Formulation of Plant–based Meat Analogues: Protein Sources, Functional Additives, and Technological Advancements

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Review

Formulation of Plant–Based Meat Analogues: Protein Sources, Functional Additives, and Technological Advancements

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Abstract: The exponential demand for plant–based meat analogues (PBMAs) can be attributed to the amassing need for sustainable and restorative proteins in the perspective of global food security. However, the development of meat analogues requires suitable physicochemical and techno–functional properties that effectively replicate the appearance, texture, sensorial characteristics, and dietary profile of conventional animal meat. In addition, consumers seek organic, ethical, clean–label, and eco–friendly products that address challenges in the current meat market. This comprehensive review provides updated information about novel protein sources from legumes, oilseeds, cereals, pseudocereals, mushrooms, fungi, and algae species; key ingredients such as binding agents, colorants, flavorants, and chemical constituents to improve the functionality of PBMAs; and technological processing strategies that enhance the microstructural organization of meat substitutes. Moreover, the nutritional composition of phyto–proteins and mycoproteins has been compiled, as understanding the fundamental role of each ingredient in PBMAs is crucial for its formulation. Future research should be directed towards improving hybrid protein–protein interactions, fiber alignment, palate diversification, and thermomechanical techniques that encourage overall health benefits. Strategies for incorporating preservatives to facilitate longer shelf–lives and feasibility for large–scale production should be further explored to drive innovation in the meat analogues industry.

Keywords: Plant–based Meat Analogues (PBMAs); meat substitutes; GHG emissions; plant proteins; mycoproteins; Texturized Vegetable Proteins (TVPs); functional ingredients; food additives; nutritional profile; extrusion technology

1. Introduction

The projected global population is predicted to reach a cumulative 9.7 billion by 2050 according to the United Nations Food and Agriculture Organization [1]. Rapid urbanization and demographic expansion over the past decades have resulted in an increasing demand of approximately 38 million tons for the production of protein–rich meat comprising high nutritional content [12]. However, meat production on an industrial scale level causes major issues such as abundant usage of arable lands, pastures, and water resources; adverse effects faced by aquatic ecosystems, and environmental fluctuations due to greenhouse gases (GHGs) emissions into the atmosphere [3]. While human activities contribute to 51% of the total GHGs, i.e., carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4), and ammonia (NH_3), which lead to acidification of ecosystems [4]; livestock production alone is responsible for 1/4th of the world's emissions [5]. The expected 70% increase in food production in conjunction with the current economic trends for meat intake may lead to the disproportionate availability of feed supplies [6]. Moreover, red and processed meat have been classified as potentially carcinogenic and group–1 carcinogen respectively, by the International Agency for Research on Cancer (IARC) of the World Health Organization (WHO) [7]. Meat consumption has also been associated with detrimental consequences on health such as cardiovascular diseases, type–II diabetes,

obesity, colorectal cancers, zoonoses, airborne illnesses, and epidemic outbreaks [8,9]. This raises a necessity for identifying sustainable and affordable alternatives that can fulfil the needs of the growing population without harmful repercussions.

Plant–based meat analogues incorporating meat–like characteristics, have emerged as suitable substitutes that confer benefits in terms of both health and ecological impact, while addressing the limitations of real meat. Proteins obtained from plants are most favored by consumers who are inclined towards minimizing the consumption of animal–derived commodities due to ethical concerns for animal welfare. Meat analogues possess substantial physicochemical characteristics that provide a variety of options for individuals with specific dietary preferences such as vegans, vegetarians, and flexitarians [9,10]. With the steadily growing number of plant–based meat consumers, the global meat substitutes market size is expected to grow tremendously, with a predicted increase of USD 74–263 billion by the year 2030 [11]. Presently, food scientists and industrial experts are exploring techniques that mimic the taste, aroma, texture, and structure of original animal tissue constructs. There are two main types of meat analogues which are being actively studied by the food research community, i.e., lab–grown tissue–engineered meat from cell cultures in contrast to whole animals or organisms, and imitation meat such as plant–based meat or mycoprotein–based meat from ascomycetes or basidiomycetes to improve the juiciness, chewiness, and appearance of analogues [8].

Plant–based proteins primarily derived from legumes, oilseeds, cereals, and pseudocereals have been widely proposed to replace meat as they form a nutritionally balanced diet with sustainable and well–preserved functionality [9]. Similarly, textural and sensorial properties are also important in obtaining realistic meat replications with desired characteristics. The fibrous matrix of spun protein filaments and texturized vegetable proteins (TVPs) constituting plant–based analogues have specific attributes that closely imitate the myofibrillar assembly of meat, thereby contributing to organoleptic structures [12]. Mycoprotein obtained from the mycelia of filamentous fungi has also been used in meat analogues as it is involved in efficient conversion of nutrients and carbohydrate from the growth media with natural meat–like texture, flavors, protein–rich profile, and inherent nutraceutical compounds. The latest industrial advancements utilizing mushroom–based meat analogues also coincide with the United Nation's Sustainable Development Goals (SDGs) [2]. Additionally, it is known for enhancing digestibility, inducing satiety, synthesizing muscle proteins, and improving lipoprotein profiles due to its rich amino acid constituents and poly–unsaturated fatty acids (PUFAs) [4].

The inclusion of hydrocolloids in meat analogue formulations has been known to improve binding between protein filaments, thus promoting textural properties. Hydrocolloids enhance the fibrous texture of meat analogues, especially when subjected to high moisture extrusion (HME) and high–temperature shear cell (HTSC) processing [13]. Coagulation, texturization, and extrusion of proteins are some of the currently available methods that are used to produce fibrillar oriented structures [14]. Thermomechanical processing (TMP) encompasses these techniques to create textured meat–like arrangements of dry and wet extrudates such as low–moisture (10% – 30%) meat analogues (LMMA) which have a spongy fibrous organization with non–uniform air pockets, and high–moisture (40% – 70%) meat analogues (HMMA) which have well–defined uniform fibrous texture resembling real meat [15].

The main objective of this study is to identify up–to–date advancements in meat analogues utilizing various protein from alternative sources, with a particular focus on their application, combination with texturizing and sensorial agents, incorporation into food substitutes, end–product quality, and implemented technology. This in–depth analysis provides a comprehensive overview of plant–based proteins, oilseeds, cereal and pseudocereal proteins, mushroom–based proteins, algal species, and fungal biomasses; in combination with binding, coloring, chemical, and flavoring agents using extrusion technology, 3D/4D food bioprinting, electrospinning, antisolvent precipitation, and mechanical elongation techniques. The resultant meat analogues were assessed for their physicochemical properties, textural and sensory characteristics, and nutritional amino acid profiles

to understand the current established research agenda in shaping consumer acceptance of commercial plant–based meat substitutes.
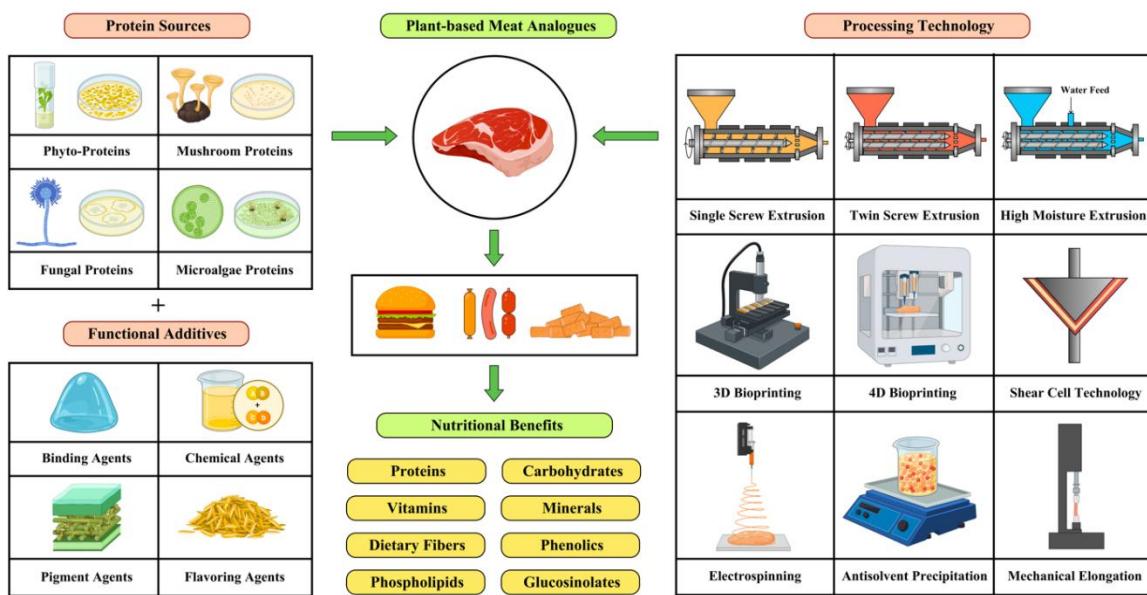

Figure 1. Plant–based meat analogues formulation strategies and nutritional composition.

2. Plant Protein Sources

2.1. Proteins from Legumes

2.1.1. Soy Protein

Soy proteins are most commonly used in meat analogues as soy protein isolates (SPI), soy protein concentrate (SPC), defatted soy flour (DSF) [16], and full–fat soy (FFS) forms [17,18]; with the highest protein content (> 90%) and moisture retention found in SPI, making it optimal for HME [19]. The nutritional profile of FFS is constituted by 38–40% protein, 33% carbohydrate, and 18–22% fat with presence of dietary fibers [20,21]. FFS is commonly combined with gluten protein to compensate for its lower protein content compared to other soy forms, contributing towards higher texturization; and imparts a suitable color which improves the appearance of meat analogues [18]. Lin et al. (2025) studied the relationship between 0–12% SPI with four texturized soy proteins (TSPs). TSPs at higher levels revealed an enhanced water binding effect and reduced cooking loss, signifying the importance of texturization in hybridized meat production [22]. Soy proteins also have characteristic functional properties such as gelling, emulsification, lipid–absorbing, and water holding capacities [23]. Furthermore, soy proteins include a good amount of essential amino acids (EAAs) with hydrophilic and hydrophobic properties that facilitate fibrous 3D interlaced matrix formation, along with a Protein Digestibility Corrected Amino Acid Score (PDCAAS) relatively equivalent to that of animal proteins [24]. Soy proteins have high shearing viscosity leading to deformation, alignment, and structural entrapment [25].

2.1.2. Pea Protein

Pea proteins are an alternative source to soy protein with an exceptional EAAs profile, especially lysine and threonine [26]. Pea proteins are listed as non–allergens with a low glycemic index and less gelling capacity than soy proteins [27–29]. While pea proteins are largely affordable, has less association to GMO–related issues, and can be cultivated in moderate climate conditions, there are challenges during structurization as heat–induced SPI gels have higher strength when compared to pea protein isolate (PPI) gels [30,31]. A few scientific studies have reported successful PPI

structurization through low and high moisture extrusion techniques by the inclusion of wheat gluten (WG) as structural support or hydrocolloids such as cellulose and pectin fibers, which provided viscoelastic strength and anisotropy by matrix elongation [25,32]. Sajib et al. (2023) evaluated the role of isolation temperature and pH levels in PPI–based PBMAs. The study revealed that pH increased from 2.0 to 11.0 resulted in improved yield rates from 37% to 79% at 20°C, with higher lipid absorption, hardness, cohesiveness, chewiness, and gumminess due to protein denaturation and surface hydrophobicity. Similarly, when temperature was augmented from 20°C to 40°C at fixed pH, the solubility, foaming, and gelation capacities were negatively impacted [33]. Pea proteins also play a vital role in preventing leukemia, cancers (breast, lung, colon, pancreas, prostate), cardiovascular diseases, type–II diabetes, colitis, and promoting muscle thickness and gut microbiota, making it a viable alternative to animal meat [34,35].

2.1.3. Mung Bean Protein

Mung bean protein, also known as "green pearl", is comprised of 25–28% proteins and 1–2% fat content with a nutritional amino acid profile akin to that of soy proteins [36,37]. Furthermore, Mung bean protein isolate (MBPI) has a Digestible Indispensable Amino Acid Score (DIAAS) of 86 which is intermediate to SPIs and PPIs that have a score of 91 and 70 respectively [38–40]. Mung bean proteins also improve the texture, gelling, foaming, and emulsification properties of meat analogues as they are made up of 25% albumin and 60% globular proteins [41]. Guo et al. (2024) identified that a 7:3 ratio of MBPI:WG low–moisture extrudates improved protein cross–linking, and a 6:4 ratio of MBPI:WG unfavorably affected the extrudate structures [42]. In another study, Angelis et al. (2023) studied the rheological properties of dry–fractionated MBPIs with 55% protein content via high moisture extrusion cooking (HMEC) with varying moisture levels (40–50%) and temperature (40–170°C). At 70°C, higher complex shear modulus was observed due to starch and MBPI gelation, indicating that higher temperatures have a predominant effect on structural anisotropy, hardness, viscosity, and cohesiveness of the extrudates [43]. Mung bean proteins also have hypoglycemic, immunomodulatory, anti-melanogenic, hepatoprotective, and detoxification properties, offering a nutritionally balanced sustainable source in replacement of animal–based proteins [37,44,45].

2.1.4. Faba Bean Protein

Faba bean protein is a novel alternative protein source which is currently being explored for its protein–rich and diverse properties such as atmospheric nitrogen fixation which is advantageous for the environment [46]. Faba beans provide a favorable source of lysine and can be cultivated in extreme climate conditions, making it easily accessible and sustainable for plant–based meat substitutes [47]. Faba bean proteins have a balanced nutritional composition with 20–41% proteins, 7–9% dietary fibers, 1–2% fat, polyphenols, and other minor compounds [48]. They also possess phenolic acids, flavonoids with antioxidant properties that regulate oxidative stress, inflammation, and prevent degenerative conditions such as Parkinson's disease [49][50]. Faba beans have exceptional emulsion stabilization and foaming abilities, although to a lesser degree than soy proteins [51]. Fan et al. (2025) investigated the role of HME with 0–6% brewers' spent grain (BSG) and faba bean proteins, where enhanced fibrous texture was obtained at 3% BSG [52]. Furthermore, Elshamy et al. (2025) studied how dry–fractionated faba bean (FB), yellow pea (YP), and wet–fractionated soybean (SB) protein concentrates influence meat–like texture. Total moisture content (TMC) affected the chewiness, hardness, and cutting strength of PBMAs, with longitudinal fiber orientation at higher temperatures [53]. Thereby, faba bean proteins can be used to produce PBMAs by dry fractionation, wet spinning, and thermomechanical processing [54,55].

