimize

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quality attributes and consumer endorsement in PBMAs scientist must have complete insight of the structural components of the real meat which are responsible for the enhancement of sensory characteristics of the meat so that they become able to synthesize PBMAs that are conformationally similar to real meat. It will also assist in choosing the appropriate processing technology based on choice of plant protein isolates (Jang et al., 2024).

Nutritional Quality of Plant Based Meat Products

Optimized formulation of PBMAs exerts a profound impact on their nutrient profile. Upon rigorous analysis it was elucidated that plant-based meat can provide augmented dietary quality but it depends on the processing methodologies. If they are meticulously processed due to presence of quality protein their nutritive quality significantly elevates. Upon recurrent assessment it was analyzed that when plant sourced meat is paired with low lipid concentration and 30% protein its nutritional profile becomes better than the traditional meat. While comparing the dietary profile of traditional meat and PBMAs the micro and macro nutrients must be critically compared to elucidate the comprehensive physiological benefits of both. Heam group is indispensable for the transport of oxygen in the blood therefore heme bound iron is efficiently absorbed into the bloodstream as compared to the non heme one. Plant based meat usually contains the non heme iron. Genetic engineering significantly plays its role in enhancing the nutrient profile of PBMAs as heme is the important determinant of the nutritional quality. Engineered microbial yeast strains are employed to produce heme protein widely recognized as leghemoglobin is administered into the PBMAs to enhance the iron profile. Cobalamin vitamin B12 required throughout the life is absent in the PBMAs. Due to abundant fiber content in plant sourced meat, it is beneficial for enhancing gut health by providing food to eubiotic gut microbiota but more research is needed to comprehend its role on gut health (Imran and Liyan, 2023).

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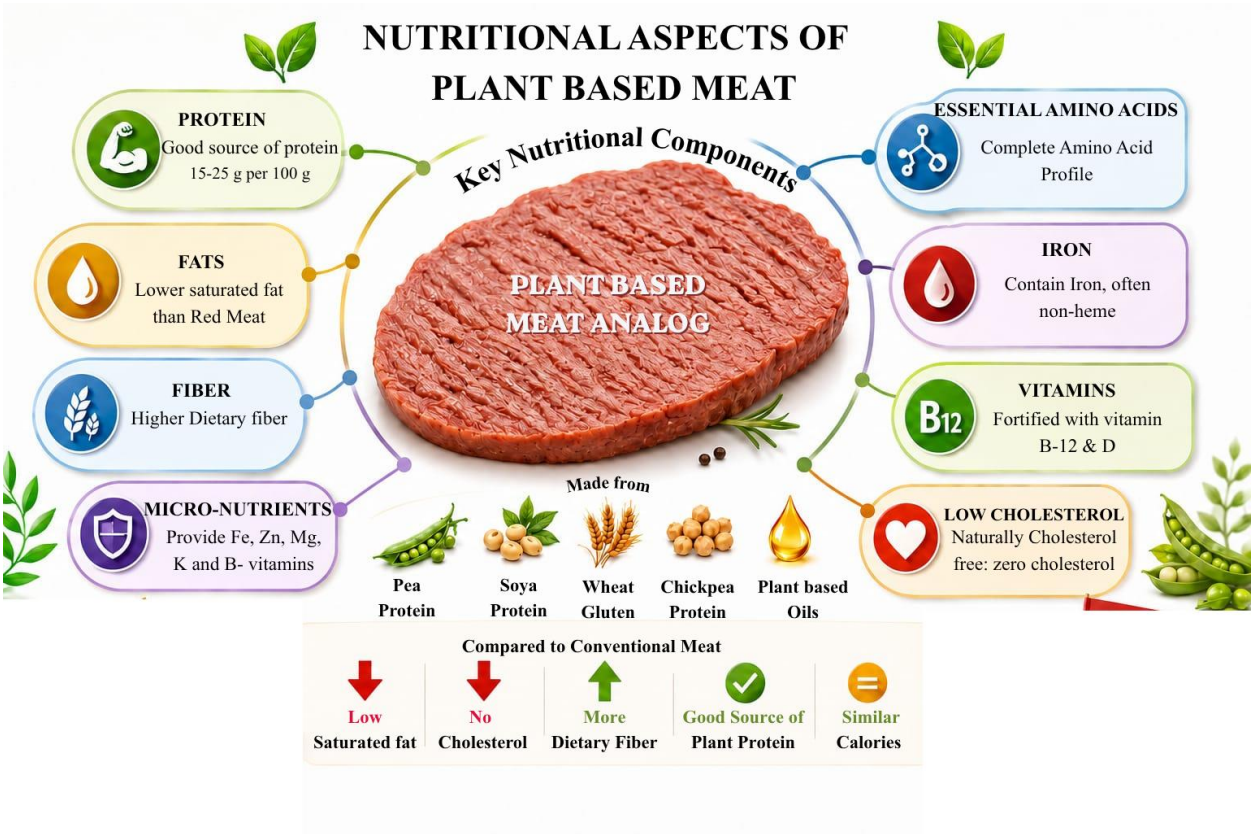


