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This research promotes sustainable food innovation by examining hybrid plant–meat products, which partially replace animal protein with plant-based ingredients. By reducing reliance on livestock production, such innovations help lower greenhouse gas emissions, land use, and water consumption, directly supporting the UN's Sustainable Development Goals, particularly SDG 2: Zero Hunger, SDG 12: responsible Consumption and Production, and SDG 13: Climate Action. This literature review explores how hybrid products can leverage the strengths of both traditional meat and plant proteins while mitigating their individual limitations. By partially substituting meat with sustainable plant-based ingredients, hybrid products can achieve better nutritional balance, more closely replicate traditional meat texture, enhance sensory acceptance and familiarity, and remain economically viable, ultimately fostering a more sustainable and widely accepted dietary shift.

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ARTICLE

Hybrid Plant-Meat Products - Addressing the Sustainability Debate Around Processed Meat Consumption: A Review

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Zuo Song [ab], Ruth M. Hamill [a] and Joseph P. Kerry *[b]

There is a growing interest in the retail availability of plant-based meat analogues amongst consumers for a wide variety of reasons. However, such products currently offered in the marketplace differ significantly from the meat products they frequently seek to imitate in terms of technological challenge, sensory attributes and nutritional profile. For consumers seeking to increase the proportion of plant-based protein in their diet without compromising the sensory experience, hybrid plant-meat (HPM) products offer a promising alternative to purely plant-based foods. This review evaluates the current scientific literature and marketing information pertaining to HPM product formulation, production and marketing success. It also discusses key challenges and future perspectives in the development of HPM products. HPM products are presented in several formats, including those containing chopped plant-based ingredients, those manufactured with plant protein extracts in powdered formats (e.g., flours, concentrates, and isolates), or those formed with texturized plant proteins. The future exploration of new technological approaches in the manufacture of HPM products is critical, especially in terms of manipulating plant proteins to more resemble meat fibres. However, HPM products continue to face challenges, including technological issues (e.g., softer texture), safety concerns (e.g., microbial contamination), consumer acceptance, and regulatory hurdles. Therefore, the processing optimisation of the techno-functional properties of incorporated plant proteins, as well as the inclusion of non-protein ingredients, will play an important role in enhancing consumer acceptance of HPM products. Overall, HPM products offer a more practical and realistic approach to achieving an environmentally sustainable balanced human diet.

Keywords: Plant-based ingredients; Meat substitutes; Meat analogues; Food Extrusion; Plant proteins

1. Introduction

Meat has been a staple protein in human diets for centuries. Consumption of meat and meat products in the human diet contributes to the intake of many essential nutrients, including complete proteins containing all of the essential amino acids, as well as highly bioavailable iron, zinc, selenium, omega-3 fatty acid, and B vitamins, especially vitamin B12 [1-3]. Demand for meat protein is rising globally, driven by human population growth, increasing individual incomes, and urbanization [4-6]. The total demand for meat in the world is predicted to increase from 253 million tonnes in 2005/2007 to 338 million tonnes in 2050 [7]. However, rising meat consumption is associated with public health, environmental, and animal welfare concerns [4, 8-10].

To help meet the increasing global demand for high-quality protein, there is a growing focus on alternative protein sources [4, 9, 11, 12]. Research into alternative sources of proteins derived from plants, fungi, edible insects, animal stem cells, precision fermentation, and microbial cells for employment in food manufacture is currently very topical and research interest is expanding [11, 13]. Within this alternative protein food sphere exists meat alternatives, also termed meat substitutes, meat analogues, vegetarian meat, amongst other terms [14-17]. Based on historical development and technological complexity, meat alternatives can be categorized into two groups: traditional and novel [4]. Traditional products, developed centuries ago as non-muscle-based protein sources, were not specifically intended to mimic meat and often emerged from religious or cultural dietary practices. In contrast, novel meat alternatives are formulated to replicate animal-based meat in terms of taste, texture, and nutritional profile. Soy-based and wheat protein-rich plant foods are the two primary types of first-generation meat alternatives [18]. One of the earliest known references is to a soy-based product, known today as tofu, which appeared in China in 965 CE [19]. Tofu and tempeh are the most widely consumed soy-based products, while seitan is the most common wheat protein-rich meat alternative. These foods have been staples in Asian cuisines for centuries due to their high nutritional value and accessibility [18]. In 1852, meat alternatives were first mentioned in the Western world. In 1896, the first commercial meat alternative - Nuttose (peanut being the main ingredient), was launched by the Battle Creek Sanitarium Bakery in the Western world [19]. Protose, a wheat-gluten and peanut-based product, was marketed in the early twentieth century as a ‘‘vegetable meat’’, establishing an early standard

[a] Teagasc Food Research Centre, Ashtown, D15 DY05 Dublin, Ireland.
[b] School of Food and Nutritional Sciences, University College Cork, T12 E138 Cork, Ireland.
* Corresponding author.

for modern meat substitutes [20]. In 1980, Tofurky and similar products were introduced to serve the growing vegetarian demographic [21]. Burger King became the first major U.S. fast food chain to introduce a veggie burger to its menu in 2002 [19]. In August 2019, KFC launched plant-based boneless "chicken wings" and nuggets created by Beyond Meat and LightLife [22]. Recently, meat alternatives have included a wide range of comminuted and restructured products, including; burgers, sausages, bacon, meatballs, and nuggets, with more complex products seeking to replicate whole muscle cuts or products like steaks, chops, shellfish, scampi and tenderloins. For example, La Vie, a French food technology company specializing in plant-based pork alternatives, launched La Vie Plant-Based Ham at Tesco [23]. Among these meat alternatives, products with plant-based ingredients are the most popular.

Plant-based meat alternatives (PBMAs) refer to food products that are developed by employing, generally but not always, texturized protein-rich extracts from pulses, legumes or grains [24-26]. They have rapidly gained popularity and are currently the most favoured choice among meat alternatives [25]. The global plant-based meat substitutes market is predicted to reach around 14.32 billion U.S. dollars by 2028 [27]. However, PBMAs also face various challenges. For example, it is difficult to convert from a meat-based diet to a strict vegan- or vegetarian-based one because of attachments to meat and meat-centric societal constructs [10]. A previous survey found that 5 out of 6 people (among 11,399 Americans) who became vegans or vegetarians reverted to consuming meat again [28]. Many consumers have strong meat attachments, thereby showing reluctance to reduce meat consumption and these consumers are less inclined to consider changing their eating habits [29]. Additionally, the textural and flavour properties of PBMAs, which are unfavourably perceived compared to traditional meat products, are frequently sought out, but in the absence of repeat purchases subsequently [26]. To create meat-like texture, juiciness, and flavour in many of these meat alternatives, there is a requirement for the inclusion of additives, sometimes in large quantities, which has given rise to consumer concerns around nutrition, food safety, clean labelling, cost implications, and overall consumer confidence in such products [30]. Furthermore, consumers have described sensory disappointment following consumption of PBMAs, primarily on textural grounds, and this in turn has led to sensory scepticism among consumers who are completely unfamiliar with PBMAs [31]. From a nutritional perspective, PBMAs frequently have less protein, iron, and vitamin B12, lower protein quality, and higher amounts of sodium compared to meat products. Anti-nutritional factors (ANFs) such as saponins, lectins, oxalates, tannins, and phytates can further reduce nutrient bioavailability [32]. While soaking, fermentation, germination, and heat treatment can help reduce ANFs, their effectiveness is dependent upon the type of ANF and the processing method employed [32].