2.1.5. Lupin Bean Protein

Lupin proteins are a largely cultivated species of legumes that can be grown in various land conditions with involvement in atmospheric nitrogen fixation and soil phosphate absorption [56].

Lupin protein has one of the highest nutritional amino acid profiles among legumes with 46% total protein content, non–digestible carbohydrates, dietary fibers, mineral bioavailability, and low level of alkaloids [57]. Lupin species such as white, yellow, blue/ narrow–leafed, and pearl lupin have been reported as feasible plant proteins for PBMAs [58,59]. Lupin proteins are also known for their low glycemic index, reducing low–density lipoproteins (LDLs), Trinitrobenzene sulfonic acid (TNBS)–induced colitis inflammation, boosting gastrointestinal function, antioxidant, anti–inflammatory, non–allergenicity, and hypocholesterolemic activities [60–62]. Ramos–Diaz et al. (2023) studied different lupin protein blend ratios (30:70, 50:50, and 70:30) using lupin protein isolates (LPI), lupin protein concentrates (LPC), and native lupin flour (LF). The texturized meat analogues (TMAs) with 30% d.m. LF retained more than 50% d.m. protein content, exhibiting fiber formation, and the lesser lupin protein isolate (LPI) content resulted in higher homogeneity [63]. Ayalew et al. (2024) explored the effect of processing temperatures (raw, 130–150°C) and immersion time (raw, 2–6 days). Highest mineral content, protein content, cooking yield, and sensory acceptability were observed at 140°C for a soaking period of 4 days. This study revealed that temperature and soaking conditions have a crucial role in the anti–nutritional attributes of PBMAs [64].

2.1.6. Chickpea Protein

Chickpea protein is the most consumed species of legumes, defined by its characteristic texture, water and oil binding capacity, fat absorbability, emulsion stabilization, solubility, foaming and gelling capacities comparable to that of soy protein isolates (SPI) and whey proteins [65]. The presence of carotenoids in chickpeas is also known for enhancing the color of meat analogues [66]. Chickpea proteins are composed of 12–31% proteins, 58–68% carbohydrates, 4–10% fat, 3–5% dietary fibers, and 10% water [67,68]. Primary processing strategies i.e., germination, dehulling, fermentation, and enzymatic catalyzation have been identified to improve the properties of chickpea proteins together with several extraction methods [69]. These techniques include dry and wet fractionation such as isoelectric precipitation, membrane filtration, air classification, and alkaline/acid/salt extraction to obtain concentrate and isolate forms [70–72]. Ma et al. (2023) explored high–pressure homogenization (HPH: 0–150 MPa) at 1–3 cycles on the physicochemical attributes of chickpea proteins, where increased surface hydrophobicity and decreased sulfhydryl content was observed [73]. In another study, Kong et al. (2023) functionalized chickpea protein hydrolysates with trypsin to support muscle and fat cell adhesion, proliferation, and differentiation in cultured meat [74]. Furthermore, Czapalay et al. (2025) investigated how gelling agents can compensate for the absence of adipose tissues, by combining 6% pea starch with 4% chickpea flour and 40% oil at 5–85°C temperature profiles, forming a starch network with adipocyte–like oil pockets [75].

Table 1. Leguminous Protein Sources for Plant–based Meat Analogues.

Legume Proteins	Latin Name	Properties	Reference
Soy	*Glycine max*	Excellent water–holding, emulsification, strong gelling, good texturization.	[76]
Pea	*Pisum sativum*	High emulsifying and water–holding, moderate foaming and gelling stability.	[77]
Mung bean	*Vigna radiata*	Extrudability and texturization, gelling and foaming capacity under medium shear force.	[78]
Faba bean	*Vicia faba*	Good emulsification, foaming, and gelling, improves microstructural properties.	[79]
Lupin bean	*Lupinus*	Good emulsification, foaming, and water–binding, enhances firmness.	[80]
Chickpea	*Cicer arietinum*	Strong water and oil binding, moderate gelation, creates a soft texture.	[81]

Kidney bean	*Phaseolus vulgaris*	Moderate water–holding and gelation; improves texture and elasticity.	[82]
Lentil	*Lens culinaris*	Good water–binding, moderate gelation, emulsification, improves firmness and chewiness.	[83]

2.2. Proteins from Oilseeds

2.2.1. Hemp Protein

Industrial hemp seeds cultivated locally as a byproduct raw material is nutritionally rich with 20–26% proteins, 25–35% unsaturated fats, >50% linoleic acid, 10–15% dietary fibers, 27–29% carbohydrates, vitamins, and minerals [84,85]. Hemp seeds comprising albumins and globulins, are commonly available in raw, roasted, and oil pressed forms [86]. They serve as a reliable source of nourishment with reduced thyroid hormones, tri–acylglycerol, antioxidant, antihypertensive, hypocholesterolemic, hypoglycemic and neuroprotective effects [87,88]. The essential amino acids (EAAs) in hemp protein are comparable to egg, casein, and soy proteins with an Arg/Lys ratio of 3.78–5.34 [89]. Moreover, processing conditions such as membrane ultrafiltration, alkaline extraction, isoelectric precipitation, and micellization influence the nutritional profile of hemp seeds [90]. Zahari et al. (2023) developed high moisture meat analogues (HMMAs) with hemp seed protein concentrate (HPC) at 60–66% moisture content, 500–900 rpm screw speeds, and 40–150°C temperature profiles. The meat analogue exhibited stronger fibrous structures, texturization, and cutting strength at higher temperatures [91]. Nasrollahzadeh et al. (2022) investigated the role of dry and wet fractionation using five different HPCs. In dry extraction, HPCs maintained their native oligomeric structure with high surface hydrophobicity, solubility, anisotropy, and low gelation. In wet extraction, HPCs had higher bound polyphenols, anisotropy, and viscosity [92]. Thus, hemp seed proteins offer both functionality and viscoelastic properties in plant meat alternatives.

2.2.2. Rapeseed Protein

Rapeseed proteins have tremendous agronomic value owing to the presence of omega–3, omega–6, and unsaturated fatty acids, vitamins, phospholipids, phenolic compounds, tocopherols, sterols, and carotenoids [93]. Rapeseed proteins also have low erucic acid content, overcoming the major limitation of erucic toxicity in hemp proteins which cause myocardial damage and fat body parenchyma [94]. Rapeseed proteins composed of 20% napins (2S albumins) and 60% cruciferins, (12S globulins) are non–allergenic, and have been largely used in bakeries, beverages, flavorings, processed meat products, and dairy industries [95]. Some of the notable bioactivities of rapeseed proteins include Angiotensin–converting enzyme (ACE) inhibition, bile acid binding capacity, immunogenicity, cell growth, cardiovascular regulation, and antithrombotic properties [96,97]. Jia et al. (2021) analyzed the potential of rapeseed protein concentrates (RPC) in meat analogues via shear cell technology. Fibrous textures with 40% d.m. were observed at 140°C and 150°C. Increased WG content in RPCs also improved the color profile, indicating their significance as an optimal protein source after soy protein concentrates (SPC) [98]. In another study, Zhang et al. (2024) investigated the substitution capacity of rapeseed proteins to soy proteins under extrusion cooking technology at 0–50% and 50–0% (w/w) concentrations. 0–20% rapeseed proteins enhanced the hardness and chewiness of extruded analogues. At higher substitution levels, lower expansion, rehydration, and brightness were observed with increased protein stability [99].

2.2.3. Pumpkin Protein

Pumpkin proteins rich in poly-unsaturated fatty acids (PUFAs) have useful nutraceutical compounds with proteins, lipids, essential and non–essential fatty acids. Natural bioactive compounds in pumpkin seeds including flavonoids, carotenoids, and squalene make it a vital component in diverse pharmacological and food sectors [100]. Pumpkin seed proteins have copious

amounts of macronutrients and micronutrients which prevent cardiovascular diseases, cancers, deficiency disorders, and protein malnutrition. Pumpkin seeds are also used to treat benign prostate hyperplasia (BHP) and deter the risk of Alzheimer's and Parkinson's diseases [101,102]. Pumpkin proteins are composed of 25–37% proteins, 18–25% carbohydrates, 37–45% lipids, and 3–6% dietary fibers [103]. Pumpkin seeds in meat analogues contribute to a savory flavor and chewy texture, as protein materials and oil–based food additives [104]. Choi et al. (2025) prepared high–moisture meat analogues (HMMAs) using SPI and pumpkin protein concentrate (PSC) blends. Increased PSC content resulted in SPI network disruption, low bonding, and alignment, with modified texture and soft gel formation crucial for replicating original meat structures [105]. Furthermore, Kong et al. (2025) prepared gelatin hydrogels using alginate (ALG) combined with PSP for plant–based food 3D–printing applications. Optimal gelation texture, hardness, springiness, and cohesiveness were observed at 2–3% ALG and 2–6% PSP with color resemblance like animal gelatin [106].

Table 2. Oilseed Protein Sources for Plant–based Meat Analogues.

Oilseed Proteins	Latin Name	Properties	Reference
Peanut	*Arachis hypogaea*	Oil binding and foaming capacity comparable to SPI; higher viscosity and gel formation post–heating.	[107]
Hemp	*Cannabis sativa*	Superior functional attributes such as foaming, gel formation, and WHC.	[108]
Rapeseed	*Brassica napus*	Strong heat–set gel forms by cruciferin under alkaline conditions.	[109]
Pumpkin	*Cucurbita maxima*	High emulsifying capacity and stability, moderate foaming, low gelling, and high WHC.	[110]
Flaxseed	*Linum usitatissimum*	High nutritional value and good techno–functional properties i.e., solubility, foaming, emulsification, gelling, and WHC.	[111]
Chia	*Salvia hispanica*	Excellent water and oil binding properties; rich in plant–based omega–3 fatty acids.	[112]
Cottonseed	*Gossypium hirsutum*	Good emulsification and WHC; contains gossypol, which requires processing for safe consumption.	[113]
Sesame	*Sesamum indicum*	Excellent source of proteins and antioxidants; good emulsification and binding properties.	[114]
Safflower	*Carthamus tinctorius*	Rich in linoleic acid and good water retention aiding in texture formation.	[115]
Sunflower	*Helianthus annuus*	Stable emulsification and foaming with comparable gelling capacity.	[116]
Black Cumin	*Nigella sativa*	Flavor enhancement with its distinctive aroma. Good oil–holding capacity aids in juiciness and texture.	[117]

2.3. Proteins from Cereal and Pseudocereal

2.3.1. Wheat Protein

Wheat protein has an elastic network structure formed by interchain cross–linking between disulfide bonds of prolamin and glutein residues via partial hydration [24]. Wheat gluten (WG), known for its high viscoelasticity, flexibility, thermal coagulation, and fibrosity, mainly consists of glutenins and gliadins, and acts as a plasticizer in meat analogues [118,119]. Moreover, the nutritional profile of wheat proteins is constituted by 11% proteins, 58% carbohydrates, 2% lipids, and a relatively unbalanced amino acid profile compensated by combining WG with other legume and starch–based proteins [120,121]. WG facilitates protein blends to form independent phases by increasing the content of β–sheets to create dense and compact fibrous structures [122]. It is largely

available as binders, fillers, and extenders in vital, texturized, and isolated forms, to improve the overall color stability, juiciness and firmness [123]. While WG is an optimal non–meat ingredient, it is also an allergen which must be taken into consideration for plant–based products. Dai et al. (2024) identified that wheat gluten enzymatic hydrolysates (WGEHs) converted disulfide bonds to free sulfhydryl groups, improving extractability and texturization degrees [124]. Sun et al. (2023) experimented xylose–induced Maillard reactions products (MRPs) at 80–120°C using WGEHs prepared by Flavourzyme [125]. At 120°C, MRPs exhibited formation of intermediates, thermal degradation, protein cross–linking, high umami flavor and low bitterness in plant meat analogues due to the presence of volatile compounds i.e., furans and furanthiols. [126].

2.3.2. Oat Protein

Oat proteins are nutritionally rich plant–derived proteins that have high heat stability due to their globulin content. Oat proteins are made up of 15–20% proteins in whole kernels, carbohydrates, dietary soluble fibers, unsaturated fatty acids, EAAs, vitamins, and minerals [127,128]. Oat proteins contain 1–12% albumins, 50–80% globulins, ~10% glutelins, and 4–15% prolamins [129]. Texturized meat analogues can be produced using oat globulins for rigid and irreversible amyloids, or semi–flexible and reversible amyloid protein nanofibrils [130]. Oat protein isolates and concentrates can be used in meat analogues as they prevent syneresis. They also have a moderate Digestible Indispensable Amino Acid Score (DIAAS) value of 0.57, a higher PDCAAS value than wheat protein, a digestibility rate of 90.3–94.2%, and an efficiency ratio of 2.25–2.38 that is closely equivalent to casein [129]. Oat protein can be used as functional thickeners, emulsifiers, stabilizers, gelling agents, and texture modifiers owing to their foaming, lipid–binding, and WHC [131]. Chemical and enzymatic treatments can improve the functionality of oat proteins which undergo denaturation in liquid and semi–solid products [132]. Brückner–Gühmann et al. (2021) investigated heat–induced gels using oat protein isolate (OPI) with two oat protein hydrolysates at pH levels of 4.5 and 8 under 90°C and 120°C respectively. Trypsin (OPT) and Alcalase (OPA) influenced gelling properties at a 2% degree of hydrolysis with variations in protein aggregation, structure, and lightness [133].

2.3.3. Rice Protein

Rice protein is one of the largest globally–produced cereal crop, composed of 32–78% protein content, including 4–22% albumins, 5–13% globulins, 1–5% prolamins, and 60–80% glutelins [134]. It contains a rich reservoir of lipids, carbohydrates, dietary fibers, vitamins, minerals, and EAAs, depending upon its genotype and growth conditions [135]. Rice protein is renowned for its hypoallergenicity, antidiabetic, anticancer, and antioxidant nature due to its polyphenols, peptides, tocopherols, tocotrienols, γ–oryzanols, and flavonoids [136]. Rice proteins have a high digestibility of 93%, and protein efficiency of 2.02–2.04% [137]. Lee et al. (2022) utilized different substitution ratios of rice protein (RP) to soy protein (SP) ranging from 0–100% (w/w) through low–moisture extrusion cooking (LMEC). SP replacement with RP resulted in increased hardness and density with decreased porosity, expansion ratio, and textural profile. This was due to the short residence time of the dough in the extruder caused by its high flow rate, which led to lower specific mechanical energy (SME) input responsible for protein denaturation and texturization. [138]. Lee et al. (2022) also prepared texturized rice protein (TRP) meat analogues by LMEC using 25–100% and 75–0% RPI–SPI blend ratios, WG, and corn starch. RPI–SPI meat analogues exhibited higher nutritional quality than commercial PBMAs [139]. Similarly, Charlie et al. (2025) developed TVPs using rice bran (R), soy protein (S), and mung bean (M) with 30% moisture content by LMEC at 125°C. MR–TVPs exhibited superior performance in terms of textural integrity, microstructure, density, binding capacity, and rehydration ratio [140].