Figure 3: Representation of Nutritional qualities of plant-based meat analog

Excessive consumption of real meat can cause severe health complications because of its high cholesterol and saturated lipid profile but these issues are not noticed in PBMAs because they are non-cholesterolemic. Plant based meat alternatives play important role in maintaining healthy lifestyle through their substantial polyphenol and fiber enriched matrix. PBMAs can be use in prevention of certain lethal diseases such as pro-inflammatory states, cardiovascular pathology, insulin resistance and metabolic dysregulation. They play significant role in inhibiting the spread of cancerous tumors through their anticarcinogenic potential. Purines are heterocyclic nitrogenous bases that can cause renal dysfunction if consumed excessively due to formation of uric acid. Purines such as adenine and hypoxanthine are present in both plant and animal sourced meat so their consumption pattern should be highly monitored to prevent kidney related disorders especially in the patients that are already suffering from nephropathy. PBMAs derived from wheat, soy, fungal sources and wheat are relatively less in purine content (Mankonen et al., 2023). Upon meticulous examination it has been elucidate that certain essential ammino acids are missing in plant derived meat products. In order to overcome this complementary protein system has been introduced. Methionine is absent in legumes and lysine is absent in grains so these both can be paired in human diet to get better nutrition (Feher et al., 2020).

During isolation and processing of soy protein some nutritional losses occur such as reduction in essential amino acid availability due to redox-induced protein modification it impacts its nutritional value and gastrointestinal breakdown efficacy. Nevertheless, soy is still nutritionally enriched due to the presence of arabinose, fructose, galactose, rhamnose and xylose. In addition, its inherent innate water affinity and contains raffinose and fractions comprising tryptophan moieties. PBMAs are designed to fully

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replace the traditional meat but it has not been yet achieved completely because of their inherent differences such as absence of certain essential amino acids PBMAs are difficult to digest. Along with that during processing sodium content entailed within it significantly increases which reduces overall dietary quality therefore keen formulations and fortification is still needed (Tso & Forde, 2021; Ismail et al., 2020; Kyriakopoulou et al., 2021).

Processing Technologies

A diverse range of processing methodologies have been devised for developing sensory and structural attributes of real meat into PBMAs. These processing strategies encompass thermos-extrusion, electrospinning, conical shear and wet spinning and many more that are elaborated upon in the following sections. Various quantitative analytical techniques encompassing photon migration method, texture studies, fluorescence polarization spectroscopy, image processing techniques, X-ray tomography, Confocal laser scanning microscope and scanning electron microscope have been employed to deeply analyze and compare the internal configuration, morphology and rheological characteristics of plant driven meat alternatives (Fu et al., 2023).