To address a potential consumer gap and provide a balanced approach to sustainable meat consumption, a novel product category has recently emerged with the potential to introduce new flavours and nutritional benefits while maintaining high consumer acceptance. HPM products, whereby a large fraction of meat is replaced by alternative proteins, are of relevance to consumers seeking to increase alternative protein consumption on health and environmental grounds, while continuing to enjoy the sensory properties of meat products. Although there is no official definition of HPM products, they can be considered as meat products with significantly reduced levels of meat content replaced by plant-based ingredients primarily for nutritional benefit. This means that the plant-based materials are not added to serve as meat extenders [10]. HPM products would therefore combine the advantages of both 100% meat products and PBMAs. HPM products offer a nutritional balance by combining meat and plant proteins, providing a complete and high quality protein option, thereby addressing deficiencies in essential amino acids often linked to PBMAs, and delivering iron and vitamin B12 from the meat component. Concurrently, HPM products contain dietary fibre and, depending on the plant-based ingredients employed, are often lower in saturated fat, cholesterol, and calories compared to whole meat products [33]. Additionally, HPM products can provide sensory properties more similar to that of meat products, whilst providing a significant proportion of plant-based ingredients. Therefore, HPM products represent an effective way for consumers to reduce meat consumption without compromising too much on the sensory experience of consuming meat [34, 35]. In consideration of the plant-based component, HPM production has a lower carbon footprint than conventional meat production [33]. Furthermore, replacing animal-based protein with plant protein is inversely associated with biological aging, although this does not necessarily apply to all major plant-based food sources [36]. Another advantage of HPM products, is that any major dietary shift, at a personal level, is a long-term process. Previous studies have shown that to be effective, an adopted dietary change taken on by an individual should not differ too much from their previous behaviour [37]. Therefore, HPM products provides an opportunity to make the substitution of meat more compatible with the modern convenience culture by introducing unfamiliar foods and ingredients into existing traditional foods and formats that consumers are familiar with and popularly enjoy. Consequently, HPM products may offer real alternatives to a wide consumer base, particularly flexitarians, who are not fully committed to a strictly vegan or vegetarian diet. The hybrid meat industry is expanding rapidly, with a global market value of $2.5 billion and a projected compound annual growth rate of 10% over the next decade [38]. Both plant-based and meat brands, including Applegate, Raised and Rooted, and KEPAK, are actively entering the hybrid market, launching a variety of products such as hybrid sausages, burgers, nuggets, and mince (Table 1).

This review explores HPM products that combine conventional animal-based resources (such as meat and fish) with various plant-based ingredients. The objective of this review is to provide insight into the manufacture of HPM products, with particular focus on formulation strategies and processing technologies. Specially, we evaluate how the incorporation of plant-based ingredients and the application of different processing methods influence the physicochemical

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properties of HPM products and, consequently their texture, flavour, and stability. In addition, this review assesses the key challenges and opportunities that exist in the wider creation and consumer adoption of these food product types.

Table 1.Representative commercial HPM products in the market.

No.	Brand	Country	Product name	Ingredient List	Hybrid type
1	Rebel Meat	Austria	Organic chicken sticks with vegetables	50% chicken, 17% cauliflower, and 14% white beans	Meat + vegetables
			Organic chicken nuggets with vegetables	40% chicken, 20% cauliflower, and 7% millet, salt	Meat + vegetables + grains
			Organic meat balls with vegetables	50% beef, 30% organic cauliflower, and 17% cooked millet	Meat + vegetables + grains
			Organic burger patties deluxe	50% beef, 30% king oyster mushrooms, and cooked millet	Meat + mushrooms + grains
2	Danish Crown	Denmark	Grønt & Gris (vegetables and pork)	50% pork and 50 % vegetables (carrots, peppers, chickpeas)	Meat + vegetables
			Grønt & Okse (vegetables and beef)	50% beef and 50% vegetables (kidney beans, peppers, chickpeas)	
3	Tesco	United Kingdom	Tesco Meat & Veg 4 Beef, Carrot & Onion Burgers	57% beef and 38% vegetables (carrot, white onion)	Meat + vegetables
			Tesco Meat & Veg Beef Mince	63% beef and 31% vegetables	
			Tesco Meat & Veg Lamb Mince	63% Lamb and 31% vegetables	
			Tesco Meat & Veg 12 Beef, Carrot & Onion Meatballs	63% beef (63%) and 31% vegetable blend (carrot, white onion, butternut squash)	
			Meat & Vegetable 5% Fat Chicken Mince	47% chicken, 15% carrot, 15% red kidney beans, and 15% onion	
4	Heck	United Kingdom	Heck 60/40 chicken red pepper & feta burgers	60% chicken, 10% red pepper, and roasted tomato	Meat + vegetables
			Heck 60/40 chicken, minted pea & spinach burgers	60% chicken, 12% peas, 3% spinach	
5	KEPAK	Ireland	The beefrootie burger	70% beef, 15% beetroot, and 15% quinoa	Meat + vegetables
			The moo-shroom burger	70% beef and 30% chestnut mushroom	
6	Perdue	United States	Chicken plus® chicken breast & vegetable dino nuggets	Chicken breast with rib meat, cauliflower, and chickpeas; 1/4 cup of chickpeas and cauliflower per serving	Meat + vegetables
			Chicken plus® gluten free chicken breast & vegetable tenders	Chicken breast with rib meat, cauliflower, chickpeas, and cabbage; 1/4 cup of chickpeas, cauliflower, and cabbage per serving	
7	Tyson Foods-Aidells (Whole Blends)	United States	All Natural sausage links	Chicken, red & white quinoa, roasted tomato, and roasted red bell pepper Chicken, bacon, quinoa, jalapeño, black beans, bell pepper, corn, and onion	Meat + vegetables
			All natural seasoned meatballs	Falafel seasoned meatballs: chicken, quinoa, spinach, and roasted green garbanzo beans. Samosa seasoned meatballs: chicken, quinoa, vegetables, potatoes and green lentils	
8	Applegate Farms	United States	Well Carved™ Organic Grass-fed Beef Burgers	Beef, cauliflower, green lentil, spinach, and butternut squash	Meat + vegetables
9	Teton Waters Ranch	United States	Mushroom and onion burger blends	Beef, mushrooms, and onions	Meat + vegetables
10	Hormel (Burke-MADE SIMPLE®)	United States	All-natural toppings	70% beef and two types of mushrooms (one dehydrated and one whole) 70% pork and dehydrated cauliflower	Meat + vegetables

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11	Waitrose	United Kingdom	Waitrose 6 British Pork & Bramley Apple Sausages	75% pork, 10% Bramley apple, and 4% dried apple	Meat + fruits
12	ICL Food	United States	Hybrid Bratwurst	50% pork and pea protein	Meat + plant protein
13	Lidl	Netherlands	Hybrid minced meat product	60% beef and 40% pea protein	Meat + plant protein
14	Tyson Foods- Raised & Rooted	United States	The blend made with beef & plants	Beef and pea protein isolate	Meat + plant protein
15	BrewDog	United Kingdom	Hybrid Burger	50% beef and 50% Beyond Meat	Meat + commercial plant-based meat

2. HPM product formulation and manufacturing

2.1 Plant-based ingredients applied in HPM products

Restructured/comminuted and reformed meat-based products, such as; mince, burgers, sausages, meatballs, nuggets etc. are categories of animal-based protein products that can be partially substituted with plant-based ingredients. A wide range of plant-based ingredients (Figure 1) can be used for HPM formulations, including; fresh/dehydrated vegetables, pulses, grains, oilseeds, mushrooms, fruit, powdered plant protein extracts (such as flour, concentrate, and isolate), and texturized plant proteins processed through use of low or high moisture extrusion. The following sections describe the most common categories of HPM products.