Table 3. Cereal Protein Sources for Plant–based Meat Analogues.

Cereal Proteins	Latin Name	Properties	Reference
Wheat	*Triticum aestivum*	High in gluten, providing elasticity and binding properties.	[141]
Oat	*Avena sativa*	Good solubility in water, high emulsifying, gelling, and WHC, moderate foaming capacity.	[142]
Rice	*Oryza sativa*	Good solubility in water, high emulsifying and stability, moderate foaming, and low gelling.	[143]
Corn (Zein)	*Zea mays*	Stabilizes oil–in–glycerol emulsion–gels, used as a fat analogue, and stabilizes foam and emulsions.	[144]
Barley	*Hordeum vulgare*	Contains β–glucans, contributing to water retention and gelation. Improves viscosity and mouthfeel.	[145]
Millet	*Panicum miliaceum*	Gluten–free and good water–binding capacity for improved texture. Rich in antioxidants and EAAs.	[146]
Sorghum	*Sorghum bicolor*	Polyphenols support texture and nutrition. Gluten–free good binding capacity for improved juiciness.	[147]

Table 4. Pseudocereal Protein Sources for Plant–based Meat Analogues.

Pseudocereal Proteins	Latin Name	Properties	Reference
Quinoa	*Chenopodium quinoa*	Higher emulsifying capacity and stability than soy, wheat and pearl millet; low gelling capacity and good water holding capacity.	[148]
Amaranth	*Amaranthus caudatus*	Improves solubility, emulsification, foaming, gelling, and water–holding capabilities subject to pH, temperature, and enzymatic hydrolysis.	[149]
Buckwheat	*Fagopyrum esculentum*	Good water retention and strong emulsification capacity with gluten–free texture enhancement properties. Contributes to a slightly nutty flavor.	[150]

2.4. Mushroom Species

2.4.1. Agaricus bisporus (Button Mushroom)

Agaricus bisporus (A. bisporus), also known as button or portobello mushroom, is a common edible mycoprotein species from the Agaricaceae family which makes up 35–45% of global mushroom production [151]. *A. bisporus* has organoleptic and nutraceutical properties with great market demand as it can be cultivated through bio–conversion techniques that convert cellulose into protein–rich biomasses [152]. *A. bisporus* is low in fat, calories, sodium, and cholesterol, with high levels of proteins, carbohydrates, phenolic compounds, and dietary fibers such as chitin, glucans, ergosterol [153]. Clinical findings have shown that *A. bisporus* can control weight gain levels, combat cognitive impairment, diabetes, and cancer by enabling natural killer (NK) cells to facilitate immunogenic activity [154]. Polysaccharides in *A. bisporus* demonstrate antioxidant, anti–inflammatory, anti-obesity, anticancer, immunogenic, and hepatoprotective bioactivities [155]. *A. bisporus* has notable aroma, taste, and texture influenced by approximately 67–150 volatile compounds and different water–soluble substances that enhance meat–like umami flavor [156]. Fu et al. (2023) partially substituted *A. bisporus* (AB) mushrooms in chicken breast at 0% (control) to 70% to evaluate its physicochemical and oxidative properties. Increased AB substitution resulted in increased moisture content and PUFAs, with decreased protein content, pH, color saturation, sensory characteristics, and delayed oxidation at 10% AB substitution [157].

2.4.2. Pleurotus ostreatus (Oyster Mushroom)

Pleurotus ostreatus (P. ostreatus), also known as hiratake or oyster mushroom, is a high–quality protein–rich mushroom species of the Pleurotaceae family comprising bioactive nutrients ideal for meat analogues [158]. *P. ostreatus* is an important nutritional source with 7.3–53.3% proteins, 50–60% carbohydrates, <4% fats, and dietary fibers such as chitin, glucans, cellulose, and hemicelluloses [159]. The vitamins present in *P. ostreatus* include thiamine, riboflavin, niacin, pyridoxine, retinol, ergocalciferol, and folates [160]. Moreover, *P. ostreatus* has notable levels of minerals, phenolic compounds, and a balanced EAA profile [161]. The dietary fibers in *P. ostreatus* have been found to improve physical properties involving texturization, gelation, thickening, emulsification, and stabilization [162]. *P. ostreatus* also has an exceptional flavor, taste, and chewy texture due to the presence of linoleic acid, palmitic acid, and oleic acid [163]. In addition, the interactions between proteins and polyphenol extracts enhances cross–linkage formation within extrudates [23]. Demircan et al. (2023) studied 3D–printed PBMA formulations using *Ganoderma lucidum* (GL) *Lactarius deliciosus* (LD), and *Pleurotus ostreatus* (PO) mushrooms. The resultant analogues demonstrated shear–thinning, viscoelasticity, and stable structures. *P. ostreatus* was involved in reducing hardness, stiffness, chewiness, redness, and beany flavors; while increasing the springiness, lightness, and re–printability [164,165].

2.4.3. Lentinus edodes (Shiitake Mushroom)

Lentinus edodes (L. edodes), also known as shiitake mushroom, is the second highest produced mushroom from the Marasmiaceae family, rich in aroma, umami, and phenolic compounds [166]. The fruiting bodies and mycelium extracts possess multifaceted therapeutic constituents such as β–glucans, terpenoids, sterols, flavonoids, and eritadenine responsible for antitumor, anticaries, antimicrobial, antioxidant, hepatoprotective, and immunomodulatory effects [167]. *L. edodes* is composed of 20–23% proteins, 58–60% carbohydrates, 9–10% dietary fibers, 3–4% lipids, and 4–5% ash content [167]. In particular, the presence of PUFAs moderate blood–cholesterol levels and cell physiological processes [168]. Santhapur et al. (2024) examined shiitake mushroom (SM) and oyster mushroom (OM) with whey protein isolate (WPI). SM had a negligible effect on thermal stability of heat–set WPI compared to OM. WPI exhibited thermal gelation and a higher isoelectric point. Furthermore, SM and OM reduced the hardness, stiffness, and lightness of the WPI gels, while increasing the intensity of its brown color [169]. Choi et al. (2025) investigated *L. edodes* mycelium (LEM) with different plant protein–based (soy, pea, mung, rice) and polysaccharide–based (agar, carrageenan, gellan gum) hydrocolloids. LEM–protein improved flowability and dispersion; whereas LEM–polysaccharide produced strengthened gel–like structures due to intermolecular β–sheet hydrogen bonding. High gel homogeneity and interconnectivity were observed in LEM–Ca, presenting the significance of *L. edodes* blends in developing liquid or solid–type PBMAs [170].

2.4.4. Coprinus comatus (Chicken Drumstick Mushroom)

Coprinus comatus (C. comatus), also known as shaggy mane or chicken drumstick mushroom, is a widespread species of the Agaricaceae family. *C. comatus* has a well–balanced nutritional profile comprising 49.2–76.3% carbohydrates, 11.8–29.5% proteins, 0.6–2.8% dietary fibers, 1.1–5.4% fat, and high levels of EAAs. It has one of the highest PUFAs at 65–66%, mainly composed of linoleic acids, with flavonoids, coumarins, hydroxybenzoic, hydroxycinnamic, and chlorogenic acids [171,172]. *C. comatus* exhibits anticancer, antidiabetic, antiandrogenic, antimicrobial, antioxidant, anti–inflammatory, acetylcholinesterase inhibitory, and hepatoprotective effects [173,174]. Its major limitation includes allergenic reactions in patients afflicted with dermatitis. They also undergo rapid autolysis and must be consumed at a young stage [175]. Yuan et al. (2022) investigated SPI blends with 15–100% of *L. edodes*, *P. ostreatus*, and *C. comatus* at 35–100% water content via thermos–extrusion. Soy protein isolate–*C. comatus* (15%) blends with 35% moisture demonstrated texture profiles closely resembling beef. The mushroom meat sausage analogues (MMSA) contained 64

volatile compounds responsible for flavor, identified using gas chromatography-mass spectrometry (GC-MS), thereby indicating the role of fermentation in enhancing aromatic flavor profiles [3]. Ren et al. (2022) analyzed freeze, microwave, infrared, and hot air–drying techniques (FD, MD, IRD, HAD). FD resulted in the highest rehydration ratio and free radical scavenging activity with the lowest color difference in dried *C. comatus* mushroom samples. MD retained polysaccharides, coumaric acid, and p–hydroxybenzoic acid with higher antioxidant activity. IRD and HAD showed the highest umami concentration, free amino acids, and flavor 5'–nucleotides [176].

Table 5. Mushroom Proteins for Plant–based Meat Analogues.

Mushroom Species	Latin Name	Properties	Reference
Button Mushroom	*Agaricus bisporus*	Enhances juiciness and nutritional profile due to its protein and fiber content, with antioxidant properties.	[177]
Oyster Mushroom	*Pleurotus ostreatus*	Increases protein and fiber content, reduces fat content, softer texture, antioxidant properties.	[178]
Shiitake Mushroom	*Lentinus edodes*	Increases moisture, fiber, nutrition and antioxidant activity, due to methionine and glutamic acid.	[179]
Chicken Mushroom	*Coprinus comatus*	Improves the textural profile and nutritional profile due to its high protein content.	[180]

2.5. Algae Species

2.5.1. Auxenochlorella protothecoides

Auxenochlorella protothecoides (A. protothecoides), are protein–rich microorganisms of the Chlorellaceae family that can be cultivated in photoautotrophic, mixotrophic, and heterotrophic conditions, with no CO_2 emissions and less water consumption [181,182]. They have exceptional antioxidant properties, bioactive compounds, and thickening capacity compared to soy, rice, and whey proteins [183]. Moreover, they are composed of high protein content, chlorophyll and carotenoids, and a high lipid accumulation ability [184]. Sägesser et al. (2024) investigated the structurability of *A. protothecoides* by HMEC in comparison with soy and pea proteins. *A. protothecoides* had higher solubility, smaller molecular weight, low hydrophobic sidechains, and pH which affected protein interactions and fibrous network [185]. Caporgno et al. (2020) examined spray–dried *A. protothecoides* with soy protein concentrate (SPC) to form texturized fibrillar extrudates. 50% of the microalgae biomass was found to considerably influence fiber formation. The increased lipid content led to lubrication, moisture regulation, and improved tenderness while supplementing vitamin B and E [10]. Processing techniques involving denaturation, pH shift, and enzymatic reactions can improve the texture of microalgae–based meat substitutes, making it a promising biomass protein source with ecological advantages and diverse applications in the food industry.

2.5.2. Chlorella vulgaris

Chlorella vulgaris (C. vulgaris), is a freshwater microalgal species belonging to the Chlorellaceae family, composed of 51–58% proteins, 12–17% carbohydrates, 14–22% lipids, vitamins, and minerals [186]. It can be cultivated through phototrophic, mixotrophic, and heterotrophic modes dependent upon external factors such as light intensity and rate of agitation [187,188]. *C. vulgaris* has numerous food–based applications, encompassing health benefits like detoxification, antioxidation, and immunomodulation [189]. However, its strain type and growth conditions could lead to the risk of contamination due to heavy metal accumulation [190]. These challenges can be tackled by optimizing protected culture systems and advanced processing mechanisms [188]. Gol et al. (2023) combined wet disrupted *C. vulgaris* (Cv) with PPI by HPH–processing at 10°C to improve gelation. The resultant

14% (w/w) Cv suspensions showed a 10x rise in apparent viscosity, and 9:1 (w/w) PPI–Cv suspensions had 2x storage modulus. Additionally, HMEC PPI–Cv meat analogues retained their hardness, appearance, and anisotropy, with no notable changes post–fractionation and spray drying [191]. Bakhsh et al. (2023) developed PBMAs using Spirulina (SPI), Duck Weed (DW), and Yellow Chlorella (YC). The YC group affected lightness with YC3 having the highest crude fat value, gumminess, and chewiness. Both YC and SPI groups had differing levels of springiness and cohesiveness, but similar DPPH radical scavenging activity [192]. These attributes indicate that *C. vulgaris* is a novel microalga for plant–based meat products.

2.5.3. Spirulina platensis

Spirulina platensis (S. platensis), is a filamentous cyanobacterium from the Microcoleaceae family recognized for its valuable macro and micronutrients [58,193]. *S. platensis* can be cultivated in alkaline bodies and has 55–70% proteins, 15–20% carbohydrates, 7% lipids, 30%–35% PUFAs such as gamma–linoleic acid, phenolic acids, polyphenols, and a balanced amino acid profile [194]. It also contains 20% phycobiliproteins such as chlorophyll, phycocyanins, carotenoids, zeaxanthin, and xanthophylls [195]. Furthermore, *S. platensis* has good protein digestibility and consists of calcium spirulan (Ca–SP), known to inhibit viral diseases such as mumps, measles, cytomegalovirus (CMV), hepatitis C virus (HCV), herpes simplex virus (HSV), human immunodeficiency virus (HIV), and influenza–A (H1N1) [196]. It also has anticancer, antioxidant, anti–inflammatory, neuroprotective, hepatoprotective, hypocholesterolemic, osteogenic, and hormone regulatory effects [197]. Guo et al. (2025) analyzed *S. platensis* emulsion gels as fat replacers compared to palm oil, oleogel, and soybean oil. *S. platensis* presented excellent juiciness and heat–tolerance owing to its energy transfer mechanisms and thermally–induced water mobility, with cooking loss and shrinkage equivalent to that of other fats [198]. Afdhaliah et al. (2024) also prepared 30–50% red palm oil (RPO)–*Arthrospira platensis* protein concentrate (APC)–Carrageenan emulsion gels (EG) as fat substitutes in beef patties. APC effectively stabilized RPO–EG, underscoring its feasibility as a functional ingredient in meat analogues [199].

Table 6. Algal Proteins for Plant–based Meat Analogues.