High Moisture Extrusion Technology

The most pervasive technique employed to acquire muscle inspired fibrillar morphology in PBMAs is high moisture extrusion process it involves a prolonged sequential procedure. Firstly, a highly viscous formulation is prepared by utilizing a special mechanical apparatus referred as single-screw or twin-screw extruder. In this machine protein enriched substrates are amalgamated together to form a viscous matrix. After that the mixture is poured into thermally regulated extrusion chamber where persistent homogenization, shear-induced deformation and thermos-processing converts the viscous mass into continuous viscoelastic network. Upon thermal exposure proteins lost their structural organization there highly modified structures such as tertiary and quaternary opens into a simple chain. After losing the conformational organization they interact with each other and form viscoelastic morphological framework. In the interior domain of thermomechanical extrusion unit protein units are co-aligned, remolded and interconnected via covalent bonds to form a fibril-interwoven structure in correspondence with the real meat. After configuration alignment highly cohesive fibrous texture is developed in synthetic plant-based meat. To stabilize the geometry and structural profile in the final step the heated material is cooled down in the cooling chamber (Vatansever, Tulbek, &Riaz, 2020). All the mechanical processes inside twin-screw extruder are performed in elevated mechanical pressure, shear stress, thermal regime and high hydration level (>40%). Throughout the process disintegration of heat sensitive vitamins such as vitamin B and C occurs along with that substances that reduce absorption of nutrients are also degraded. Additionally, some bioactive compounds like polyphenols, carotenoid and flavonoids are gradually lost. On meticulous observation it is evidenced that upon interaction with oxygen lipid molecular fragmentation occurs along with that starch becomes resistant and by absorbing water appears in a gel like texture this helps in lowering the glycemic index (Wittek et al., 2021). Final texture of the product depends on the manufacturing practices and working efficacy of the machine such as screw speed and feed rate. Five basic components of the apparatus are shown in the figure it includes (1) conditioning chamber (2) input conveyance system (3) extrusion screw assembly (4) extrusion barrel (5) mold or shaping orifice (Wittek et al., 2021).

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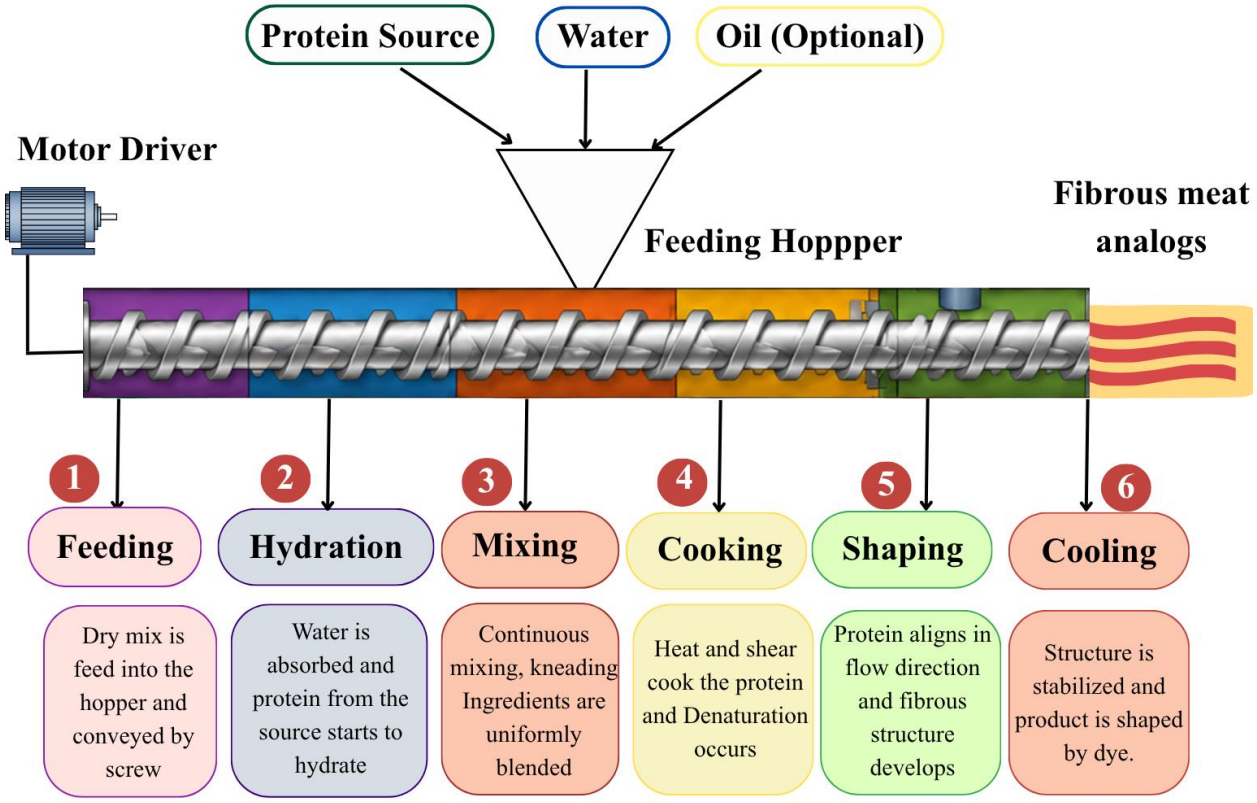