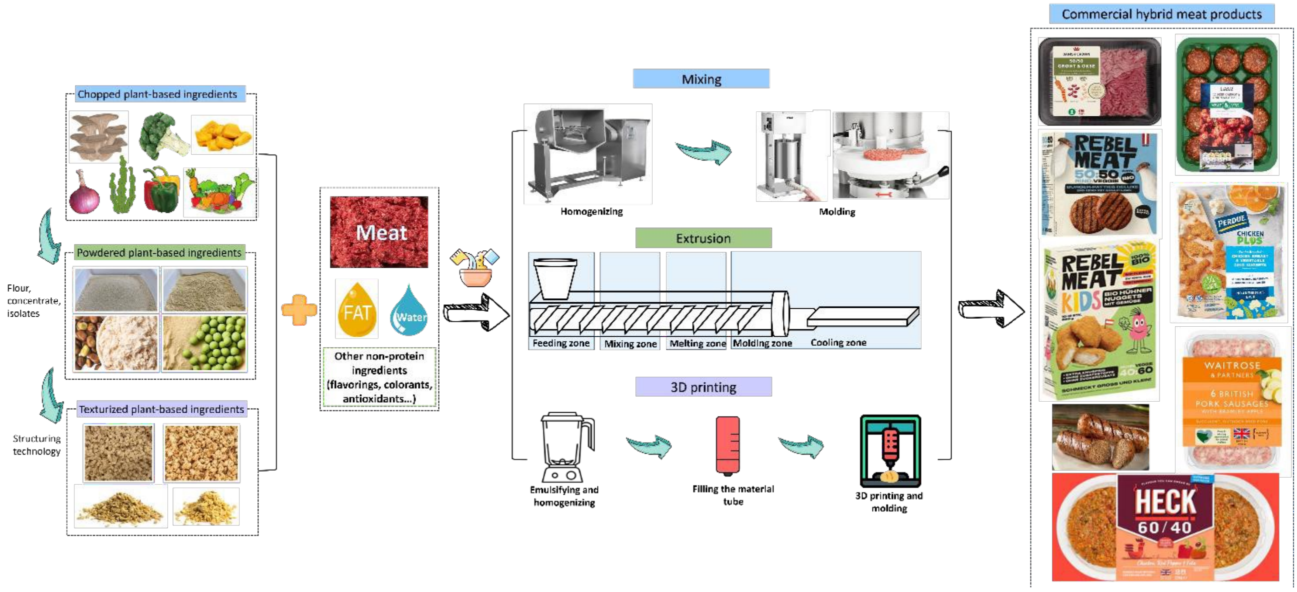

Figure 1. Process flow for preparation HPM products and commercial examples.

2.1.1 Incorporation of fresh and dehydrated plant-based foods in HPM products

Fresh and dehydrated plant-based ingredients, including chopped vegetables, fruits, mushrooms, and their by-products, have been widely explored in hybrid sausages, patties, and meatballs (Table 2) [39-41]. These ingredients are primarily incorporated for their ability to enhance moisture retention, texture, nutritional content, and introduce antioxidant properties. In hybrid patties, plant-based ingredients such as jackfruit have been used as partial meat substitutes, influencing sensory attributes like tenderness and juiciness [40]. Studies indicate that moderate incorporation (e.g., 25–50%) improves texture and consumer acceptability, while higher levels may significantly alter structure and binding properties [40]. Similarly, hempseed meal has been introduced in sausages, enhancing antioxidant potential while maintaining a balanced texture at moderate inclusion levels [41].

A number of commercial companies, including Tesco, Heck, Applegate Farms, have launched meat products with chopped plant-based ingredients [10]. Some companies emphasized a rationale for inclusion of vegetables rather than meat reduction, such as increasing vegetable servings and adding nutritional benefits to their HPM products [42]. In creating such products, it is important that product development address potential consumer perceptions of over-processing, as such developed opinions may deter consumers from adopting plant-protein based products [43]. Therefore, careful and considered incorporating of chopped vegetables and fruits into meat products could improve consumers' acceptance of HPM products if minimal processing strategies are adopted. However, challenges pertaining to HPM product colour, texture,

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and flavour, owing to the employment of chopped vegetables or fruits (Figure 2) complicate utilisation and therefore, must be carefully considered.

2.1.2 Incorporating plant-based proteins as flour, concentrate, or isolate

Plant-based ingredients naturally contain protein levels above 20%. An important typology of HPM products incorporates plant-protein in extracted or enriched form, with purities ranging from flours (<65% protein concentration, produced by grinding plant organs into powder), to concentrates (>65% protein concentration, manufactured by removing some carbohydrates from defatted plant flour), and isolates (>90% protein concentration, where most soluble proteins, fats, and carbohydrates are removed from defatted plant flour) [44-47]. Plant protein type and its inclusion level contribute to variability in technological properties (Table 2). For example, soy, pea, and sunflower protein demonstrated good compatibility with meat matrices, resulting in better emulsion stability compared to meat emulsion with fava bean and rice protein [48]. Hybrid meat emulsion with fava bean protein showed the lowest values for all texture parameters, which can be directly related to the higher carbohydrate content in the fava bean protein concentrate and which hinders protein-protein interaction, thereby resulting in a weak protein network. Additionally, the texture parameters of HPM products decrease as the level of meat replacement with hydrated plant protein increases. This is most likely to be attributable to the different structures of plant proteins compared to those of meat, consequently leading to unique water-binding interactions and protein network formations [49-51]. Commercial HPM products employing plant-derived protein sources are available in the marketplace [52]. The hybrid bratwurst which consists of 50% meat along with pea protein isolate, herbs and spices from ICL Food is claimed be to healthier, contribute to sustainability efforts, and help reduce greenhouse gas emissions compared to the original meat-based version [52]. Lidl Netherlands has launched a 300g hybrid minced meat product, blending 60% beef with 40% pea protein. It claims to cost 33% less than ground beef and reduces CO_2 emissions by 37.5% [53]. Incorporating plant proteins into meat products can significantly affect textural changes, with plant proteins impeding the structural-self-association of meat proteins [54]. Previous research has focused on the effects of different types and inclusion levels of plant proteins on the properties of HPM products, demonstrating variability in their technological quality. Careful selection of plant proteins is crucial for achieving the desired texture and enhance the sensory appeal of HPM products. Investigating the effect of plant protein purity and their impacts when processed into meat products requires future study. Furthermore, plant proteins often exhibit lower solubility, emulsification, or gelation capacity compared to animal proteins, which restricts their functionality in HPM products [55]. To address these challenges, protein modification methods could be further explored to improve their functional properties and enhance compatibility with animal proteins.

Table 2. Summary of HPM models/products prepared with chopped, powdered, and texturized plant-based ingredients.

Product name	Meat ingredients	Plant-based ingredients	Inclusion level	Processing method	Main effects			Reference
					Effects on colour	Effects on texture	Effects on sensory	
Meat emulsion system	Chicken	Chinese yam (*Dioscorea polystachya*-CY), arrowroot (*Maranta arundinacea*-AR)	50%-100%	Mixing ingredients using a food processor.	AR50 had a similar colour profile to the 100% chicken meat emulsion (control).	Samples with 50% meat substitution showed significantly lower hardness, gumminess, and chewiness values compared to the control, yet remained within the range of commercial chicken sausages.	Na	39
Patty	Beef	Unripe jackfruit	25%, 50%, 75%, and 100%	Mixing ingredients using a blender.	Na	Na	25% substituted unripe jackfruit are the most prefer meat patties in sensory evaluation.	40
Patty	Chicken	Fresh grey oyster mushroom (*Pleurotus sajor-caju*)	25%/50%	Mixing ingredients using a mixer.	Decrease in L* and b* values, with no change in patty redness	The texture parameters except springiness significantly decreased with increasing oyster mushroom level.	Na	56
Sausage	Turkey	Broccoli, insect flour, brewer's spent grain (BSG)	35%	Mixing ingredients using a food processor.	The optimized mixture of 22% broccoli, 3% BSG, and 10% insect flour showed higher colour result than the reference.	The optimized mixture exhibited higher chewiness than the reference.	The optimized mixture exhibited similar juiciness and odour to the commercial sample, while surpassing it in terms of appearance.	57
Sausage	Chicken	Hempseed meal	10%, 20%, 30%, and 40%.	Mixing ingredients using a blender.	L* and a* values decreased with increasing hempseed meal content.	Incorporating hempseed meal softened chicken sausage texture.	Na	41
Hybrid aqueous model system	Pork	Potato protein isolate	20, 40, 50, 60, 80, and 100%	Mixing meat and potato proteins.	Na	Significant textural modifications occur since plant proteins can disrupt the self-association of meat proteins.	Na	54