Algae Species	Properties	Reference
Auxenochlorella prototothecoides	High in lipids and carotenoids, potential for enhancing nutritional profile and color.	[200]
Chlorella vulgaris	High protein content, vitamins, minerals, and omega–3 fatty acids. Improves nutritional profile, shelf life, and sensory attributes.	[201]
Spirulina platensis	High protein content, vitamins, minerals, and rich in EAAs; contributes to improved texture, stability, and color.	[202]

2.6. Fungi Species

2.6.1. Aspergillus oryzae (Koji Mold)

Aspergillus oryzae (A. oryzae), also known as Koji mold, is an aerobic filamentous fungi belonging to the Aspergillaceae family with both agronomic and medicinal significance, widely used in the production of food processing enzymes [203,204]. Optimal conditions for cultivating *A. oryzae* include temperature ranges between 32–36°C and pH levels ranging from 2.0–8.0 [205]. While *A. oryzae* has been commonly employed in fermented products such as soy sauce, soybean paste, rice koji beverage, and black rice vinegar, it has also expanded into PBMAs [206]. Fermented fungus is prepared by introducing *A. oryzae* to rice, soybean, oat flour, or wheatgrass substrates to produce enzymes responsible for breaking down proteins, fats, and starches into amino acids, fatty acids, and sugars

[207]. These substrates also contain nutrients desirable for fungal growth in submerged fermentation (SmF) systems. Yeast and lactic acid bacteria facilitate fermentation to obtain the end–products [208]. Gamarra–Castillo et al. (2022) developed burger patties using *A. oryzae*, flours, binders, and colorants under moderated conditions of the growth medium. The study revealed that biomass production was maximized at 6 days of incubation with 90 g/L maltodextrin. Additives such as quinoa flour, carboxymethylcellulose, and beet extract resulted in formulations with texture and appearance that closely resembled the control meat [4]. Thus, fungal proteins can be further explored to develop nutritious food in alignment with consumer preferences [209].

2.6.2. Neurospora intermedia

Neurospora intermedia (N. intermedia), is a natural hyphal fungus from the Sordariaceae family with an extensive history in food applications. *N. intermedia* is commonly utilized in Oncom, Cassava–based beverages, and milk cheese [210]. It can be readily cultivated by submerged and solid–state fermentation (SSF) using straw and molasses carbon substrates to effectively break down complex compounds into protein biomasses [211]. *N. intermedia* can also be grown on isolated plant byproducts such as brewer's spent grain, oilseed cakes, pomace, and plant–milk waste [212]. Its processing parameters are largely dependent upon temperature, pH, agitation rate, duration, and inoculum. *N. intermedia* is normally grown for 3–5 days at 30℃, with pH between 5.5–6.5, inoculum volumes of 1–5%, and agitation rates of 100–200 rpm [213]. *N. intermedia* has a rapid growth cycle with a high nutritional value and is considered as a safe fungal species as it does not encode mycotoxins when compared to *Aspergillus* and *Penicillium* variants [210]. Wang et al. (2024) investigated the role of *N. intermedia* at 3–7 pH levels and 0–6% soluble starch (SS) to create mycoprotein gel meat (CMGM). At pH 7, CMGM showed good elasticity, recovery, and a scant internal structure; whereas decreased pH resulted in increased water retention and gelling post–steaming. At 6% SS, CMGM exhibited improved hardness and WHC, with reduced porosity and elongation. These findings present the crosslinking ability of mycelial fibers in the gel matrix to produce mycoprotein–based meat substitutes [214].

2.6.3. Fusarium venenatum

Fusarium venenatum (F. venenatum), is a single–celled fungal biomass of the Nectriaceae family composed of a natural fibrous matrix with cellulose, chitin, glucans, 15–45% proteins, dietary fibers, and low fat [215]. Mycoprotein from *F. venenatum* is produced by continuous fermentation on a glucose substrate at high metabolic rates in an air–lift or solid–state bioreactors [216]. Nutritional supplements typically include vitamins, biotin and choline, and other minerals such as calcium, potassium, magnesium, sulfur, phosphorus, iron, manganese, molybdenum, and copper. In addition, carbon and nitrogen sources, are introduced into the culture medium to fulfil amino acid and sulfate metabolism, lipid and phospholipid biosynthesis, and gluconeogenesis [217,218]. Although *F. venenatum* has low digestibility, it is well–suited for human consumption as it has low allergenic potential, regulates cholesterol, induces muscle protein anabolism, and controls glucose–insulin levels [219]. Furthermore, *F. venenatum* contains 1–8% nucleic acid levels which is lower than that of bacteria and yeast, thereby reducing undesirable flavors and providing a meat–like texture to plant–based meat products [220]. Li et al. (2025) investigated the nutritional profile of *F. venenatum* mycoprotein–based Harbin red sausages, which revealed that increased mycoprotein content and volatile organic compounds subsequently create a rich flavor, promoting consumer acceptance [221].

Table 7. Fungal Proteins for Plant–based Meat Analogues.

Fungi Species	Properties	Reference
Aspergillus oryzae	Imparts a fibrous structure with high protein content and uses various substrates for cultivation.	[222]

Neurospora intermedia	Enhances chewability, gelation, and palatability when combined with soluble starch at optimal pH levels.	[223]
Fusarium venenatum	Mimics meat–like texture and enhance nutritional profile; widely used in commercial mycoprotein products like Quorn.	[224]

3. Nutritional Amino Acid Profiling

The nutritional quality of plant-based meat analogues is highly dependent upon their protein content including essential amino acids (EAAs) and non-essential amino acids (NEAAs), lipids, vitamins, minerals, carbohydrates, and dietary fibers, which provide a holistic nutraceutical profile crucial for improving metabolic health. The nutritional profiles of predominant plant-based proteins such as soy, pea, mung bean, faba bean, lupin bean, peanut, and oat proteins are represented in Table 8. Among these plant-based sources, soy protein provides an optimal EAA profile high in lysine, methionine, and iron content, making it suitable for replicating the flavor of conventional meat. Similarly, pea protein contains regulatory branched-chain amino acids (BCAA) such as leucine, isoleucine, and valine, which help facilitate muscle growth and repair. Furthermore, lupin bean protein offers a high methionine content and dietary fibers. High levels of lysine and methionine are important factors in effectively mimicking the sensory properties of meat, as they are responsible for protein synthesis and imparting umami flavors. Among the mycoprotein sources indicated in Table 9, *Agaricus bisporus* and *Pleurotus ostreatus* possess balanced EAA profiles with suitable vitamins and minerals. Fungal proteins such as *Aspergillus oryzae* and *Fusarium venenatum* also contain high quantities of branched-chain amino acids and histidine, which contribute to a meat-like texture. While *Auxenochlorella protothecoides* is limited in its lysine and methionine content, it serves as a functional algal protein source primarily due to its rich presence of omega-3 and omega-6 fatty acids.

3.1. Nutritional Profile of Plant Protein Sources

Table 8. Nutritional Value of Major Plant Proteins.

Total Protein Content (g/100g)	Chicken Breast [225]	Soy [226]	Pea [227]	Mung bean [228]	Faba bean [229]	Lupin bean [230]	Peanut [231]	Oat [232]
Isoleucine (Ile)	4.64	2.0 – 4.2	2.3 – 4.5	3.9	3.9	3.5	0.8 – 1.5	3.8 – 4.1
Histidine (His)	3.04	1.0 – 2.3	1.6 – 2.5	2.8	2.4	2.7	0.6 – 1.1	2.1 – 2.4
Leucine (Leu)	8.27	3.0 – 6.7	5.7 – 6.4	7.4	7.4	6.8	1.6 – 2.9	6.9 – 7.6
Methionine (Met)	2.84	0.5 – 1.1	0.3 – 1.1	1.3	0.8	2.8	0.3 – 0.5	2.2 – 3.3
Lysine (Lys)	7.55	2.7 – 5.3	4.7 – 5.7	6.2	7.0	4.5	0.9 – 1.5	3.5 – 4.1
Phenylalanine (Phe)	4.14	2.1 – 4.5	3.7 – 5.5	9.0	4.1	4.9	1.3 – 2.2	5.0 – 5.5
Tryptophan (Trp)	1.04	0.5 – 1.1	0.7 – 1	0.6	0.8	0.6	0.2 – 0.4	0.8 – 0.9
Threonine (Thr)	4.51	1.7 – 3.1	2.5 – 3.9	2.0	3.4	2.9	0.8 – 1.1	3.1 – 3.4
Valine (Val)	5.07	2.0 –4.0	2.7 – 5.0	4.6	4.3	3.2	1.0 – 1.8	5.2 – 5.8
Alanine (Ala)	5.33	1.9 – 3.5	3.2 – 4.3	3.6	4.1	2.9	0.9 – 1.7	4.4 – 4.9
Arginine (Arg)	6.44	3.1 – 6.6	6.6	6.4	9.4	10.0	3.0 – 5.0	6.1 – 7.1
Aspartic acid (Asp)/Asparagine (Asn)	9.06	10.2 – 12.0	8.9 – 11.5	8.5	10.7	9.7	3.0 – 4.9	7.6 – 8.7
Cysteine (Cys)	1.01	0.6 – 1.0	0.2 – 1.0	1.3	1.3	2.8	0.3 – 0.6	1.9 – 2.5
Glutamic acid/Glutamine (Glu)	13.52	7.8 –17.5	12.9 – 13.2	12.5	16.5	22	5.2 – 8.3	20.9 – 27.3
Glycine (Gly)	4.0	1.8 – 3.6	2.8 – 4.1	3.2	4.3	3.7	1.5	4.6 – 5.3
Proline (Pro)	3.4	2.3 – 4.9	3.1 – 4.5	3.0	3.9	3.2	1.1 – 1.9	5.5 – 6.9
Serine (Ser)	3.99	2.3 – 4.5	3.6 – 5.3	3.8	4.6	4.3	1.2 – 1.7	3.8 – 5.6

Tyrosine (Tyr)	3.54	1.5 – 3.2	2.6 – 3.8	9.0	2.7	4.9	1.0 – 1.6	2.7 – 3.5

Total Fat Content (g/100g)	Chicken Breast	Soy	Pea	Mung bean	Faba bean	Lupin bean	Peanut	Oat
Saturated fat (g)	1.0 – 1.2	2.88	0.071	0.348	0.066	1.16	6.28	1.11
Monounsaturated fat (g)	0.8 – 1.2	4.4	0.035	0.161	0.079	3.94	24.4	1.98
Polyunsaturated fat (g)	0.8	11.3	0.187	0.384	0.164	2.44	15.6	2.3
Essential fatty acids– Omega–3 (mg)	32 – 107	1330	35	27	12	446	3.0	100
EFA– Omega–6 (mg)	559	9920	152	357	152	2000	15600	2200

Vitamin Content	Chicken Breast	Soy	Pea	Mung bean	Faba bean	Lupin bean	Peanut	Oat
Vitamin A (RAE, UI) (μg, UI)	6, 21	1, 22	38, 765	6, 114	1, 15	–	–	–
Vitamin B1 (Thiamin) (mg)	0.07	0.874	0.266	0.233	0.097	0.64	0.64	0.46
Vitamin B2 (Riboflavin) (mg)	0.114	0.87	0.132	0.621	0.089	0.22	0.135	0.155
Vitamin B3 (Niacin) (mg)	9.45 –13.7	1.62	2.09	2.25	0.711	2.19	12.1	1.125
Vitamin B5 (Pantothenic acid) (mg)	0.965	0.793	0.104	1.91	0.157	0.75	1.77	–
Vitamin B6 (mg)	0.6 –1.0	0.377	0.169	0.382	0.072	0.357	0.348	0.1
Vitamin B9 (Folate) (μg)	4.0	375	65	625	104	355	246	56
Vitamin C (Total Ascorbic acid) (mg)	–	6.0	40	4.8	0.3	4.8	–	–
Vitamin D	0.1 –2.5	–	–	–	–	–	–	–
Vitamin E (alpha– toco–pherol) (mg)	0.27	0.85	0.13	0.51	0.02	–	8.33	0.42
Vitamin K (Phylloquinone) (μg)	0.3	47	24.8	9.0	2.9	–	–	2.0

Mineral Content	Chicken Breast	Soy	Pea	Mung bean	Faba bean	Lupin bean	Peanut	Oat
Calcium (Ca) (mg)	6.0 –18.0	277	25	132	36	176	92	52
Iron (Fe) (mg)	1.04 –1.07	15.7	1.47	6.74	1.5	4.36	4.58	4.25
Magnesium (Mg) (mg)	29	280	33	189	43	198	168	138
Phosphorous (P) (mg)	228	704	108	367	125	440	376	410
Potassium (K) (mg)	343 –460	1880	244	1250	268	1010	705	362
Sodium (Na) (mg)	74	2.0	5.0	15	5.0	15	18	6.0
Zinc (Zn) (mg)	1.0 –1.6	4.89	1.24	2.68	1.01	4.75	3.27	3.64
Copper (Cu) (mg)	0.049	1.66	0.176	0.941	0.259	1.02	1.14	0.391
Manganese (Mn) (mg)	0.017	2.52	0.41	1.04	0.421	2.38	1.93	–
Selenium (Se) (μg)	28.4	17.8	1.8	8.2	2.6	8.2	7.3	28.9

Nutritional Content	Chicken Breast	Soy	Pea	Mung bean	Faba bean	Lupin bean	Peanut	Oat
Ash *(g/100g)*	1.06	4.87	0.87	3.32	0.81	3.28	2.33	–
Carbohydrates *(g/100g)*	–	30.2	14.4	62.6	19.6	40.4	16.1	67.7
Total Dietary Fibers *(g/100g)*	–	9.3	5.7	16.3	5.4	18.9	8.5	10.1
Total Sugars (Glucose, Fructose, Lactose, Maltose, Galactose) *(g/100g)*	–	7.33	5.67	6.6	1.82	–	4.72	0.99
Calories *(kcal)*	165	446	81	347	460	371	567	379

3.2. Nutritional Profile of Mushroom/Algae/Fungi Species

Table 9. Nutritional Value of Major Mushroom/Algae/Fungi Species.