Figure 4: Schematic diagram showing the working of Twin-Screw Extruder

High-temperature conical shear cell (HTSC)

In order to prepare protein-augmented and nutrient-concentrated vegetal meat analogues highly sophisticated mechanical system referred as high-temperature conical shear has been developed. It is composed of coaxial cone-in-cone arrangement and the apical base region of the cone is reconfigurable through rotation. The encapsulated space between the two cones is hermetically sealed so that during processing the steam cannot escape out and the internal conditions remain optimum. Temperature ranging from 95-140 °C is applied on processing substrate. Plant proteins usually wheat gluten + soy protein and pea protein + wheat gluten is used as substrate in this apparatus to make PBMAs. For 15 minutes duration the material is exposed to continuous thermos-mechanical deformation it assists in rearrangement of the protein structure. After that the final product is cooled at room temperature for one hour as a result fibers are monodirectional structured (Sha & Xiong 2020). Proteins synthesized from the combination of pea protein and gluten and soy protein and gluten were administered to various temperatures 110, 120 and 130°C gradually. Peak strength of pea protein-gluten and soy protein-gluten fibers was attained at 140°C. When subjected to 110 and 120°C their strength was relatively decreased but showed comparable textural properties to chicken meat when externally imposed mechanical load was 50-100kPa (Lyu et al., 2022).

3D Printing Technology

By the addition of plant protein in controlled amount muscle like hierarchical assembly is being produced in PBMAs through modernized additive manufacturing technology commonly referred as 3D printing technology. During this process a proteinaceous matrix is formed by convective blending of water and dehydrated protein fraction after this the viscous formulation is configured in

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a stratified arrangement that bears resemblance with myofibrillar assembly of conventional meat matrices. Intermolecular bridging agent transglutaminase is added to provide cohesiveness and structural rigidity. In addition to that some fortifying compounds are added to enhance palatability and rheological attributes. For the preparation of meat-like formulations this composite matrix is used. In order to mold the mixture into real meat 3D printing technology was administered which resulted in formation of product like turkey meat. This technology was vastly adopted by nova meat to make beef stakes and other meat products from PBMAs (Lamb, 2020).

Table: 1 Demonstrating Comparative Analysis between emerging technologies for production of PBMAs Traditional vs new processing Technologies

Attribute	High temperature Conical Shear Cell (HTSC)	High-Moisture Extrusion (HME)	3D Printing Technology	References
Mode of operation	On composite protein matrices carefully modulated thermomechanical forces are applied inside a frustoconical apparatus.	Proteinaceous matrices are chilled after shear-induced deformation, homogenization, thermal processing and molding.	In order to copy the structural organization of original meat, proteins are accreted in multilayered structures through digital fabrication process.	Vatansever et al., (2020); Wittek et al., (2021); Sha & Xiong (2020); Lamb (2020)
Mechanistic framework	To create oriented fibrous assemblies proteinaceous formulations are conferred to sustained thermomechanical cycling.	To produce fibrillar configurations proteinaceous structures undergo conformational disruption, macromolecular unfolding transition, molecular orientation and polymeric network stabilization.	To accomplish mayo architectural configuration proteinaceous paste is subjected to sequential accretion.	Vatansever et al., (2020); Sha & Xiong (2020); lamb (2020)
Optimum processing parameters	Subjected to shear for an approximate period of 15 minutes in thermally isolated environment from 95 to 140°C temperature.	Moisture abundant formulations pertaining more than 40 % moisture are subjected to intensified thermomechanical, compressive and stress regimes.	Transglutaminase is used in constrained fabrication setting to optimize material flow behavior.	Wittek et al., 2021; Sha & Xiong, 2020; Lamb 2020
Feed stock utilized	Legume protein-wheat gluten blend	Through twin-screw extruder	Proteinaceous plant systems integrated	Vatanserver et al., 2020; Sha &