Meat emulsion model system	Bovine meat	Soy protein concentrate (SPC), pea protein concentrate (PPC), rice protein concentrate (RPC), fava bean protein concentrate (FBPC), sunflower protein concentrate (SFPC)	50%	Mixing ingredients using a food processor.	Colour parameters were affected by both plant protein colour and reduced myoglobin content.	Soy, pea, and sunflower proteins integrated well with the meat matrix, providing suitable texture. Rice and fava bean proteins led to a lower texture profile.	Na	48
Patty	Beef	Pea protein isolate (PPI), rice protein (RP), lentil flour (LF)	3%/7%	Mixing ingredients using a mixer.	Increase L*, a*, and b* values.	PR hardens, LF softens hybrid patty texture.	Na	58
Patty	Pork	Pulses flours (lentil, chickpea, pea, and bean)	10-44%	Mixing ingredients in a food processor.	Burgers with lentil flour had the lowest L*, while those with bean flour had the highest. Pea, chickpea, and bean flour burgers showed higher a* values than the control, and pea and chickpea flour additions resulted in higher b* values.	Decreased hardness values.	Sensory evaluation showed excellent acceptability for formulations with the highest flour addition and intermediate water/flour ratio, regardless of flour type.	59
Patty	Beef	*Vicia faba* protein isolate (VFPI), soya protein isolate, pea protein isolate	20%	Na	Na	Na	Na	60
Patty	Beef	Wheat germ protein flour (WGPF)	8, 14, and 20%	Mixing ingredients using a blender.	Redness decreased and yellowness increased.	Reduced shear force and compression with increasing WGPF addition level.	Wheat-like aroma, flavour, juiciness, and tenderness increased with higher WGPF inclusion.	50
Patty	Beef	Quinoa and buckwheat flour	15%/30%	Kneaded ingredients by hand for 5 min.	Na	Hybrid buckwheat flour beef burgers had highest hardness and chewiness.	Hybrid quinoa burger and hybrid buckwheat burger have higher sensory results.	61
Patty	Beef	Faba bean, pea, and rice protein	12.5%	Mixing ingredients using a blender	Increased L* and decreased a*	Rice protein contributed to a firmer texture, whereas pea protein and faba bean protein	Na	62

						were associated with softer textures.		
Burger	Chicken	Yellow pea flour, chickpea, and lentils	25%, 50%, and 75%	Mix all ingredients in a bowl.	Na	The textural properties of hybrid burgers at 50% and 75% substitution levels were significantly decreased compared to the control.	Na	49
Steak	Beef	Pea protein isolate (PPI), rice protein (RP), lentil flour (LF)	10.75-25.75%	Use a hand crank filler and apply PiVac technology.	L*, and a* (raw), and L* (cooked) were significantly affected by the formulations.	Decreased hardness and gumminess with increased LF.	Consumers over 65 preferred the control, while the optimized formulation with added seasoning was least liked by older consumers.	63
3D-nugget	Chicken	Pea protein isolate (PPI)	12%-30%	3D Printing process.	Na	PPI paste and PPI chicken paste exhibited weak gel behaviour. 20% chicken mince paste addition improved printability and fibre structure.	Na	64
3D-nugget	Chicken	Refined wheat flour (RWF)	25%-50%	Extrusion-based 3D printing.	Na	The hardness of the material decreased with an increased amount of GC. The material with 1/3 RWF had higher springiness and cohesiveness, suitable for extrusion-based printing.	The post-processed product got acceptable sensory scores from 20 semi-trained panellists.	65
Sausage	Chicken	Soy protein isolate (SPI)	40%, 80%, and 100%	Mixing ingredients using a bowl chopper.	L* decreased and b* increased with SPI addition.	The plant proteins in the emulsion system resulted in a poor folding/elasticity and gel quality.	Sensory evaluation showed high acceptability with plant protein replacing chicken.	35
Sausage	Buffalo meat	SPI	15% and 25%	Mixing ingredients in a bowl cutter.	Hunter L and b values increased, while a values decreased.	Hardness decreased with SPI addition.	Incorporating SPI improved the sensory characteristics, such as colour, texture, and juiciness quality.	66
Sausage	Beef	Lupin (Lupinus angustifolius) flour	12%, 18%, 24%, 30%, and 36%	Mixing ingredients in a	b* increased in raw sausages with more lupin flour. In cooked	Lupin-enriched beef sausages had softer texture (textural strength	Beef sausages can acceptably incorporate up to 12% lupin flour.	67

				meat bowl chopper.	hybrid sausages, L* decreased, while a* and b* increased.	decreased) and higher adhesiveness.		
Canned Pork Pâté	Pork	Pea protein isolate	12.5%, 25%, 37.5%, and 50%	Ingredients were homogenized to form a batter, which was manually distributed into metal cans and sealed using a can seamer.	The meat hybrid showed decreased a* and increased b* values.	The meat hybrid exhibited reduced the hardness, gumminess, and chewiness.	Substitution levels of 37.5% and 50% maintained similar sensory acceptability to the control, while up to 25% pork meat replacement showed superior quality.	51
Minced Model System	Pork	Wet extruded proteins from pea (Pea I, II), pumpkin (Pumpkin I, II, III), and sunflower	5, 15, 20, 40, 60, 70%, and 100%	Mixing chopped extrudates, minced meat, salt and chemical acidifier.	Na	Adjusted the initial and time-dependent pH.	Na	68
Patty	Beef	Extruded products made from mixed flours (soy, rice and bean)	50%	Mixing ingredients, applying technologies like high-hydrostatic pressure processing (HPP) and sous-vide cooking (SVCOOK).	Hybrid patties resembled beef patties in colour, while HPP-treated plant-based and hybrid patties shifted to less red and more yellow tones.	Hybrid patties were similar to beef patties in texture. HPP and SVCOOK technologies have potential to enhance hybrid patty quality.	Na	69
Patty	Beef	Soy-based textured vegetable protein (TVP)	10%, 20%, 30%, and 40%	Mixing ingredients using a mixer.	Incorporating a higher level of TVP resulted in reduced L* values.	The addition of TVP decreased cohesiveness and hardness, while increasing gumminess and chewiness.	Patties with 40% TVP exhibited detectable sourness, astringency, umami, and saltiness. TVP can substitute 10-40% in beef patties without	70

							compromising quality, with hybrid patties at 10-20% resembling the control.	
Patty	Pork	Texturized pea isolate, oat flour	25, 40, and 50%	Mixing ingredients.	Higher pea protein substitution in hybrid patties led to increased yellowness.	Hybrid patties with more pea protein had softer texture. Soaking reduced off-flavours, increased humidity and pH, but decreased texture. Oat flour improved texture with higher pea protein levels, but not with soaked deodorized proteins.	Na	71
Sausage	Pork	Pea protein isolate (PPI), pea low moisture extrudate (LME), pea high moisture extrudate (HME)	20%	Mixing ingredients in a bowl chopper.	Inclusion of texturized pea proteins into meat sausages resulted in significant colour changes.	Adding texturized pea proteins made meat sausages softer. Extruded pea protein products caused large cavities with jelly-like excretion.	No significant deviations observed in hybrid sausage made with PPI compared to its reference. However, sausages made with HME and LME were regarded as unacceptable.	72
Sausage	Pork	Texturized pumpkin seed proteins	12.5, 25, 37.5, and 50%	Mixing ingredients in a bowl chopper.	Higher addition of texturized pumpkin seed proteins increased L* and b* and decreased a*.	Decreased cohesiveness, springiness, and chewiness with higher texturized protein addition.	Na	73
Sausage	Beef	Texturized vegetable protein (TVP)	10, 20, 30, 40%	Mixing ingredients in a food processor.	Increased L* and b* with TVP addition, no significant difference for a*.	Decreased hardness with TVP addition.	The optimal substitution level is 30%, with no significant difference in consumer acceptance compared to the control.	74
Meatballs	Pork	Wet or dry textured protein from regional pea, sunflower or Styrian pumpkin seeds	30%	Mixing ingredients in a bowl cutter.	Na	The inclusion of textured plant proteins shows promise as an additive to produce meat hybrid with improved texture.	Na	75
Meatballs	Beef	Texturized soy protein (TSP)	15%/30%	Mixing ingredients in a food processor.	Internal colour: decreased a*, increased b*.	Samples with 15% TSP were similar in hardness to the control,	TSP-containing samples had higher texture acceptability scores than the control, while	76

External colour: decreased a*, increased L* and b*.	while those with 30% TSP were softer.	those with 15% TSP and yeast received the highest flavour and overall acceptability scores.