Total Protein Content (g/100g)	Chicken Breast [225]	*A. bisporus* [233]	*P. ostreatus* [234]	*L. edodes* [168]	*A. oryzae.* [209]	*A. protothecoides* [235]	*P. limosum* [236]	*F. venenatum* [237]
Isoleucine (Ile)	4.64	1.37	1.02	0.62	13.2	0.31	NS	1.51
Histidine (His)	3.04	0.17	0.27	0.84	0.75	0.09 – 0.96	NS	7.22
Leucine (Leu)	8.27	1.20	1.23	1.29	2.5	NS	NS	1.90
Methionine (Met)	2.84	0.22	0.26	0.42	0.59	Low	NS	4.21
Lysine (Lys)	7.55	1.09	1.18	1.91	1.83	0.184 – 0.224	NS	5.81
Phenylalanine (Phe)	4.14	0.19	0.25	0.83	4.7	Low	NS	3.01
Tryptophan (Trp)	1.04	0.3	0.4	0.28	0.15	0.36	NS	NS
Threonine (Thr)	4.51	0.36	0.38	1.01	0.3	0.23	NS	3.31
Valine (Val)	5.07	0.68	0.42	1.05	1.27	NS	NS	6.05
Alanine (Ala)	5.33	0.77	0.62	1.17	2.52	NS	NS	2.41
Arginine (Arg)	6.44	0.74	0.23	2.45	1.72	NS	NS	7.12
Aspartic acid (Asp)/Asparagine (Asn)	9.06	1.92	0.87	1.73	1.69	NS	NS	NS
Cysteine (Cys)	1.01	0.14	0.18	0.08	0.5 –1.0	NS	NS	2.11
Glutamic acid/Glutamine (Glu)	13.52	1.06	0.98	4.93	5.7	0.56 – 6.88	NS	NS
Glycine (Gly)	4.0	0.6	0.47	0.89	0.57	NS	NS	3.50
Proline (Pro)	3.4	0.69	0.68	0.82	2.5	NS	NS	NS
Serine (Ser)	3.99	0.62	0.26	1.04	6.19	NS	NS	NS
Tyrosine (Tyr)	3.54	0.28	0.65	0.54	0.72	Low	NS	NS
Total Fat Content	**Chicken Breast**	*A. bisporus*	*P. ostreatus*	*L. edodes*	*A. oryzae*	*A. protothecoides*	*P. limosum*	*F. venenatum*
Total Fat Content *(g)*	3.5 – 3.6	0.34 – 0.41	0.41	0.49 – 3.0	3 – 5	21	2.9	2.9
Saturated fat *(g)*	1.0 – 1.2	0.09	0.06	~0.23	~1.2	NS	0.7	0.7

	Chicken Breast	A. bisporus	P. ostreatus	L. edodes	A. oryzae	A. protothecoides	P. limosum	F. venenatum
Monounsaturated fat (g)	0.8 – 1.2	0.21 – 0.23	0.03	~0.3	NS	NS	0.5	0.5
Polyunsaturated fat (g)	0.8	0.07 – 0.1	0.12	~0.2–0.24	NS	High	1.4	1.8
Essential fatty acids–Omega–3 (mg)	0.032–0.107	0.1	Low	Low	Low	High	NS	6.9
EFA– Omega–6 (mg)	0.55 – 3.5	53 – 68	3.1 – 5.4	1.04	0.22	27.6	3.0	3.0
Vitamin Content	**Chicken Breast**	*A. bisporus*	*P. ostreatus*	*L. edodes*	*A. oryzae*	*A. protothecoides*	*P. limosum*	*F. venenatum*
Vitamin A (RAE, UI) (mg, UI)	0.006, 21	0	0.23 – 21, 2.93	0.01	NS	NS	NS	0
Vitamin B1 (Thiamin) (mg)	0.07	1.05	NS	0.05	0.2	0.1	NS	0.07
Vitamin B2 (Riboflavin) (mg)	0.114	0.42	NS	0.15	0.3	0.5	NS	0.114
Vitamin B3 (Niacin) (mg)	9.45 – 13.7	4.55	NS	0.99	3.6	2.0	NS	~13.7
Vitamin B5 (Pantothenic acid) (mg)	0.965	1.75	NS	0.5	1.5	0.5	NS	1.58
Vitamin B6 (mg)	0.6 – 1.0	0.082	NS	0.1	0.1	0.2	NS	0.921
Vitamin B9 (Folate) (µg)	4.0	NS	NS	21.51	500	100	NS	NS
Vitamin C (Total Ascorbic acid) (mg)	–	NS	16.46	2.1	NS	1.0	NS	0
Vitamin D (µg)	0.1 – 2.5	0.2	29	NS	NS	NS	NS	0.025
Vitamin E (alpha–toco–pherol) (mg)	0.27	NS	21.50	NS	NS	0.5	NS	NS
Vitamin K (Phylloquinone) (µg)	0.3	NS	NS	NS	NS	NS	NS	NS
Mineral Content	*Chicken Breast*	*A. bisporus*	*P. ostreatus*	*L. edodes*	*A. oryzae*	*A. protothecoides*	*P. limosum*	*F. venenatum*
Calcium (Ca) (mg)	6.0 –18	0.047	342 – 410	18	2.0	20	NS	5
Iron (Fe) (mg)	1.04 – 1.07	0.013	17 – 21	0.9	10	5.0	NS	0.45
Magnesium (Mg) (mg)	29	115	7.0	40.7	NS	NS	NS	NS
Phosphorous (P) (mg)	228	860	695 – 1060	778	NS	NS	NS	NS
Potassium (K) (mg)	343 – 460	4015	2080 – 2280	356	230	300	NS	255
Sodium (Na) (mg)	74	3.0	193	NS	NS	NS	NS	NS

Nutritional Content	Chicken Breast	A. bisporus	P. ostreatus	L. edodes	A. oryzae	A. protothecoides	P. limosum	F. venenatum
Zinc (Zn) *(mg)*	1.0 – 1.6	0.013	12.96	1.0	1.5	1.0	NS	0.8
Copper (Cu) *(mg)*	0.049	52 – 350	91 – 116	14.8	NS	NS	NS	NS
Manganese (Mn) *(mg)*	0.017	4.8	16 – 23	2.0	NS	NS	NS	NS
Selenium (Se) *(µg)*	28.4	NS	NS	46.1	NS	NS	NS	NS
Ash *(g/100g)*	1.06	1.35	8.22	6.0	4.0	4.0	4.0	2.0
Carbohydrates *(g/100g)*	–	3.3	43.42	64	50	20	50	12
Total Dietary Fibers *(g/100g)*	–	11.01	21 – 47	33.6	14	NS	30	6.0
Total Sugars (Glucose, Fructose, Lactose, Maltose, Galactose) *(g/100g)*	–	14.08	1.11	4.40	~2.0	3.5	NS	1.0
Calories *(kcal)*	165	22	33	34	300	300	300	93

[Note: NS → Not Specified].

4. Formulatory Composition

4.1. Binding Agents

4.1.1. Carboxymethyl Cellulose (CMC)

Carboxymethylcellulose (CMC), a cellulose derivative, is widely used in plant–based meat analogues since it enhances texture, moisture retention, and structural stability. CMC acts as a hydrocolloid, possessing remarkable water–holding capacity and viscosity, forming a 3D network structure that improves rheological properties and overall mouthfeel of meat analogues. Earlier studies suggest that CMC may help lower food products' glycemic index. Through the formation of a matrix around starch granules, CMC retards enzymatic hydrolysis, digestion, and nutrient absorption [238]. Additionally, CMC has been shown to be successful in lowering the absorption of fat in fried foods. 1% CMC–coated French fries lowered fat absorption to 65.1%, compared to 14.1% fat in uncoated samples [239]. CMC is compatible with other edible gums–kinds like guar gum or xanthan gum. It is essential for reproducing the fibrous meandering structure in meat analogues since it reduces interfacial tension between the water and oil phases, which is perfect for emulsification [240]. In varying pH conditions and processing conditions, CMC's robustness in industrial applications. While its cost is higher than alternatives like starch and pectin, CMC remains a preferred choice due to its superior ability to deliver desired texture, binding, and moisture retention in plant–based meat analogues.

4.1.2. Methylcellulose (MC)

Methylcellulose is an important binder and texturizing agent. It is frequently utilized because it may decrease oil leakage and purge loss, increase emulsion stability, and improve textural qualities. It's particularly effective in water and fat binding, helping to retain moisture and fat in the products. MC is the most commonly used ingredient in PBMA burgers because of its binding capacity and unique reversible thermal gelation [241]. It helps to bind texturized vegetable proteins (TVP) and

other ingredients together in comminated and emulsion–type PBMA products, such as burgers and sausages. The binding results in a consistent gel network, which improves the product's mouthfeel and texture. Despite its effectiveness, methylcellulose has an "E number" designation, a European Union (EU) labelling system used to indicate the presence of food additives which may not appeal to consumers who perceive additives as inorganic constituents [242]. However, it remains a key ingredient in many commercial plant–based meat products due to its functionality. Alternatives such as alginate, hydroxypropyl methylcellulose, and other hydrocolloids are considered but they cannot match methylcellulose's unique properties.

4.1.3. Xanthan Gum (X)

Plant–based meat substitutes majorly utilize xanthan gum, an extracellular polysaccharide fermented from Xanthomonas species, because of its gelling, thickening, stabilizing, and emulsifying qualities [239]. It enhances texture and fibrous structure by encouraging the development of cohesive and organized networks in protein matrices, particularly in formulations that contain wheat gluten and pea protein isolate [243]. Additionally, xanthan gum interacts with pectin and low acyl gellan gum, to improve the mechanical qualities and mimic a meat–like texture. Since xanthan gum has a higher yield strength than protein–based binding agents, it may be used to create intermediate fibres and improve structural compactness in soy protein isolate (SPI) blends [244]. Xanthan gum also serves to enhance both 3D printing performance along with gel stability in plant–based formulations, rendering syneresis impossible, delaying staling, and capable of maintaining shape at freeze–thaw cycles [245]. Although the utilization of hydrocolloids such as xanthan gum has raised controversy upon several occasions due to their nutritional effects and safety, no significant evidence is available to date to support complaints or concerns about health hazards (EFSA Panel on Food Additives and Nutrient Sources added to Food, 2018).

4.1.4. Carrageenan (CA)

Red seaweeds like *Chondrus crispus and Eucheuma sp.* are the source of Carrageenan, a polysaccharide used in the food industry for its thickening, stabilizing, and emulsifying qualities [246]. The range of applications includes the stabilization of emulsions in dairy and meat products, as well as an improvement in the texture and lipid oxidation reduction of formulations such as sausages, ham, and PBMAs [247]. Additionally, carrageenan is essential for enhancing emulsion stability and water–holding capacity, both of which are critical for yielding the appropriate texture in meat substitutes. The textural properties in mushroom–based sausage analogues that include carrageenan improve when compared with soy protein concentrate and casein, including reduced purge loss and gumminess. Earlier studies showed that its gelling and thickening ability improves product stability and consistency as well as cooking loss reduction [248]. Carrageenan is also utilized to make edible films and coatings for fresh meals. Beyond food, it has other health benefits like regulating cholesterol levels and aiding in wound healing [249]. Kappa–carrageenan (k–carrageenan) is one of the most widely used forms and is particularly known for its strong gelling properties, which are commonly used in meat analogues for structural integrity.

4.1.5. Guar Gum (GuG)

A multipurpose polysaccharide derived from *Cyamopsis tetragonolobus* seeds, Guar gum is well-known for its ability to bind, thicken, and emulsify [250]. Its high water-holding capacity (WHC) and viscosity–modifying characteristics make it a significant component in plant–based meat preparations. It increases water retention and enhance 3D printing performance in soy protein isolate gels while inhibiting syneresis during freeze–thaw cycles [251]. In food–based applications, guar gum reduces the absorption of fats, for instance, French fries coated with 1% guar gum that saw a decrease of 60.2% fat content in relation to the control samples [252]. Methods to retain the moisture content and textural properties in meat analogues have been researched extensively to ensure improved

juiciness and mouthfeel. Studies have revealed that addition of hydrocolloids such as guar gum in plant-based meat formulations enhances the water holding capacity, subsequently simulating the fibrous structure of real meat [14]. Despite occasional debates over the nutritional impact of edible gums, including guar gum, no substantial evidence has been found to suggest any health risks, further solidifying its role as a safe and effective binding agent (EFSA Panel on Food Additives and Nutrient Sources added to Food, 2018). Furthermore, guar gum can effectively interact with other hydrocolloids and proteins, allowing for the creation of a harmonious texture that is crucial for product acceptance. This property is essential for companies seeking to appeal to a broad range of consumers.

4.1.6. Gellan Gum (GeG)

Gellan gum, a microbial hydrocolloid derived from Sphingomonas sp., is widely renowned for its remarkable gelling properties [253]. Plant-based meat substitutes and various products, including jams, jellies, crackers, chicken nuggets, yogurt, and frozen desserts, can benefit from their ability to produce strong, stable gels that withstand heat and pH changes [240]. Consequently, it elevates the cohesion and mouthfeel of the finished product. When appropriately balanced salt concentrations are employed, the network of gellan in a protein matrix forms a cohesive structure [244]. Gellan gum has two forms–high acyl and low acyl, each exhibiting different properties and performance in plant-based meat formulations. High Acyl Gellan Gum form is a more flexible gel because it is softer and more elastic than acyl groups. Therefore, it is useful for applications in which a tender texture is desirable, such as frozen desserts and yogurts. On the other hand, low acyl gellan gum forms firm, brittle gels since they lack acyl groups. Its structural rigidity and fibrousness are desirable in meat analogs and textured products. When combined, these forms can balance textural properties to mimic the fibrous structure of traditional meat. Salt concentrations further enhance plant- based meat's functionality, mechanical, and textural characteristics [254].

4.1.7. Other Hydrocolloid–Based Binders in PBMAs

Pectin is a polysaccharide predominantly found in the cell walls of fruits and is widely recognized for its gelling properties. Although primarily used in jams and jellies, pectin's ability to form gels makes it a candidate for PBMAs. Pectin has proven to enhance the structural integrity of meat analogues, contributing to a more cohesive protein matrix when combined with other hydrocolloids. Low methylated pectin with calcium chloride ($CaCl_2$) in blends containing PPI has been found to facilitate gelation, resulting in thin fibril formations within the protein matrix, thereby improving the overall texture [244]. Pectin's unique egg–box model mechanism allows it to stabilize gels through electrostatic interactions with cations, which is crucial for achieving the desired consistency in meat alternatives [254]. Furthermore, pectin can lower the glycemic index, making it an advantageous ingredient in PBMA formulations [238].

Brown seaweed is the natural alginate source, a polymer sold as sodium alginate [255,256]. Because of its free hydroxyl and carboxyl groups, they interact with water effectively and can be used as a gelling agent, thickener, stabilizer, and emulsifier. It serves as a source of dietary fiber that may help reduce cholesterol and blood glucose levels. Notable sources include *Laminaria sp.* and *Sargassum sp.* Alginate improves product stability throughout freeze-thaw cycles and provides exceptional adhesion. Additionally, it improves the texture by binding vegetable proteins and reducing oil absorption [257]. Overall, while alginate may be less commonly utilized than other binders in PBMAs, its unique properties present promising opportunities for innovation.