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	matrices (pea and soy based).	heterogenous plant protein matrices are processed.	with functional ingredients and water.	Xiong 2020; Lyu et al., 2020; Lamb 2020
Equipment Layout	Hermetically sealed enclosure with dynamic cone-in-cone shear apparatus.	Feed stock conditioning module, feed conveyance unit, helical transport component, extrusion cylinder and profile-forming nozzle.	Digitally controlled additive manufacturing system with an extrusion-based dispensing nozzle.	Wittek et al., 2021; Sha & Xiong 2020; Lamb, 2020
Competitive edge	In comparison with extrusion and effective anisotropic structuring.	Non-stop and resource-efficient fabrication of fibrillar structures and industrial scale feasibility.	Stringent control over ingredients homogeneity, morphology, mouthfeel properties and microstructure configuration.	Wittek et al, 2021; Lyu et al., 2022; Lamb 2020
Market Competitiveness	Nascent technology at pre-commercial and experimental scale.	Industrially dominant and widely validated manufacturing system.	Developing technological approach with escalating commercial attention but limited commercial scale utilization.	Wittek et al., 2021; Lyu et al., 2022; Lamb 2020

In order to make fibers in resemblance with original muscle fibers contemporary and classical processing technologies have been extensively used. On microscopic analysis it has been reported that the muscle like structure can be copied but the detail structural organization remains unattained. Tenderness of the meat depends on its water captivating capacity fresh meat traps about 85% of water in its myofibrillar spaces (Puolanne & Halonen, 2010). As intermyofibrillar compartments are responsible for aqueous retention if throughout thermal processing they remain unaltered it will foster organoleptic characteristics of meat. Through fluorescence technique Evertz, Morrow, Greising, Sieck and Kaufman (2026) evaluated that for moisture retention extracellular fluid present between fiber fascicle is a key contributor. Modern technologies have been still struggling to develop water retention system within PBMAs but it remains elusive but other sensory attributes like chewiness have been successfully developed.

Health Implications and Food Safety

Label trans piracy is a huge issue faced by consumer while selection for PBMAs because to preserve textural stability, extend product longevity, maintain emulsion stability and to enhance visual resemblance to meat many synthetically active compounds are added that are not clearly mentioned on them (Berman, 2019). These synthetic additives include lecithin titanium dioxide and methylcellulose. On a detailed inspection of dietary profile of PBMAs it was noted that 7 highly consumed meat substitutes entailing hams, nuggets and burgers pertain 20 to 30 formulation constituents that are detrimental to health (Bohrer, 2019). Earlier investigations

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ISSN: (e) 3007-1607 (p) 3007-1593

have pointed out that PBMAs are causing certain lethal diseases including renal dysfunction and cardiovascular diseases due to the presence of elevated sodium content, substantial saturated fat concentration and abundant additive incorporation. Formation of heterocyclic aromatic amines occurs during culinary processing due to the denaturation of proteins entailed within them. HAAs are one of the root causes of malignant tumors because of their carcinogenic propensity (Baregar, Kamankesh, & Mohammadi 2019). On comparison with the real meat, it was noted that when PBMAs were exposed to charbroiling, immersion frying, oven baking and radiant heat processing toxin formation occur due to alteration in protein structure but these all practices enhance the quality, texture and taste of real meat. Fortification of phenolic bioactive with free radical-scavenging capacity in PBMAs inhibits production of noxious substances on frequent thermal processing it can be applied to ensure food safety of plant-based meat alternatives (Sha & Xiong 2020).