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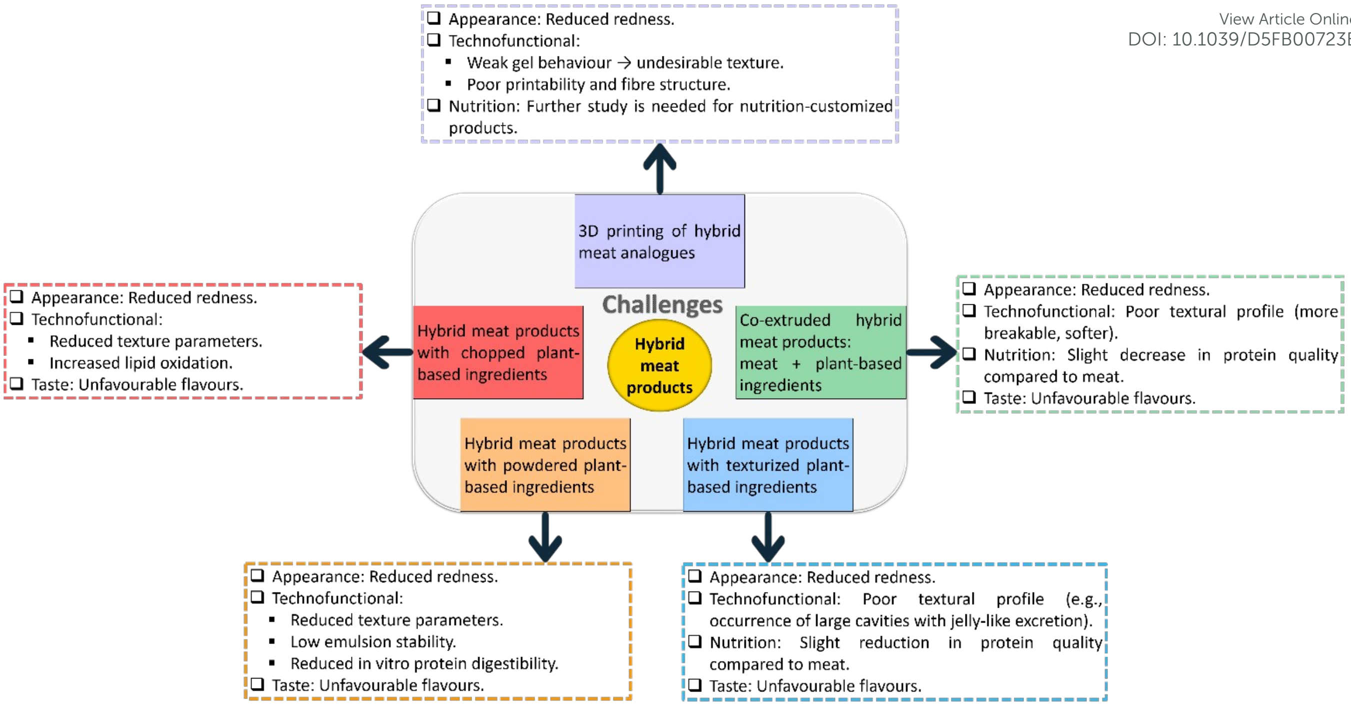

Figure 2. Challenges associated with various approaches to preparation of HPM products.

2.1.3 Incorporating texturized plant-based ingredients

Texturized plant-based ingredients have also been successfully used to create HPM products (Table 2). For example, Baune, Jeske [75] substituted 30% pork meat with wet or dry textured protein from regional pea, sunflower or Styrian pumpkin seeds and canola oil. The hybrid meatballs showed improved nutritional profiles with increased essential fatty acids like linoleic and α-linolenic acid, a better ω-6: ω-3 ratio, and a hypothetical rise in dietary fibre content. Although the protein quality was slightly reduced in this textured product compared to meat, its usage still surpassed that of employing raw plant-based materials. Environmentally, all hybrid meatballs reduced the environmental impact of pork-based products by 10-30%, especially with wet extrusion processing. Broucke, Van Poucke [72] also noted that the process of extrusion improved nutritional quality of the plant protein ingredient by reducing anti-nutritional factors (ANFs) and pea allergen content. However, incorporating extruded pea protein showed that its usage could produce large cavities with jelly-like exudates in hybrid sausages; all of which were regarded as unacceptable by panellists [72]. Bakhsh, Lee [70] suggested that textured vegetable protein (TVP) can be substituted at levels of 10-40% in beef patties without compromising overall quality when compared to full meat beef patties. However, hybrid patties with higher levels of TVP inclusion showed noticeable developments in flavours, including sourness, astringency, umami, and saltiness.

The extrusion process reduces levels of ANFs and allergens in plant proteins, hence, incorporating texturized plant proteins could improve nutritional product profiles. Additionally, owing to the presence of meat, HPM products exhibit better protein quality compared to PBMAs. However, incorporating texturized plant proteins also presents challenges. For example, the high-temperature extrusion process used in producing PBMAs can result in nutrient loss and the formation of toxicants and carcinogens [22]. Other techno-functional challenges, such as weaker texture, colour changes, and off-flavour developments, should also be considered when developing HPM products employing texturized plant proteins. Commercial HPM products that contain both meat and texturized plant proteins are rare, likely due to higher costs, as the protein texturization process is energy-intensive [75].

There are several options for incorporating plant-based ingredients into meat products, including chopped fresh and dehydrated plant-based foods, powdered plant proteins, and texturized plant proteins. Chopped plant-based foods can address potential consumer concerns about unfamiliar or over-processed foods while contributing dietary fibre. Plant protein flours, concentrates, or isolates provide protein enrichment, emulsification, and improved water-holding capacity, resulting in lower cooking loss. Texturized plant proteins contribute a fibrous, meat-like texture, enhancing chewiness and mouthfeel of HPM products; extrusion can improve protein digestibility and modify allergenicity. Each type of ingredient has its advantages and limitations, and careful selection and modification of plant-based ingredients is required to optimise the nutritional, technological, and sensory properties of HPM products.

2.2 Role of non-protein ingredients in HPM products

To achieve a meat-like texture and sensory attributes, non-meat ingredients (Table 3) are incorporated into hybrid formulations, to help the HPM products more closely mimic the sensory experience of 100% meat products.

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Table 3. Common non-protein ingredients employed in HPM products as sourced from formulations developed and reported in the scientific literature and ingredient listings reported via commercial HPM product labelling.

Category	Ingredients	Functions
Fats	Buffalo fat, canola oil, coconut oil, olive oil, pork back fat, palm oil, rapeseed oil, sunflower oil, soybean oil, vegetable oil	Contribute to juiciness, tenderness, mouthfeel, and flavour release.
Thickening agents & Emulsifier	Carboxymethylcellulose, cornflour, corn starch, carrageenan, egg, guar gum, konjac gum, mono- and di-glycerides of fatty acids, methyl cellulose, pea flour, potato starch, pre-gelatinized maize starch, rice flour, soy lecithin, triphosphate emulsifier, wholemeal wheat malt flour, wheat flour, wheat starch	To bind water, immobilize fat, enhance texture, stability, and consistency, and emulsify oils [22].
Flavourings	Apple juice concentrate, basil, black pepper, black pepper extract, bay leaf, brown sugar, coriander, caramelised sugar syrup, celery powder, dextrose, dextrose monohydrate, dried leek, dried garlic, dried mushroom, dehydrated garlic, garlic powder, herbs, honey, marjoram, mint, molasses, nutmeg, onion, onion powder, onion oil, oregano, paprika, parsley, rosemary extract, sodium chloride, spices, smoked flavour, sugar, tomato powder, white pepper, yeast extract, other spices and flavourings	To improve product flavour (aroma and taste).
Colorants	Beet juice, paprika extract	Simulate a similar colour to meat products.
Minerals	Calcium lactate, selenium, zinc	To increase the nutritional value.
Vitamins	Retinol (vitamin A), pyridoxine (vitamin B6), folic acid (vitamin B9), cobalamin (vitamin B12), ascorbic acid (vitamin C), tocopherols (vitamin E), phylloquinone (vitamin K1)	To provide vitamins and improve the nutritional value.
Adhering agents	Transglutaminase	To bind protein particles [22].
Preservatives	Sodium metabisulphite, sodium sulphite, sulphur dioxide, sodium tripolyphosphate, sodium nitrite	Increase product shelf life while retaining original nutritional values, colour, texture, and flavour.
Antioxidants	Ascorbic acid, sodium erythorbate, sodium ascorbate	To prevent or reduce the damage caused by oxidation, such as fat rancidity and colour changes.
Stabilisers	Diphosphates, disodium diphosphate, tetrasodium diphosphate	To maintain or enhance products original texture, physical, and chemical characteristics.
Acidity regulator	Citric acid, calcium lactate, glucono-δ-lactone, sodium bicarbonate	To preserve the original taste and colour of the product and enhance food safety.