Agar, a polysaccharide derived from red seaweeds such as *Gelidium spp.* and *Gracilaria spp.,* is recognized for its stabilizing, thickening, and gelling properties [258]. In the context of PBMAs, agar can enhance texture and provide desirable elasticity, making it an effective binder that contributes to meat alternatives' overall mouthfeel and structure. Its capacity to gel enables better cohesiveness between plant proteins. Additionally, agar's high melting point ensures that the structural integrity

of PBMAs is maintained during cooking. Given its functionality and cost-effectiveness due to the abundant availability of seaweeds, agar presents a viable way to improve the quality of plant-based meat substitutes.

Gum Arabic, sometimes called gum acacia, is an exudate from Acacia trees characterized by branched polysaccharides, including β–D–galactopyranosyl units [259]. In PBMAs, gum Arabic enhances emulsification and foaming properties, particularly in sausage–type meat analogues, where it helps maintain stable emulsions. It improves binding efficiency, maintains suspension, and contributes to bulk volume and cloudiness in formulations. Its functionality at alkaline pH further supports its use in various meat alternatives. Gum Arabic enhances texture and improves mouthfeel, making it a valuable ingredient in plant-based meat products.

Konjac mannan gum, derived from the tubers of Amorphophallus konjac, is a polysaccharide characterized by high molecular weight and water solubility [260]. It is an excellent gelling and emulsifying agent, making it particularly useful as a binder. In plant-based formulations, konjac mannan gum helps reduce moisture loss during cooking and frying, improving meat alternatives' overall texture and sensory attributes. For instance, vegan meat sausages formulated with konjac mannan gum have been shown to closely resemble traditional meat sausages in terms of hardness, slicing ability, and water–holding capacity [261]. Additionally, its ability to enhance non-digestible fiber content makes konjac mannan gum suitable for low–calorie food applications.

Locust bean gum, derived from the seeds of the Ceratonia siliqua tree, is a high–molecular–weight polysaccharide recognized as a natural food additive [280]. It can prevent aggregation, stabilize emulsions, and improve texture by reducing syneresis and stabilizing freeze-thawing in starch–based formulations [262]. Its composition—primarily D–mannopyranose units with side chains of D–galactopyranose—allows it to function effectively as a binder while supporting gut health and reducing fat absorption [282]. Overall, locust bean gum is a valuable ingredient for enhancing the stability and sensory attributes of PBMAs.
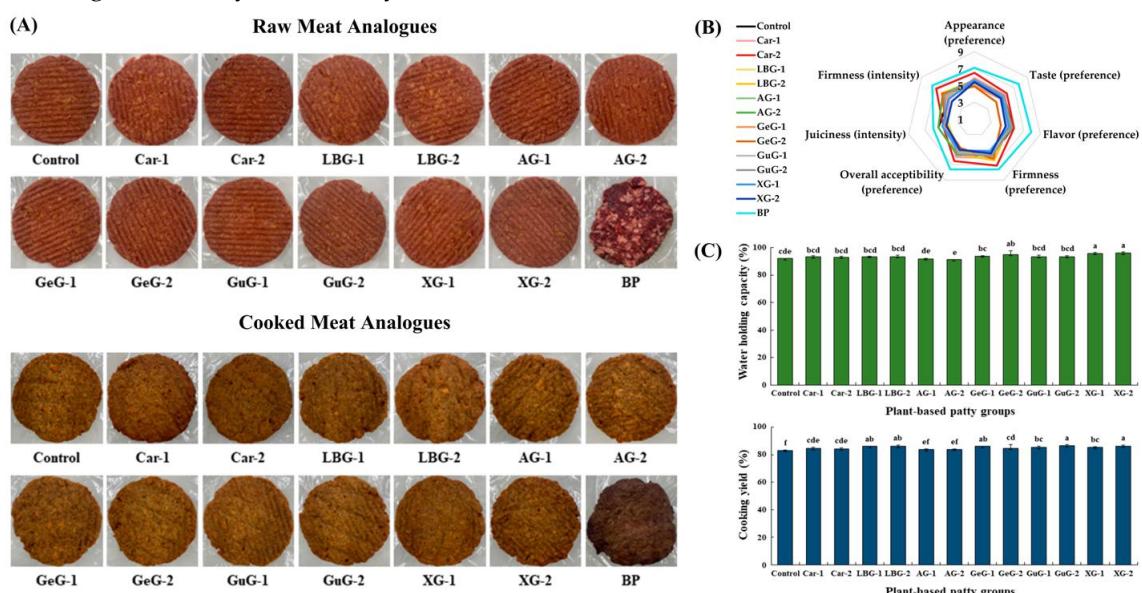

Figure 2. (A) Plant-based meat analogues with different concentrations of hydrocolloids (Control: plant-based patty without polysaccharide; Car–1: 1% κ–carrageenan, Car–2: 2% κ–carrageenan; LBG–1: 1% locust bean gum, LBG–2: 2% locust bean gum; AG–1: 1% Arabic gum, AG–2: 2% Arabic gum; GeG–1: 1% gellan gum, GeG–2: 2% gellan gum; GuG–1: 1% guar gum, GuG–2: 2% guar gum; XG–1: 1% xanthan gum, XG–2: 2% xanthan gum; BP: Beef patty); (B) Sensory properties of plant-based meat analogues; (C) Water–holding capacity (WHC) and cooking yield of plant-based meat analogues. Reproduced with permission [263]. Copyright Multidisciplinary Digital Publishing Institute (MDPI), 2023.

Table 10. Types of Hydrocolloids in Meat Analogues.

Hydrocolloids (Food additive code)	Latin Name	Properties	Reference
Carrageenan (E407)	*Chondrus crispus*	Acts as a binder, stabilizer, and moisture retainer. ● Kappa: Forms strong, rigid gels(K^+). ● Iota: Forms soft gels(Ca^{2+}) ● Lambda: Used as a thickener.	[264]
Xanthan gum (E415)	*Xanthomonas campestris*	Exhibits pseudoplasticity. Maintains stability over a wide temperature (10–80°C) and pH (5–10) range.	[265]
Guar gum (E412)	*Cyamopsis tetragonoloba*	Functions as a thickener, texture enhancer and fat substitute. Maintains stability in a wide pH range (1.0–10.5).	[266]
Konjac gum (E425)	*Amorphophallus konjac*	Exhibits texture control and forms thermo–reversible and irreversible gels. Stable at 85°C in the presence of mild alkali (pH 9–10).	[267]
Low acyl Gellan gum/ Gelzan (E418)	*Sphingomonas elodea*	Forms strong, brittle gels that are heat– and pH–stable, providing a fibrous structure.	[268]
Locust Bean Gum (E410)	*Ceratonia siliqua*	Functions as a thickener, emulsifier, and stabilizer. Has a neutral flavor and prebiotic properties that improve hydration.	[269]
Gum Arabic/Acacia (E414)	*Senegalia senegal*	Highly water-soluble, low viscosity, and optimal at pH 3.5. Structure–forming transitions shift to higher pH as protein content increases.	[270]
Flaxseed gum	*Linum usitatissimum.*	Improves mouthfeel, moisture retention, and uniform texture while preventing ingredient separation.	[271]

Table 11. Types of Starches and Enzymes in Meat Analogues.

Starches	Latin Name	Properties	Reference
Corn starch	*Zea mays*	Enhances viscosity and elasticity. Exhibits WAC and gelatinization properties. Reduces off–flavors.	[272]
Modified starch	*Amylum modificatum*	Enhances viscosity, elasticity, resilience, chewiness, and ductility. Reduces off–flavors and off–colors.	[273]
Potato starch	*Solanum tuberosum*	Increases fibrous content through thermo–irreversible gelatinization and freeze-thawing processes.	[274]
Wheat starch	*Triticum vulgare*	Exhibits thermal stability, retrogradation properties, and swelling index. It develops fibrousness due to glutenins and gliadins ratio.	[275]
Maltodextrin	–	Functions as a thickener, binding agent, and mouthfeel enhancer. Provides a creamy, spreadable texture similar to hydrogenated fat.	[276]

| Transglutaminase | – | Induces crosslinks between protein molecules, improving binding properties and cutting strength. Enhances the overall texture. | [277] |

Table 12. Types of Crosslinking Gelling Agents in Meat Analogues.

Cross–linking Gelling Agents	Latin Name	Properties	Reference
Calcium ions (Ca^{2+}, lactate, acetate) + Sodium alginate/ alginin	–	Functions as an adhesive and forms a cold–set gel in the presence of divalent cations, improving texture and moisture retention.	[278]
Agar	*Gracilaria verrucosa*	Serves as a plant–based alternative to gelatin. Provides palatability and does not require high sugar concentrations to form a gel.	[279]
Pectin	*Saccharomyces cerevisiae*	High– or low–methyl–esterified pectin forms gels when combined with sugar and acid.	[280]

4.2. Coloring Agents

Natural colorants in plant–based meat analogues have attracted significant attention because of growing concern over synthetic colorants' safety and health risks. Numerous natural colors, including betalains, carotenoids, anthocyanins, chlorophyll, and heme proteins, have been investigated for potential use in plant–based meat substitutes [281]. However, each pigment poses shortcomings concerning stability, pH sensitivity, thermal degradation, and oxidation, [282]. Leghemoglobin (LegH), one of the most used pigments, has shown great promise since it resembles myoglobin, the primary protein that gives animal meat its red hue. LegH is produced via microbial fermentation, wherein genetically modified yeast or bacteria are used for the production of a heme-containing protein with properties/functions similar to those of animal-derived myoglobin. Despite the success achieved in color matching, concerns about consumer acceptance of genetically modified organisms remain an ongoing challenge [281].

Chlorophyll–derived pigments have also been investigated as natural colorants. Chlorophyll is utilized to synthesize Fe–pheophytin through ion exchange methods, resulting in a more stable pigment [283]. However, chlorophyll and its derivatives are very sensitive to pH and oxidation, requiring stabilization techniques, including encapsulation and emulsification. Anthocyanin extraction from sources like black beans has been investigated for adding red to plant–based meat substitutes. Chromatographic examination of the isolated anthocyanins revealed that, on a temporal level, absorption peaks scanned at 277, 515, and 546 nm identified delphinidin–3–mono glucoside (D3G) at 3.1 and petunidin–3–mono glucoside (P3G) at 5.1 [283]. Such pigments provide natural alternatives to synthetic red dyes but are very pH–pH-sensitive, changing from red in acidic to blue or green in alkaline conditions [281]. Carotenoids like *lycopene, beta–carotene, and astaxanthin* are another class of natural pigments used in PBMAs. Depending on concentration and processing conditions, these pigments are sourced from tomatoes, carrots, and microalgae–based colors within a range of red to orange. Studies have also shown that the meshing of carotenoids with other pigments, like anthocyanins or betalains, can be more dynamic and stable. However, due to high lipophilicity, delivery systems are necessary to stabilize and enhance their bioavailability [282].

Betalains, which are produced from plants like red beet, have shown the ability to replicate the color of fresh meat. When red beet (0.4–1.5 mg/g) and cacao pigments (1.1–1.3 mg/g) were combined, the color produced matched that of well-cooked beef [284]. The ideal concentrations were determined using response surface methodology (RSM). However, betalains are very sensitive to light, temperature, and pH, necessitating co–pigmentation and microencapsulation. Microbial pigments

from *Monascus, Fusarium venenatum,* and *Neurospora intermedia* have been studied for their ability to impart natural red colors with a pH-dependent color change in plant-based meat analogues [285]. However, certain microbial pigments produced by Monascus, can also create hazardous byproducts, requiring purification measures. Overall, the development of natural pigments for plant–based meat analogues must employ multidisciplinary approaches wherein pigment stability, safety, and consumer acceptability are considered.

Table 13. Types of Coloring Agents in Meat Analogues.

Coloring Agents	Latin Name	Shade	Pigments	Reference
Annatto extract/ Achiote	*Bixa orellana*	Yellow–Orange to Red	Carotenoids – Bixin and Norbixin	[286]
Caramel	*Calamellus*	Golden Brown	Heated sugars – Caramelization	[287]
Malt extract	*Hordeum vulgare*	Brown	Heated grains – Maillard reaction	[288]
Beet extract	*Beta vulgaris*	Red–Purple	Betalains – Betanin	[289]
Elderberry extract	*Sambucus nigra*	Purple–Red	Anthocyanins	[290]
Lycopene	*Lycopersicon esculentum*	Red	Carotenoids	[291]
Paprika	*Capsicum annuum*	Yellow–Orange to Red	Carotenoids – Capsanthin and Capsorubin	[292]
Turmeric	*Curcuma longa*	Right Yellow	Curcuminoids	[293]
Spirulina extract	*Arthrospira platensis*	Blue–Green	Phycocyanins	[294]
Chlorophyllin	*Chlorophylle*	Green	Chlorophyll	[295]
Pomegranate concentrate	*Punica granatum*	Red–Purple	Anthocyanins and Ellagitannins	[296]

4.3. Chemical Agents

The preparation of plant–based meat analogues involves the use of several chemical agents to regulate texture, stability, color, and other properties concerning product quality. These compounds primarily mimic the sensory and functional attributes of meat. Understanding their roles can allow manufacturers to advance the development of PBMAs to illustrate the characteristics and properties of meat adequately. Certain chemical agents are used to fortify the taste and control oxidation. One example is *monosodium glutamate (MSG)*, which largely replicates the meaty flavor of animal protein from traditional meat [297]. Sodium erythorbate and ascorbic acid act as antioxidants that lower lipid oxidation and stabilize plant–based proteins, therefore minimizing undesirable off-flavors [298]. Dealing with oxidation is an ongoing challenge among plant–based formulations; naturally, highly unsaturated lipids can degrade quickly because of rancidity. Antioxidants eliminate this constraint and facilitate stability and freshness for extended periods. On the other hand, Choline chloride acts as an emulsifier, allowing fat and moisture to distribute uniformly within plant–based compositions. The emulsifying materials are highly useful in preventing different phases from separation and influencing the end product's mouthfeel [299].