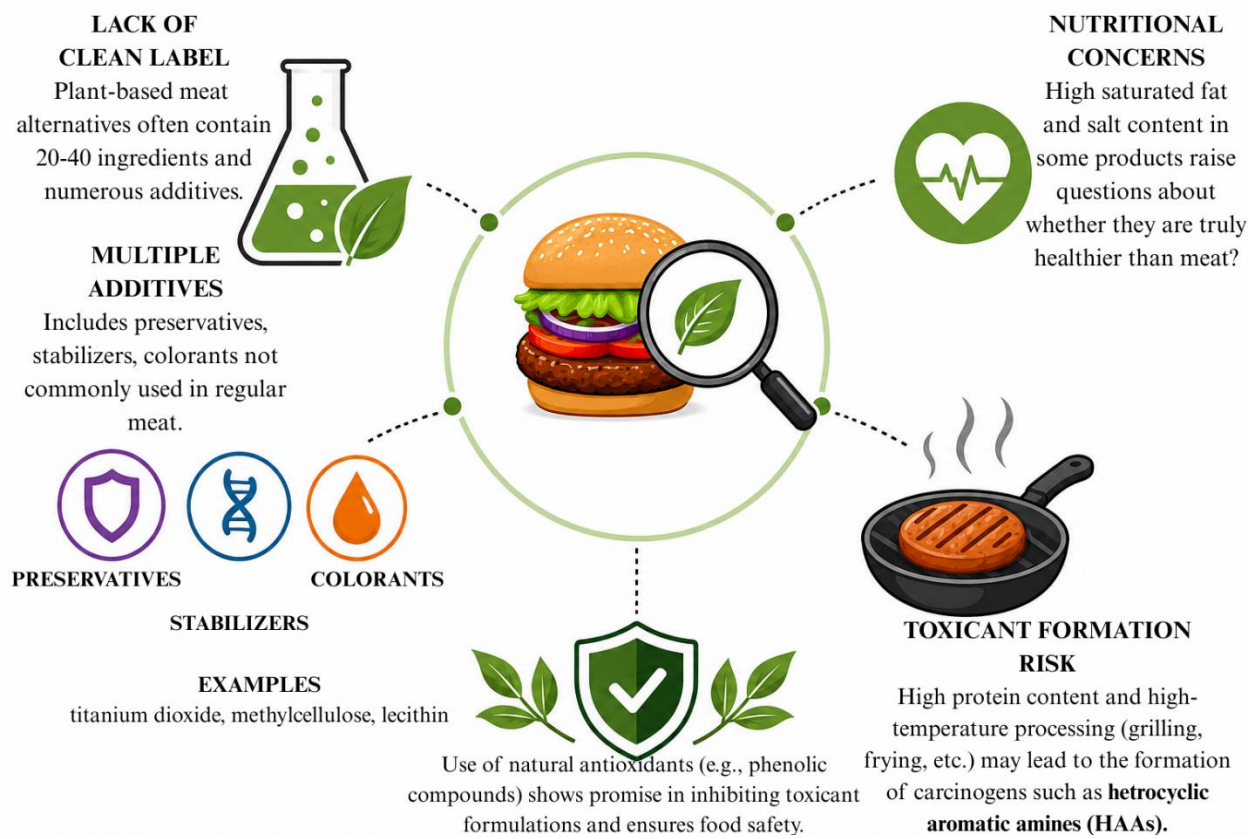


Figure 5: Demonstration of Health Implications and Food Safety Risks associated with PBMAs

Table 2: Overview of nutritional characteristics, health outcomes, and associated challenges of plant-based meat alternatives (PBMAs)

Perspective	Core Conclusion	References
Amino acid profile	PBMAs pertain prominent degree of protein if intricately formulated similar to that of animal protein but still it lacks certain essential ammino acids. Protein quality should be assessed	Tso & Forde, 2021; Kyriakopoulou et al., 2021

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	through both macro and micro nutrient composition.	
Micronutrient spectrum and enrichment approaches	Cyanocobalamin and heme bound iron is absent in PBMAs but is naturally present in real meat. However, it can be fortified in PBMAs.	Imran and Liyan, 2023; Tso & Forde, 2021
Iron biological accessibility	Leghemoglobin produced via yeast fermentation increases absorbable fraction of Fe in plant sourced meat.	Imran and Liyan, 2023
Gastrointestinal microbiota	Plant sourced meat substitutes enhance gastrointestinal health through their high fiber content but more research is still needed.	Imran and Liyan, 2023
Nutritional benefits	Play significant role in enhancing metabolic flux through their free radical scavenging activity, low fat and high fiber content.	Tso & Forde, 2021; Kyriakopoulou et al., 2021
Purine fraction	Soy, wheat and pea contain relatively less purine content but some plant sources are rich in Hypoxanthine and adenine that can leads ko uric acid stone formation.	Maukonen et al., 2023
Industrial formulation constraints	Escalated levels of sodium and non-native ingredients can cause significant clinically relevant health risks.	Kyriakopoulou et al., 2021