Fats and oils contribute to tenderness, juiciness, mouthfeel, and flavour release in HPM products [22]. Plant-based fats like coconut are often blended with liquid oils, such as sunflower oil and canola, which are rich in unsaturated fatty acids, to mimic the

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melting behaviour and mouthfeel of animal fat [22]. Carbohydrate ingredients, acting as stabilizers, gelling agents, thickeners, and emulsifiers, help bind water and fat, enhancing both texture and appearance [22]. Starches or flours can improve texture and consistency of the product (e.g. 2% potato starch was incorporated into hybrid meatballs) [75]. Other binding ingredients like algae, bamboo, citrus, and oat fibres serve as natural binders and texturizers, improving HPM products form and stability. Some studies have incorporated 0.9% carboxymethyl cellulose (CMC) into chicken sausages [35], and 0.5% carrageenan with 0.5% CMC into hybrid sausages [57]. However, neither study specifically explored the effects of these ingredients on the techno-functional properties of HPM products. Consumers are increasingly seeking out less processed foods, and in this context, inclusion of these non-store-cupboard ingredients should be carefully considered.

Black pepper, sugar, yeast extract, herbs, and other flavour ingredients are also added to HPM products to mimic the intense and complex aroma of cooked patties, sausages, and other processed meat products. These flavours not only help to achieve the ''meat-like'' flavour, but also mask beany off-flavour of certain legume proteins [35]. The role of colouring agents, such as beet juice and paprika extract, is to simulate similar colours of meat products at before, during, and after cooking HPM products. The supplement minerals and vitamins could improve the nutritional values of HPM products and overcome their deficiencies close to that of regular meat products. The role of preservatives, antioxidants, and acidity regulators is to protect HPM products by inhibiting microbial growth, inactivating free radicals or metals, and reducing or adjusting pH levels, respectively [77].

The application of strategies optimized in plant-based products to enhance the quality of HPM products is presented in Figure 3. One advantage of HPM products, when compared to PBMAs, is that fewer non-protein ingredients are required. The lack of a clean label is a common challenge for PBMAs, which usually contain over 20 additives, including colorants, stabilizers, and preservatives, that are not commonly used in regular meat products [26].

Although HPM products may still require some additives to achieve a fully meat-like texture and flavour, the presence of meat allows for a reduced amount of these additives overall. Additionally, since a single ingredient rarely provides all the desired characteristics in HPM products, combinations of functional additives may be necessary. The use of natural non-protein ingredients is encouraged in HPM products. Furthermore, achieving the desired functionality requires a deep understanding of ingredient interactions and the effects of processing conditions on their performance.

2.3 Processing strategies for developing HPM products

A number of processing technologies have been utilised to develop HPM products in an attempt to create and simulate the textural characteristics associated with pure meat products (Figure 1). The manufacture of HPM products commences by selecting a specific animal-based protein, such as poultry, beef, pork, or some other meat source, as the foundation material.

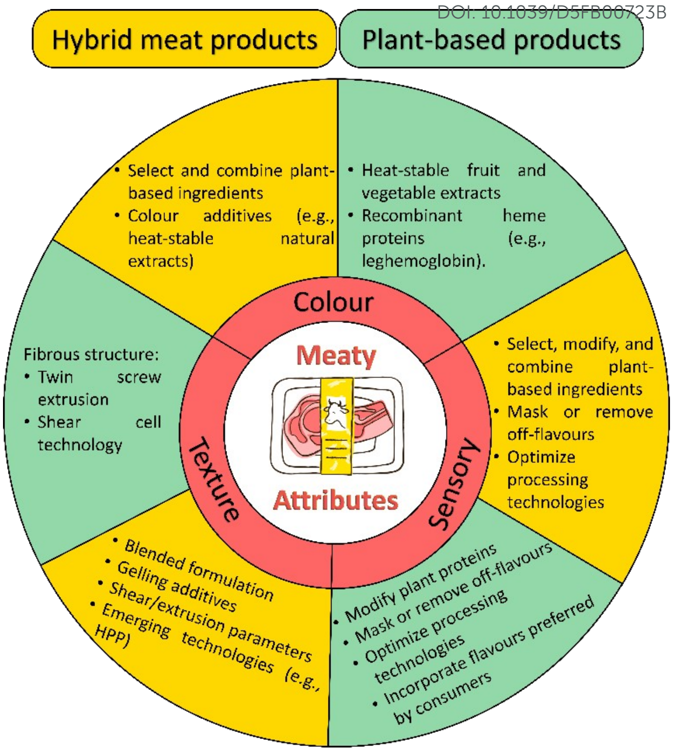

Figure 3. Strategies employed in HPM products to mimic the colour, structure, and sensory characteristics of meat using approaches optimised in plant-based products. Fig [Strategies employed in HPM products to mimic the colour, structure, and sensory characteristics of meat using approaches optimised in plant-based products], adapted/reproduced from ref [4] with permission from [Springer Nature] [N. R. Rubio, N. Xiang and D. L. Kaplan, Nature Communications, 2020, 11, 6276], copyright 2020.

Then, plant-based ingredients and processing conditions should be carefully selected to complement the animal protein, providing an effective mimic of the template meat product. Finally, all mixed ingredients are processed appropriately (e.g. mould/casing/extrusion) to develop the target HPM products, whether patties, meatballs, nuggets, sausages, etc.

The mechanism behind structure formation during high-moisture extrusion process (HMEP) is primarily based on protein denaturation and alignment of molecular structures in the direction of flow [78]. During the shear flow process, the hot protein melts and the water mixture separate into two distinct phases that are immiscible, a phenomenon similar to spinodal phase separation observed in polymer physics. The formation of fibrous structures during HMEP is influenced by both spinodal phase separation and thermodynamic incompatibility, particularly for proteins that were already aggregated before undergoing further processing with high-moisture extrusion (HME) [78]. However, the precise mechanism is not fully understood due to complex interactions between parameters and the 'black box' nature of the process. However, regarding plant-based meat analogue production, this method shows great promise for wider adoption and usage. It also represents an innovative method for creating HPM products i.e. co-extrusion of meat with plant-based ingredients, which results in a fibrous, meat-like structure for the HPM products which may closely match the target typology [33]. In this approach, meat and

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plant ingredients are premixed and then fed into the extruder. The mixture is then processed in the extruder to generate a product with a meat-like structure (Table 4). While the process is not fully understood, it is thought that the creation of disulfide bonds between protein molecules plays an important role in protein polymerization, which consequently contributes to the desirable textural functionality of the proteins. To gain a further understanding of the fibril formation during extrusion, Nisov, Aisala [79] measured thiol group formation as an indication of the degree of disulfide bond formation in both pea and fish samples during the extrusion process. They observed that gutted fish samples had higher amounts of free thiol groups in comparison to samples made with whole fish, which could explain why whole fish extrudates possessed weaker structures as evidenced by tensile strength and microscopy measurements [79]. Unlike fish protein, pea protein undergoes wet processing that involves pH fluctuation and possible heating steps. These steps alter the native state of the protein. Under these conditions, proteins undergo a transformation where their coiled structure begins to unfold, exposing reactive groups, such as thiol groups. As these exposed groups interact with each other, protein aggregation occurs, resulting in a dense structure with thiol groups enclosed within the protein aggregates. Thus, the detectable concentration of free thiol groups is low. However, during the extrusion process, the aggregated proteins are unfolded and rearranged into a more organized network. This could explain why the amount of free thiol groups in the unreduced pea protein sample increased after extrusion. Therefore, a unique restructuring and combination of plant-based proteins and meat is possible as a result of employing co-extrusion processing successfully [80]. The resulting structure of the meat and plant blend is shaped, not just by the formulation, but also by the specific parameters employed in the extrusion process [80]. However, research on co-extruded HPM products is limited and significantly more study is required in this area, especially in relation to the manipulation of ingredient formulations and processing parameters.

Table 4. Summary of co-extruded meat and plant-based ingredients.