The texture of plant–based meat analogues is pivotal for mimicking the mouthfeel of conventional meat. Sodium metabisulfite and potassium metabisulfite are employed to maintain protein interactions and to inhibit discoloration [3]. Sodium chloride and calcium chloride are used to improve water retention and gelling properties, producing a distinctive chewier structure. Salt ions

interact with plant proteins, enhancing their gelling ability and bonding power [300]. Glycerin is popularly included to stimulate moisture retention, thus allowing for a juicier bite. It acts as a humectant, preventing the product from becoming overly dry while maintaining textural quality throughout storage and cooking. Hydrocolloids such as methylcellulose and carrageenan are frequently used to give elasticity and create structural cohesion, strengthening the meat–like consistency [301]. With balance among these texture enhancing agents, manufacturers can achieve more realistic meat–like textures when fortifying plant-based products. Choline chloride offers further stabilizing support to these formulations by impeding phase separation whilst enhancing moisture retention [302].

Nonane, methanol, and *acetonitrile* aid lipid extraction and flavor compound analysis to identify ideal processing conditions. Hydrochloric acid and sodium hydroxide act as pH regulators during protein isolation, improving protein solubility and structural properties. Altering the pH is important to optimize protein functionality, whereby properties such as WHC and gel formation are affected [303]. Other popular natural colorants are purple potato powder, which provides a high brightness level, and beetroot extract, a rich source of betanin that imitates the red shades of raw meat. In addition, some analyses use bromophenol blue to monitor changes in pH. These additives ensure that product quality and visual presentation remain consistent, which is vital to how the products are received in the marketplace. Overall, they provide very critical considerations that formulate appropriate manufacturing parameters, satisfactory sensory qualities, functional stability, and consumer satisfaction with the finished product. Continuous advancements in ingredient technology and processing techniques are expected to refine the use of these chemical agents, further improving the sensory and nutritional attributes of plant-based meats.

Table 14. Types of Chemical Agents in Meat Analogues.

Cellulose	Chemical Formula	Properties	Reference
Carboxymethyl cellulose (CMC)	$(C_6H_{10}O_5)_n$	Odorless, white, or yellowish powder. Preserves structure and stops ingredient separation.	[304]
Methylcellulose (MC) (E461)	$C_{20}H_{38}O_{11}$	Known for its binding capacity and unique reversible thermal gelation. Functions as a stabilizer and emulsifier.	[241]
Hydroxypropyl methylcellulose (HPMC) (E464)	$C_{56}H_{108}O_{30}$	Provides binding, gelling, texture improvement, and stabilization. Functions as an emulsifier with thermal gelation properties.	[305]

4.4. Flavoring Agents

Flavor and sensory aspects are central to consumer acceptance of plant–protein–based meat substitutes. This quest to imitate meat comes with the challenge of replicating taste profiles via Maillard reaction, lipid oxidation, and umami compounds. Thus, various odor and umami enhancers have been integrated into multiple formulations, including yeast extracts, nucleotides, and lipid-based fermentation products [302]. In meat analogues, hydrocolloids like methylcellulose, konjac gum, and carrageenan can enhance binding and water retention, improving juiciness and cohesiveness [306]. The addition of monosodium glutamate (MSG) and mushroom extracts increases the richness of flavors in plant-based alternatives. Aging processes often intensify this flavor by breaking down proteins into umami-rich amino acids. Yeast extracts are an inexpensive flavor enhancer that owes their umami character to nucleotides like Inosine monophosphate (IMP) and guanosine monophosphate (GMP). Research indicates that when combined with amino acids and peptides from hydrolysed proteins, yeast extract enhances the meat–like tastes of plant-based alternatives. Soy sauce and Aspergillus oryzae–fermented products impart savory notes and mask undesirable bean flavors from a legume–based proteins. The effects of fermented plant extracts

derived primarily from wheat and barley have also been identified, as they curtail bitterness and improve palatability [297].

Many lipid-based solutions–including vegetable oils infused with heme–like molecules and volatile compounds give meat analogues their characteristic aroma and juiciness. Heme proteins like soy–derived leghemoglobin closely mimic the iron-rich animal muscle protein, myoglobin [307]. Other lipid sources such as coconut oil and algal lipids contribute to mouthfeel and act as delivery systems for lipid-soluble volatile compounds produced during TMP. The meaty fragrance production mainly depends on lipid oxidation pathways, where PUFAs serve as precursors to aldehydes and ketones [300]. Heat-induced reduction of sugars and amino acids by the Maillard reaction produces a new class of volatile chemicals, such as pyrazines, thiols, and aldehydes that resemble the distinctive grilled and roasted flavors of cooked meat. It has been demonstrated that adding cysteine and ribose to plant–based analogues increases the synthesis of volatile chemicals. [308]. Furthermore, sulfur-containing compounds such as thiols derived from methionine contribute significantly to the umami notes of meat alternatives [118]. Modern biotechnology has brought about additional fermentation-derived aroma compounds, particularly short–chain fatty acids, esters, and ketones with fatty, cheesy, and buttery notes, via microbial strains such as Bacillus and Lactobacillus.

Modifying plant proteins through enzymatic action has also been used to minimize off–flavor associated with grassy and beany notes, which are usually specific to protein sources like soy and pea. Palatability is improved by the enzymatic breakdown of proteins into smaller peptides and free amino acids [309]. Different innovative culinary approaches are being explored, including precision fermentation and metabolic engineering of yeast strains to generate customized flavor compounds like those found in meat [107]. Despite advancements, several challenges remain in achieving a balanced meat-like flavor. The interactions between plant proteins and added flavor enhancers are complicated and lead to inconsistent tastes among different formulations. Variation in the flavors of meat analogues is largely influenced by ingredient sources, processing techniques, and storage conditions, all of which contribute to consumer taste perception [310]. With consumers shifting towards clean-label foods, more integrated studies should focus on plant-derived umami compounds from seaweeds, tomato concentrates, and miso fermentation in place of artificial additives [76].

Table 15. Types of Flavoring Powders and Pulps in Meat Analogues.

Powders and Pulps	Latin Name	Properties	Reference
Purple potato powder	*Ipomoea batatas*	Provides natural color, enhances texture, and is rich in antioxidants.	[311]
Konjac powder	*Amorphophallus konjac*	Functions as a gelling agent, imparts a chewy texture, and is low in calories.	[312]
Meat flavor powder	–	Adds a savory, umami–rich flavor.	[313]
Paprika powder	*Capsicum annuum*	Contributes color with a mild, slightly sweet flavor.	[314]
Cumin/Jeera powder	*Cuminum cyminum*	Imparts an earthy, warm, and slightly nutty flavor.	[315]
Citric acid powder	*Acidum citricum*	Provides a tangy flavor and helps extend shelf life.	[316]
Ascorbic acid powder	*Acidum ascorbicum*	A source of vitamin C, prevents oxidation, and maintains freshness.	[317]
Mustard powder	*Brassica juncea*	Delivers a sharp, tangy, and slightly spicy flavor.	[318]
Onion powder	*Allium cepa*	Adds a rich, savory base flavor.	[313]

Garlic powder	*Allium sativum*	Enhances depth and richness of flavor.	[314]
Panela/Jaggery powder	*Saccharum officinarum*	Provides a subtle sweetness that balances flavors.	[319]
Tomato powder	*Solanum lycopersicum*	Enhances natural color and imparts a rich, tangy flavor.	[320]
Pepper powder	*Piper nigrum*	Adds depth with a bold, spicy kick.	[321]
Flaxseed powder	*Linum usitatissimum*	High in omega–3 fatty acids and dietary fiber, contributing to texture and nutrition.	[322]
Ground jackfruit pulp	*Artocarpus heterophyllus*	Provides a fibrous texture and is a good source of dietary fiber.	[323]

Table 16. Types of Flavoring Agents in Meat Analogues.

Flavoring Agents	Properties	Reference
Monosodium glutamate/ Ajinomoto	A sodium salt of glutamic acid that enhances savory, umami flavors.	[324]
Yeast extracts powder	Provides umami flavor and helps mask bitter or earthy off–notes.	[301]
Soy leghemoglobin	A heme protein derived from genetically modified yeast; it enhances the meaty taste in plant–based products.	[325]
Beet and lemon juice	Adds natural red color and brightness to foods.	[310]
Cooked onion and carrot juice concentrates	Enhances savory depth, while natural carrot pigments improve color.	[326]
Salt	Enhances overall flavor by balancing and intensifying taste perception.	[327]

Table 17. Types of Sweetening Agents in Meat Analogues.

Sweeteners	Properties	Reference
Dextrose	20% less sweet than sucrose, contributes to the Maillard reaction and caramelization when combined with cysteine.	[328]
Glucose	Actively participates in the Maillard reaction, enhancing browning and flavor development.	[329]
Sucrose	Serves as a bulking agent and preservative. Hydrolyzed into glucose and fructose during processing.	[330]
Fructose	Undergoes the Maillard reaction, though its effect is less pronounced compared to glucose and dextrose.	[331]
Sugar alcohols (erythritol, sorbitol)	Lower glycemic impact, contribute to a smooth, creamy texture, help retain moisture, and prevent drying.	[332]
Brown Sugar	Imparts a rich caramel flavor due to its molasses content.	[333]

Table 18. Emulsification Agents in Meat Analogues.

Emulsifying Agents	Latin Name	Properties	Reference
Corn oil	*Maydis oleum raffinatum*	Rich in PUFAs, primarily linoleic acid (58–62%). Contains high levels of phytosterols (8,300–25,500 ppm) and tocopherols (1,130–1,830 ppm).	[334]

Soy oil	*Soiae oleum raffinatum*	Contains PUFAs like linoleic acid (48–58%) and isoflavones.	[335]
Peanut/ Groundnut oil	*Arachis hypogaea*	High in monounsaturated fats, primarily oleic acid (45–72%). Mild flavor with a high smoke point. Used in oleogel production for fat stabilization.	[336]
Rapeseed oil	*Brassica campestris*	Rich in unsaturated fats, particularly oleic acid. Contributes to smooth texture and stability.	[337]
Canola oil	*Brassica napus*	Contains 7% saturated fat, monounsaturated fat, and ALA omega–3 fatty acids. It has a mild flavor, and a high smoke point.	[338]
Sunflower oil	*Helianthus annuus*	High in PUFAs, mainly linoleic acid (55–75%). High smoke point and naturally rich in vitamin E.	[339]
Safflower oil	*Carthamus tinctorius*	Contains high levels of PUFAs, mainly linoleic acid. Enhances texture and moisture retention.	[340]
Palm oil	*Elaeis guineensis*	Semi–solid at room temperature, contributing to moisture retention and succulence.	[341]
Red palm oil	*Elaeis guineensis (or) Elaeis oleifera*	Contains saturated and monounsaturated fats, with high palmitic acid and carotenoids. Enhances mouthfeel, juiciness, and richness in formulations.	[342]
Coconut oil	*Cocos Nucifera*	92% saturated fat, making it a stable fat source. Used in 3D–printable fat analogues for meat substitutes when combined with glucomannan.	[343]
Orange oil	*Citrus sinensis*	Acts as a masking agent to reduce the bean odor of soy–based products. Exhibits strong antioxidant activity (DPPH radical scavenging activity).	[344]

5. Existing Technology

5.1. Single Screw Extrusion

Plant–based meat analogues (PBMAs) are majorly produced using single–screw extrusion due to their simplicity and cheap operating costs. A single revolving screw is used to apply pressure to a combination of plant proteins, water, and other ingredients. Heat and shear from this process cause the proteins to become denatured and fibrous. It is capable of producing a range of textures, including meat–like ones. Nevertheless, in comparison to more sophisticated techniques such as high–moisture extrusion (HME) or twin–screw extrusion, the fibrous structures produced are generally less defined, leading to a product that lacks the chewiness and structural integrity of actual meat. Despite this limitation, single–screw extrusion remains a feasible option for producing plant–based meat alternatives in large quantities, especially for products such as textured vegetable protein (TVP). This extrusion process is also energy efficient and runs at comparatively low expenses, making it ideal for bulk production [345]. Furthermore, improvements in extrusion parameters like screw speed, moisture content, and temperature can improve the texture and protein quality of the finished product [346]. Further, it has also been proven to enhance digestibility in plant proteins by denaturing, unfolding, and cross–linking them during the process. While twin–screw extrusion is more suitable for producing a meat-like structure compared to single–screw extrusion, its economic feasibility and scalability make it a widely accessible technology for developing PBMAs [347].

5.2. Twin Screw Extrusion

Twin–screw extrusion (TSE) is a more sophisticated and intricate process than single–screw extrusion, providing better control over the protein structure. It involves the use of two intermeshed screws, generating greater shear stress and enabling easier manipulation of plant protein networks,

which aids in forming layered and fibrous structures. The use of twin–screw extrusion has been shown to be especially useful in producing high–moisture PBMAs that closely mimic the meat–like mouthfeel and texture of natural meat. With the fine control of processing conditions like screw speed, temperature, and pressure, TSE can produce fibrous, elastic, and meat–like products [348]. Specifically, TSE enables protein molecules to align into layered configurations that mimic muscle fibers in meats from animals [308]. The technique can also combine different protein sources, such as soy, wheat gluten, and pea protein, to maximize the final product's mouthfeel and structural quality [349]. Current research aims at maximizing the extrusion process, such as screw design and thermal versus mechanical energy input balance, to enhance product quality and manufacturing productivity. Through optimization of these parameters, TSE has the potential to meet the increasing demand for PBMAs.

5.3. High Moisture Extrusion

High moisture extrusion (HME) is among the most effective techniques for manufacturing PBMAs that mimic the fibrous structure of animal meat [309]. HME is a process where a protein blend is extruded at high pressure and temperature, typically with a moisture level above 70%. The synergy of shear forces, heat, and pressure produces a fibrous structure that is similar to the texture of whole–muscle meats such as chicken and beef [350]. One of the significant benefits of HME is that it can enhance the mouthfeel of PBMAs. By adjusting temperature, screw rate, and moisture, the texture may be modified [351]. To encourage protein alignment and limit expansion, HME uses a twin–screw extruder and cold die at above 50% moisture content, resulting in a final product that resembles structured meat [352]. The capability of synthesizing analogues from proteins such as soy, hemp, pea, lentils, and faba beans has made HME a widely accepted process in the manufacture of PBMAs [353]. Despite its merits, HME is energy-demanding and needs sophisticated machinery, which may raise production costs and make scaling difficult [297]. However, HME is still among the most promising technologies for PBMA production, with high productivity, nutrient retention, and minimal waste production [308]. Although soy, wheat, and peanut proteins are frequently used in HME, research on other protein sources, including hemp and lupin, has increased the technology's applicability.