Environmental Sustainability of Plant-Based Meat Alternatives

In comparison with the conventional meat products, it has been elucidating that PBMAs possess enhanced environmental sustainability because they produce less greenhouse gases that contribute to global warming. Animal meat production requires an extensive array of natural resources encompassing terrestrial resources, water reserves, fodder and power resources. On the other hand, PBMAs consume fewer natural resources and promote ecological viability by promoting afforestation and reducing the rate of floods. Substantial greenhouse gases including nitrous oxide, carbon dioxide and methane are produced by ruminant livestock. On statistical analysis it has been validated that in juxtaposition to beef burgers vegetarian burger analogues a substantial (up to 90%) mitigation of greenhouse gas emission was noted. Depending on the preparatory operations, formulation and packaging materials involved the environmental benefits attributed to PBMAs vary from product to product (Poore & Nemecek, 2018; Santo et al., 2020; Tso & Forde, 2021).

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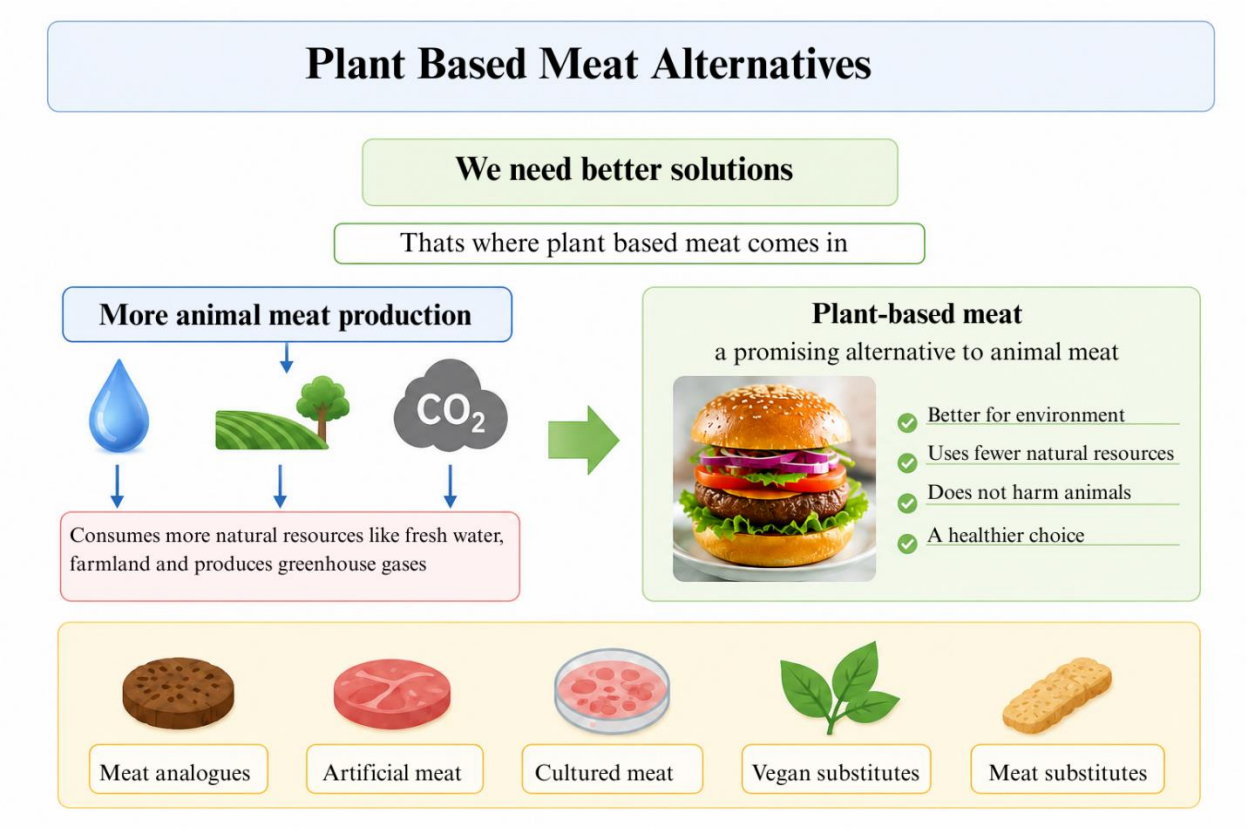