Product name	Ingredient list	Inclusion level	Processing method	Main effects	Reference
Hybrid meat extrudate	Minced beef (with 7% fat or 17% fat), pea protein isolate, texturised pea protein concentrate	50% meat and 50% PI/TPC	High-moisture extrusion	1. Hybrid extrudates with PI were softer and layered; those with TPC were harder with smaller fibres. 2. Beef fat content had no significant effect on texture. 3. Both hybrid extrudates retained their meaty odour and umami taste.	78
Hybrid meat extrudate	Pork meat, soy protein concentrate, water	50% meat and 50% soy protein concentrate	High-moisture extrusion	1. The structure of texturized meat/soy product was comparable to pure soy texturized products. 2. Texturized meat/soy product was slightly softer than pork meat. 3. Combined meat/soy product structure depends on recipe and extrusion parameters.	80
Hybrid plant-fish meat analogue	Gutted fish/whole fish, pea protein isolate, salt	70% whole/gutted fish and 30% pea protein isolate	High-moisture extrusion	1. All samples resisted tearing cross-sectionally but broke easily longitudinally. 2. Pea protein sample had the strongest fibril alignment and the whole fish sample had the weakest. 3. Microbiological quality was similar in all extrudes made from whole fish, gutted fish or pea protein isolate. 4. Whole fish and gutted fish extrudates showed uniform flavour- and odour-related sensory profiles.	79

Knoch [80] investigated the texturization of a meat/soy product developed using co-extrusion, combining 50% pork meat and 50% soy protein concentrate with water. Fibres formed in the cooling die as the hot protein melt flowed and solidified during extrusion. These fibres contributed to the product's distinct structure and texture, with sensory attributed comparable to those of conventional meat products. However, the combined meat/soy sample was slightly softer than the pork meat comparator. Hybrid extrudates were also produced by using a 1:1 mixture of minced beef with either pea protein

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isolate (PI) or milled texturized pea protein concentrate (TPC) [78]. Hybrid extrudates containing PI had a layered and fractured structure, while hybrid extrudates containing TPC had a more distinct fibrous structure and stronger texture. The hybrid extrudates containing TPC exhibited a meat-like flavour that was more prominent and less similar to peas compared to those containing PI. The difference in flavour could be attributed to the pre-texturization of TPC, which consequently reduced the amount of volatile compounds present. Furthermore, the addition of starch in TPC may have enhanced the separation of phases and the formation of a fibrous structure during the extrusion process.

3D printing technology, also known as ‘‘additive manufacturing’’, is potentially useful for developing a muscle-like architecture by precise control of meat and plant protein batter addition [22] . Some studies have compared printing of hybrid mixtures with 100% plant-based mixtures. Hybrid chicken nuggets were 3D printed using pea protein isolate and chicken mince [64], after preparation of the paste by mixing raw chicken paste with PPI paste. Results showed that hybrid chicken nuggets containing 20% chicken paste achieved better printability and fibre structure compared to hybrid chicken nuggets consisting of 50% chicken paste. Extrusion-based 3D printers may struggle with the extrusion pressure required for harder food inks, making it difficult to mimic the texture of 100% meat products. This highlights the challenges presented in attempting to bring 3D hybrid meats from concept to plate, with softness of texture being a primary hurdle for consumer acceptance. While coaxial 3D printing shows the potential in constructing artificial muscle fibres, it is still largely confined to a laboratory setting. However, the softer texture of printed HPM products makes them well-suited for elderly individuals and patients with swallowing difficulties.

The processing technologies used for HPM products, which typically include blending and homogenization, focus more on the interaction/gelling properties between meat and plant proteins in the mixed matrix. Therefore, research and development to date in relation to HPM products have largely focused on restructured products, utilizing a range of ingredients from chopped fresh or dried vegetables and fruits to extracted and extruded plant proteins. However, using co-extrusion processing technologies for the development of HPM products can diversify HPM product types by creating fibrils that structurally resemble muscle fibres. Beyond extrusion, several emerging processing technologies have been developed to construct muscle fibre analogues, for example, wet spinning, electrospinning, freeze structuring, and shear cell/conical shear. Each method produces distinct morphological and structural characteristics, as detailed in previous studies [81, 82]. For examples, in a typical spinning process, fibres are produced by extruding an aqueous protein solution through a spinneret at an appropriate pH, forming fine filaments. Freeze structuring, on the other hand, relies on freezing a protein emulsion to generate a fibrous structure; upon ice crystal removal, the resulting porous and aligned protein network closely mimics the texture of animal muscle [82]. While these technologies have been extensively explored in PBMAs, their application in HPMs remains largely unstudied. Integrating these innovative structuring methods into HPM production could enhance meat-like characteristics and expand product versatility. Further research is needed to assess how these techniques interact with animal proteins and optimize processing parameters for hybrid formulations. Although extrusion temperature can reach approximately 170°C [33], the meat portion in a co-extruded HPM product is unlikely to be fully cooked during HMEP due to the short residence time at high temperature. Therefore, food safety and storage stability of fibrous HPM products should be further investigated.

3. Nutritional properties

Addition of plant-based ingredients as a meat substitute certainly impacts on the chemical composition of HPM products. Crude fat and protein content in HPM products could be lower [39-41, 67], similar [73] or higher [48, 57, 58] compared to 100% meat products depending on formulation approach. The balance between animal-based and plant-based components in HPM products could potentially provide a nutritional profile that reduces the risks associated with high consumption of red and processed meats, while addressing nutrient loss and ensuring the provision of essential vitamins and minerals.

The role of fat in meat products lies in its crucial role in delivering desirable mouthfeel, texture, and flavour quality [83]. Commonly enjoyed meat products, such as; beef patty, frankfurter, and bologna sausage usually have a fat content ranging from 20-30%, while the fat content of fresh pork sausage and salami ranges from 30-50% [84]. The World Health Organization (WHO) suggests that saturated fatty acids (SFA) should make up about 10% of the overall fat intake, and that dietary fat consumption should constitute between 15% and 30% of the total dietary energy [85]. Most consumers attempt to reduce fat intake without compromising product quality [86]. Previous research [39-41, 67] has shown that HPM products incorporating plant-based ingredients have lower fat content compared to 100% meat products. This is likely due to myosin’s role in securing lipids in position within the meat matrix [39], along with the contribution of specific plant proteins and fibres to improve stability within the meat emulsion system [67]. Conversely, the native fat composition in plant ingredients could also explain the lower or higher fat content observed in HPM products [48]. For example, the total fat content decreased in hybrid meatballs with increasing soy substitution owing to the lower fat content in texturized soy protein (1%) compared to lean beef (4.5%) [76]. Furthermore, the decrease in fat content could also have resulted from the dilution effect caused by using water to hydrate plant ingredients and the defatting of plant ingredients (via solvent or manufacturing processes like extrusion) [50, 70, 74].

The low protein content in HPM products may be due to the lower protein content of plant proteins compared to meat [39, 57]. For example, the protein content in Chinese yam (3.6-8.5%) and arrowroot (10.8-21.1%) compares poorly to that of raw chicken meat (27-31%) [39]. Not surprisingly, similar test results showed that hybrid meat sausages containing the largest proportion of

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broccoli had the lowest protein content, owing to the low natural protein content associated with broccoli (4.4g/100g) [57]. While some other research incorporated plant ingredients which possessed higher protein contents than the examples provided previously, HPM products still demonstrated reduced protein contents. This is because the protein concentration may have been diluted after hydration and before incorporating into meat products, thereby resulting in reduced protein content in HPM products [41, 49, 67]. For example, the reduction of protein content in beef patties following the addition of wheat germ protein flour (WGPF) was observed [50] and attributed to WGPF being hydrated to three times its weight. However, the inclusion of chickpeas and lentils did not significantly decrease the protein content of hybrid chicken burgers, which could be attributed to their higher protein contents of 23.6% and 29.5%, respectively [49]. Regarding the amino acid profile of HPM products, Broucke, Van Poucke [72] demonstrated that incorporating 20% pea products (protein isolate, LME or HME) into emulsified cooked sausages had no implications on amino acid profile. Moreover, using LME and HME reduced ANF trypsin and chymotrypsin inhibitors and the allergenic pea convicilin contents.