5.4.3. D–Bioprinting

3D–bioprinting technology has been a groundbreaking tool in developing PBMAs. Recent research by Keerthana et al. (2020), illustrated the capability of 3D–printing to manufacture mushroom–based meat analogues. [152]. 3D–printing or additive manufacturing is used to produce customized texture, shape, and nutritional composition, where food bioinks are added in layers to produce meat analogues with the texture of muscle fibers [354]. However, printing mushroom products is difficult owing to its fibrous network, which can clog the printing nozzle. Extrusion, binder jetting, and inkjet printing are some 3D printing techniques used in the food processing industry. Foods that are semi–solid, such meat purees and doughs, work well for extrusion–based printing. Inkjet printing is utilized in low–viscosity fluids; whereas binder jetting accommodates powder forms such as sugar or cocoa powders. Of the various methods, the extrusion technique stands out as the most widely researched for food printing, where nozzle diameter, material deposition rate, and print speed influence the printability and structure of the final product [355]. The other two main aspects of 3D food printing include its capacity to provide high degrees of customization, such that food texture, shape, and nutritional composition can be tailored. Studies have also investigated the application of food hydrocolloids to enhance printability [356,357]. While there are limitations in mirroring the intricate fibrous texture of animal meat, advancements in protein sources continue to enhance the quality of meat analogues [358,359].

5.5.4. D–Bioprinting

Building upon this, 4D food printing adds the aspect of time and environmental stimuli so that printed foods can transform in terms of shape, color, taste, or nutritional content. This new technology uses food–grade shear–thinning inks, which can flow when subjected to external force but become stable once the force is released. This property allows for the development of food structures that are capable of dynamically changing during printing or post-processing. One of the capabilities of 4D printing is the conversion of shiitake mushrooms and potato purees, with ergosterol being converted to vitamin D2 through UV irradiation [360]. This concomitant conversion illustrates how 4D printing can produce sophisticated shapes in food and improve nutritional qualities. Synergistic integration of 4D printing with other processing steps can add much value to food products [361]. This capacity to alter food structure and nutritional value creates new opportunities for personalized nutrition and functional foods [360]. 4D–bioprinting technology has excellent potential for developing novel, flexible food items that can satisfy various customer demands and tastes [152].

5.6. Shear Cell Technology

Shear Cell Technology (SCT) is used to create plant-based meat substitutes that closely mimic the structure of animal meat [14]. It consists of rotating blades or cylinders that subject plant protein blends to high shear forces, forming elongated, fibrous strands [362]. SCT can control the network alignment and protein density with high precision as it increases the cohesiveness and elasticity of the protein [307]. SCT also consumes less energy than conventional extrusion processes, making it more economical for small-scale production [363]. The resultant products have a very high level of anisotropy and can mimic fibrous characteristics effectively [364]. However, SCT also faces limitations in scaling up and ensuring consistency in the finished product. Control of shear force and temperature is needed to achieve the desired texture, which can be challenging in large–scale production. Denaturation of the proteins due to excessive shear stress can potentially affect the quality of PBMAs. Nonetheless, SCT remains a promising technology for producing PBMAs, with ongoing studies focused on improving processing efficiency.
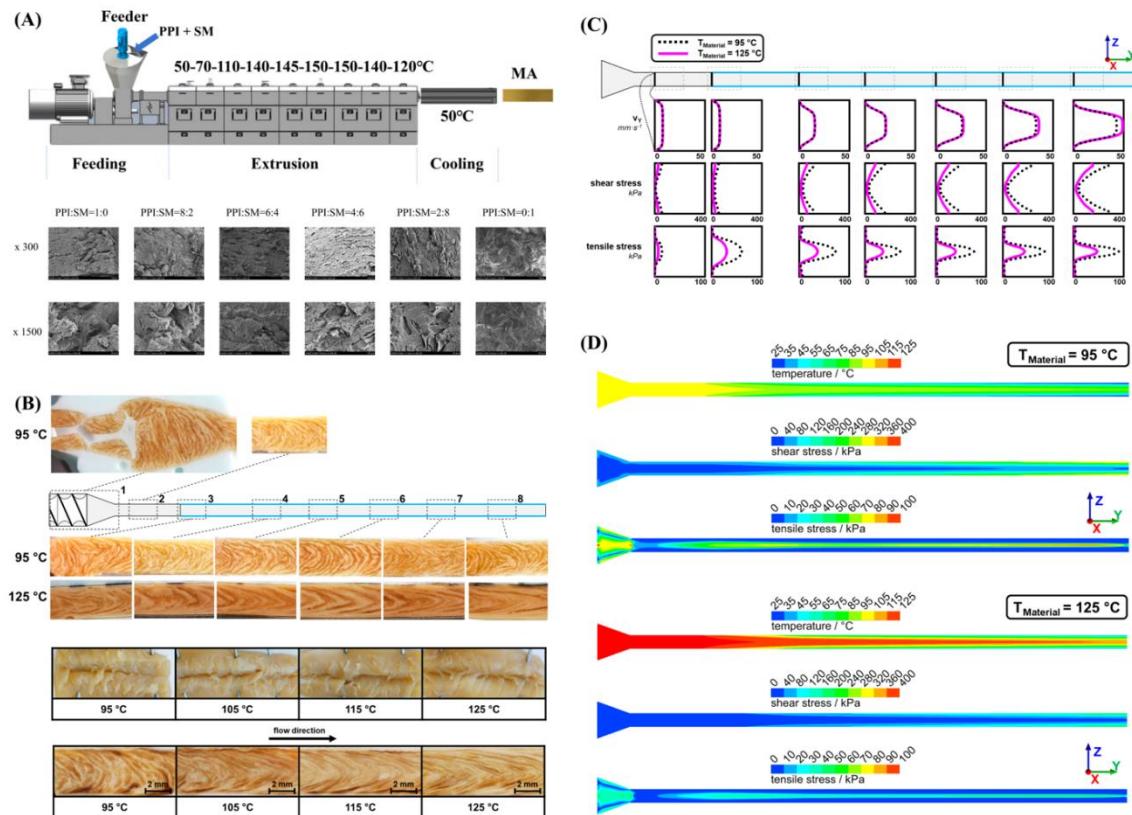
Figure 3. (A) Schematic diagram of the high–moisture extrusion process and microscopic images of Pea Protein Isolate (PPI):Soybean Meal (SM) meat analogues at varying concentration ratios. Reproduced with permission [364]. Copyright Multidisciplinary Digital Publishing Institute (MDPI), 2024. (B) Cryo–images of high–moisture extruded meat analogues in dead–stop trials at $T_{Material}$ = 95°C and 125°C, with extrudate morphology at four different material temperatures. (C, D) Velocity, shear stresses, tensile stresses, and temperature profiles along the die length. Reproduced with permission [365]. Copyright Multidisciplinary Digital Publishing Institute (MDPI), 2021.

5.7. Electrospinning

Electrospinning is a possible technique for creating micro–fibrous structures in PBMAs, which uses an electric field to draw a molten substance or polymer solution into thin strands. Plant proteins such as pea and soy may be electrospun to produce PBMAs, which are a network of fibres that resemble the fibrous structure of animal muscle tissue [350]. The fibers can be harvested onto a substrate to create a scaffold, which can be processed further into a meat–like form. Electrospinning is especially beneficial for producing textured products with a high surface area and increased protein alignment, which replicates the muscle fiber structure. This process enables great control over the diameter, orientation, and density of the fibers, which directly influence the end texture and mouthfeel of the PBMA [307]. Nevertheless, it poses problems of scaling up to industrial applications since it is still labor–intensive and necessitates optimizing solution viscosity, voltage, and the collection system [366]. Despite complications, electrospinning is promising for fabricating plant-based meat products with complex fiber structures mimicking the mouthfeel and texture of actual meat. Future studies will probably be directed toward optimizing the electrospinning process to enhance yield and scalability for commercial production.

5.8. Antisolvent Precipitation

Antisolvent precipitation is a technique employed to create plant protein networks through the precipitation of proteins from a solvent system, commonly using ethanol or acetic acid as solvents [14]. In antisolvent precipitation, a concentrated protein solution is combined with water or another antisolvent, precipitating the proteins and creating a solid network structure. This technique allows for thick, cohesive protein matrices with meat–like textures and is typically used with proteins like zein, soy, or wheat gluten. The networked precipitates can be additionally treated and processed to enhance texture and stability, which makes them favorable for PBMAs. Antisolvent precipitation provides an effective and straightforward approach to producing protein networks with high structural integrity. By regulating precipitation conditions, including temperature, solvent, and protein concentration, it is possible to adjust the final product's texture [258]. One disadvantage of this approach is the possibility of denaturation or loss of protein functionality, particularly when employing severe solvents such as ethanol or acetic acid. Moreover, it might be necessary to add steps to eliminate impurities of solvents and test the product's safety for eating. In spite of these complexities, antisolvent precipitation remains a valuable process for creating PBMAs that have better texture and protein integrity [367].

5.9. Mechanical Elongation

Mechanical elongation is a technique used to stretch plant protein matrices to replicate meat's fibrous structure. Protein mixes are often subjected to a mechanical force throughout the procedure, which causes the proteins to lengthen into long fibres resembling the muscle fibers in animal flesh [14]. The elongation process can be done using various techniques, including stretching doughy protein mixtures or employing specific machines, stretching and twisting the protein network. Mechanical elongation is usually blended with other processing methods, including high–moisture extrusion, to improve the final product's texture and extensibility [370]. The final product is more integrative and contains better chewability, bringing the texture closer to animal muscle tissue. One

of the strengths of mechanical stretching is that it can regulate the extent of fiber alignment and protein matrix density, which greatly influences the final texture of the PBMA. Yet, some of the challenges are to optimize the elongation conditions, i.e., the applied force, the protein blend employed, and the moisture level, to get the required texture without over–denaturing the proteins. Mechanical elongation is also energy–consuming and may require special equipment. Despite all these difficulties, this method has successfully produced high–quality PBMAs with improved fibre structures that resemble whole–muscle meat[368].
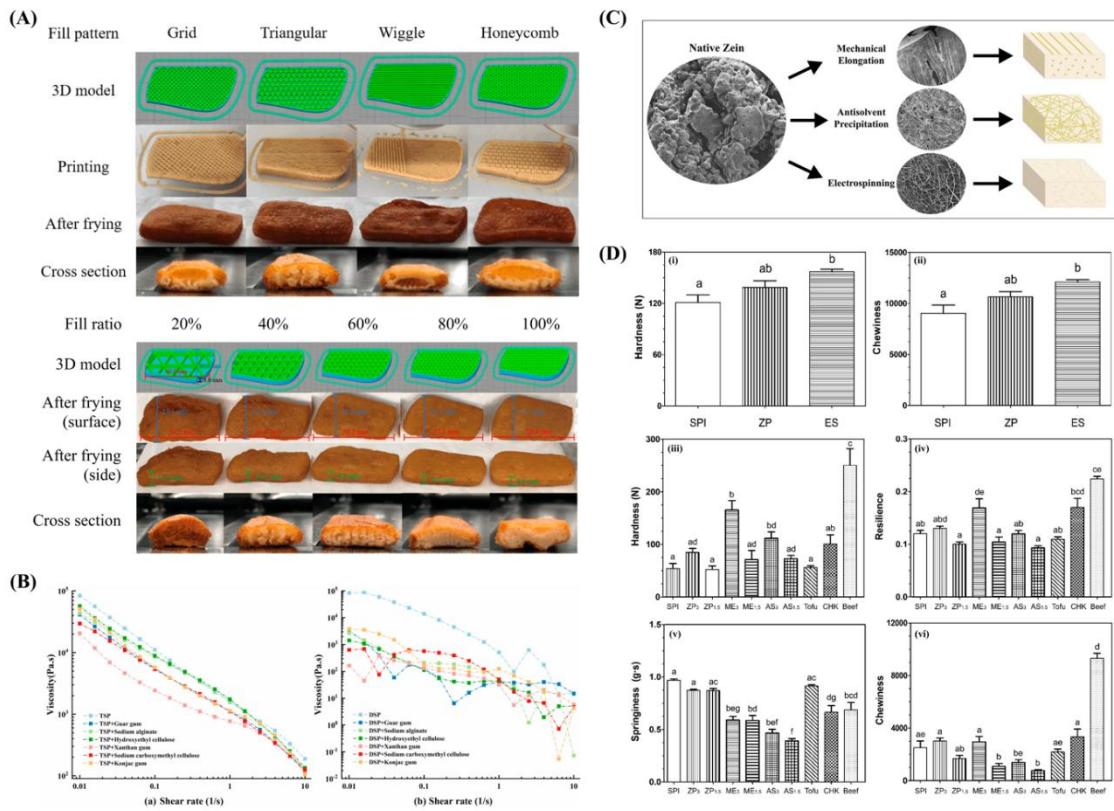
Figure 4. (A) 3D–printed meat analogues with different infill patterns and ratios. (B) Viscosity curves of composite inks: (a) textured soybean protein (TSP) with varying hydrocolloids, and (b) drawing soy protein (DSP) with varying hydrocolloids. Reproduced with permission [368]. Copyright Multidisciplinary Digital Publishing Institute (MDPI), 2021. (C, D) SEM images and texture profile analysis of fibrous material produced from zein (ZP) by mechanical elongation (ME), antisolvent precipitation (AS), and electrospinning (ES) with SPI control. Reproduced with permission [14]. Copyright Elsevier, 2020.

6. Conclusion

The PBMA industry is constantly expanding as more people prefer meat alternatives due to rising demand, ecological concerns, and changing preferences. From early soy–based originals to evolved multi-ingredient analogues present today, the history of PBMAs demonstrates perseverance in gaining sensory and nutrient equivalency to conventional meat with no concomitant environmental repercussions. The development of meat analogues is a precise balancing process, requiring proportionate blends of plant–derived proteins, polysaccharides, and lipids. This synergy of ingredients created through plant biochemistry, allows for the production of products that highly mimic the mouthfeel associated with meat consumption. Technological advancements also have a significant role in controlling both material composition and architecture. These technologies, coupled with novel flavoring and coloring agents, enhance the overall taste and texture. The alternative meat sector is expected to continue its growth in the near future. Nonetheless, several

challenges still remain, including the presence of off–note flavor profiles and micronutrient deficiencies. These limitations can be addressed through further exploration into volatile and non–volatile compounds to improve savoriness, minimize additives, and use fortified nutrient–dense plant resources per clean–label trends. Meeting consumer needs in the context of taste, texture, acceptability, and affordability are also critical to the success of the meat analogues industry. Essential strategies for overcoming food neophobia include encouraging familiarity with PBMAs through effective marketing, raising awareness, and emphasizing the role of sustainability in conscious food production and consumption. PBMAs have the potential to advance the global food scene, where increased investments in R&D, curated formulations, and processing technologies contribute to the development of ethical consumer-oriented food systems.

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