Figure 6: Representation of Ecological Benefits of PBMAs

Future perspective

Plant sourced meat alternatives are gaining extensive market penetration and consumer endorsement but unlike most of the people are unacquainted about their existence. In order to increase public receptiveness towards PBMAs public awareness along with commercialization strategies, brand communication activities, judiciously formulated knowledge dissemination is yet needed. During the manufacturing of PBMAs the main concern was to copy the visual and aromatic profile, palatal sensation and structural consistency of original meat for this purpose scientists tried their best to match the dietary profile of PBMAs with the real meat. Over the course of time after multiple researches PBMAs have been developed that have structural and visual appeal analogous to animal derived meat. For confronting immediate and long-term challenges there is need for improvement in nutritional adequacy, economic viability, flavor fidelity and textural authenticity to grab market acceptance towards plant-based meat alternatives. Companies should build their trust in consumers by adopting effective marketing strategies. Through technological innovations changes are being made in PBMAs for enhancing their quality it will lead to wide consumer acceptance regarding PBMAs (Zhang et al., 2021). Shelf life plays a pivotal role in commercial acceptance of any food product therefore enhancing the shelf life of PBMAs fortification of free radical scavenging agents referred as antioxidant have been done to prevent them from spoilage (Sun et al., 2021; Pakseresht et al., 2022). Right now, industries regarding manufacturing of plant sourced meat alternatives are facing severe challenges like inferior meat-mimetic texture, insufficient public awareness, elevated manufacturing expenditure and nutritional inadequacies. Time to time consumer demands regarding formulation refinement increases so the PBMAs

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manufacturing industries need to improve their formulations to compete each other in addition there is need of ecofriendly PBMAs to reduce the pollution rate. In consideration to present and future concerns research professionals and industrial food manufacturers must develop new strategies that reduce the formation of harmful by products. Many industrial technologies encompassing cryogenic preservation technologies such as vacuum-assisted immersion chilling, cryopreservation, subfreezing refrigeration, hydrodynamic fluidization freezing, high-velocity cryogenic solidification, jet-stream cryogenic freezing, pressure induced phase transition freezing and other non-thermal preservation modalities like cold plasma technology and elevated hydrostatic pressurization are vastly used for increasing the shelf life of PBMAs. There is still need of research to study their detailed impact on human health (Kolodziejczak et al., 2021).

Cost intensive processing approaches and expensive fortifying agents are used while the production of plant sourced meat alternatives to copy the sensory attributes of the real meat they cost more than ordinary meat. Therefore, there is need of production methods that enhance the quality of PBMAs and are budget friendly as well. In order to prevent contamination by unicellular fungal organisms, molds and bacteria there is need to keenly monitor the product encapsulation, logistic conveyance, post-product preservation and market allocation. Industries regarding the manufacturing of PBMAs must follow the laws regarding promotion and advertisement of PBMAs they should not spread false information regarding the plant sourced products. Additionally, they should make labels that are understandable to common man so that they may not confuse the plant sourced meat substitutes with the real meat (Baig et al., 2025).

Conclusion

Plant-based meat alternatives (PBMAs) have emerged as promising substitutes for conventional meat products in response to growing concerns regarding environmental sustainability, food security, animal welfare, and public health. Advances in ingredient selection and processing technologies, including high-moisture extrusion, shear-cell processing, and 3D food printing, have significantly improved the texture, appearance, and sensory characteristics of PBMAs, enabling them to more closely resemble animal-derived meat products. From a nutritional perspective, PBMAs offer several benefits, such as lower saturated fat content, absence of cholesterol, and the presence of dietary fiber and bioactive compounds. However, challenges related to protein quality, micronutrient bioavailability, and the need for appropriate fortification remain important considerations.

PBMAs also present substantial environmental advantages, including reduced greenhouse gas emissions, land use, and water consumption compared with conventional livestock production. Despite these benefits, concerns regarding ultra-processing, high sodium content, food additives, and consumer acceptance continue to limit their widespread adoption. Furthermore, achieving the complex texture, flavor, and juiciness of animal meat remains a significant technological challenge. Future research should focus on improving nutritional quality, sensory attributes, clean-label formulations, and processing efficiency while reducing production costs. The integration of novel protein sources, precision fermentation, and sustainable manufacturing approaches may further enhance the quality and acceptance of PBMAs. Overall, PBMAs represent an important component of future sustainable food systems and have considerable potential to contribute to healthier diets and environmentally responsible food production.

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