The amount of fibre plays a crucial role in determining the textural properties of plant-based meat analogues. Fibre also supports digestive health and helps lower cholesterol levels [39]. A positive correlation exists between the fibre content in HPM products and the proportion of plant ingredients incorporated into these products, namely because meat is devoid of such dietary fibre naturally. For example, the more Chinese yam or arrowroot that was incorporated into chicken meat emulsions, the higher the fibre content in these hybrid meat emulsions [39]. Similar results were shown when levels of oyster mushroom [56] and sunflower and pumpkin products [75] increased in HPM product formulations.

Several commercial HPM products highlight improved nutritional profiles by incorporating vegetables, legumes, and grains alongside meat. Applegate Farms' blended burgers combine meat with whole organic vegetables, offering a more balanced nutritional composition while appealing to health-conscious consumers [87]. Perdue Chicken Plus line [42] blends chicken breast with cauliflower, chickpeas, and cabbage, providing added fibre and micronutrients while maintaining a familiar taste. Well Carved Organic Grass-Fed Beef Burgers contain a mix of beef, organic cauliflower, spinach, lentils, and butternut squash, delivering a third of a cup of vegetables per serving. Nutritional analysis shows that Well Carved burgers have fewer calories, lower fat content, and reduced saturated fat levels compared to conventional beef burgers, demonstrating the potential health benefits of HPM products [88].

While plant-based ingredients generally contain less total saturated fat and higher amounts of fibre and complex carbohydrates [89], they typically lack essential amino acids and differ considerably in the levels of certain essential nutrients present, such as; iron, zinc, and vitamin B12 compared to meat products. This is where the meat component present in HPM products balances the formulation and addresses the negative compositional discrepancies presented owing to the use of plant-based ingredients.

4. Technological properties

While the reasoning behind HPM product development has been comprehensively outlined and described at this point, the specific quality requirements of what must be delivered when attempting to create commercial products to meet consumer expectations have not. While HPM products should work in harmony from a compositional and processing perspective to form a commercial product, one must never lose sight of the fact that consumers desire these products to look like and mimic meat products, at least for the time being. Therefore, in discussing HPM products further, it is important to address the factors that impact upon the meat quality attributes associated with such products especially in relation to sensory and stability issues.

4.1 Colour

Colour is a critical quality attribute that influences consumer purchasing decisions for meat products. Previous studies [39, 41, 58, 74] have stated that incorporating plant-based ingredients can significantly alter their appearance due to differences in myoglobin content and the inherent colour of each plant-based ingredient employed.

Lightness (L*) values in raw HPM products vary depending on the plant-based ingredients employed and the manner in which water binding occurs within the HPM products. For example, beef patties manufactured using rice protein and lentil flour showed increased L* values, likely influenced by their natural colours and light-scattering properties. Conversely, adding dark-coloured plant ingredients can reduce L* values. Additionally, lightness may decrease due to reduced light scattering caused by the expansion of chickpea protein concentrate upon water absorption, along with the lower presence of white (animal) fat [90]. When considering the impacts of adding plant ingredients into HPM products, and considering the impacts that such additions can have on water and fat contents in these products as previously discussed, it is important to point out that increases in fat oxidation [74] and moisture content [72] in such products can cause increases in product L* values.

Most researchers have observed a decrease in the redness (a*) values associated with raw HPM products [39, 41, 59, 66, 69], and this is not unexpected considering that significant proportions of red meat have been replaced with plant-based ingredients. The presence of dark green plant-based components, such as hempseed [41], reduced a* values. The dilution of myoglobin, the primary red pigment in meat, also contributes to this decrease [72]. In contrast, raw HPM products often show an increase in yellowness (b*) [41, 67, 71, 73]. This is often attributed to the presence of yellowish compounds such as phenolic compounds (e.g., anthocyanins and flavonols) in plant ingredients [71].

The colour of cooked HPM products generally follows the same trends observed in their raw state [56, 62]. After cooking, some HPM products showed lower L* values than meat-only

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controls, likely due to myoglobin degradation during heating [39]. In contrast, higher L* values in HPM products may be attributed to pigments such as leghemoglobin present in legumes [70]. The a* values of cooked HPM products are lower than those of meat products [48, 72]. However, hybrid burgers containing lentil flour have been shown to possess higher a* values, most likely influenced by the elevated carotenoid content of lentils [59]. Additionally, the increased b* values observed in cooked hybrid meat/hempseed products may be attributed to the breakdown of chlorophyll in hempseed meal during heating [41].

The colour differences between meat and HPM products depend on the type and proportion of plant-based ingredients used, as well as their interaction with the meat matrix. However, colour modifications can be achieved through the use of natural colorants [51], a method extensively utilized in commercial meat products [48] and plant-based meat alternatives [22]. Previous sensory evaluations indicated that consumer willingness to buy HPM products is influenced more by meat-like taste than by appearance [91]. Therefore, improvement in colour should be considered after achieving satisfactory flavour, taste, and texture. Notably, Zając, Guzik [92] found that the green colour in meat products when derived from known sources, such as plant ingredients and spices, did not negatively impact consumer expectations. This may explain why some commercial HPM products include green vegetables such as spinach and why most are formulated with chopped vegetables and fruits.

4.2 Mechanical properties

The texture of cooked HPM products is influenced by multiple factors, including water content, nutrient composition, the type and proportion of plant-based ingredients, the meat used, and the processing methods applied [41]. Understanding these factorial influences is crucial, as texture is one of the most challenging aspects of replicating traditional meat products [39, 41, 67, 72, 73].

Texture profile analysis (TPA) is a useful tool for assessing the textural attributes of HPM products and examining how well they replicate the sensory properties of conventional meat products [39]. TPA measures attributes such as hardness, cohesiveness, gumminess, springiness, chewiness, resilience, and adhesiveness [41]. Research generally indicates that incorporating plant-based ingredients tends to weaken the texture of meat products, thereby presenting a major challenge in achieving desirable textural qualities [39, 41, 67]. The following section highlights textural differences between meat and HPM products, along with factors contributing to these variations.

Hardness refers to the force required to break down a food product while chewing. In general, hardness values observed in cooked meat products are higher when compared to those determined in HPM products and this difference can be attributed to the denaturation and thermal shrinkage of myofibrillar proteins such as myosin and actin [93]. Heat-induced protein unfolding and aggregation cause contraction of the protein matrix and the expulsion of fats and water, which increases protein-protein interactions and strengthens gel or matrix structure. However, the reason that HPM products generally exhibit lower hardness values is due to weaker intermolecular interactions that exists amongst plant proteins [41] and disruptions in the protein matrix caused by the presence non-meat proteins and carbohydrates [67]. Additional factors contributing to reduced hardness include increased moisture and fat retention [56], higher fibre content, and the formation of air bubbles [41] or large cavities [72], which create a looser structure. Other textural attributes, such as cohesiveness [67], gumminess, springiness, and chewiness [39], often follow the same trend as hardness, decreasing when plant-based ingredients are incorporated. Conversely, the incorporation of certain plant-based ingredients can increase the hardness of HPM products [58, 61, 74]. This effect is typically linked to lower moisture content, imbalances in the emulsion process leading to water and fat separation [58], or the presence of charged amino acids in ingredients like quinoa flour and buckwheat flour. These amino acids form non-covalent bonds with lysine, glutamic acid, and aspartic acid in meat myofibrillar proteins, resulting in increased hardness, springiness, cohesiveness, and chewiness [61].

Since the texture of HPM products differs significantly from that of traditional meat, microscopy analysis provides valuable insights into how plant-based ingredients influence the structure of HPM products. Conventional meat products have a uniform protein matrix with a cohesive structure and minimal porosity [39]. In contrast, HPM products typically exhibit a more heterogeneous and porous microstructure [48, 94]. Therefore, further research is needed to modify functional properties of plant protein ingredients, explore combination of different plant proteins, optimize processing technologies, and incorporate clean-label ingredients that enhance gelling properties. These advancements could help improve the texture of HPM products, making them more comparable to 100% meat products. Furthermore, as discussed previously, research on the textural properties of co-extruded HPM products is limited. Investigating the texturization potential of these products to achieve a fibrous, meat-like structure would be valuable.

5. Shelf-life and food safety considerations in HPM products

HPM products present food safety challenges due to microbial contamination, shelf-life reduction, and potential allergen risks [95, 96]. Contamination of plant-based ingredients can occur due to poor hygiene during vegetable cultivation and handling [97]. Even plant-based meat alternatives can be susceptible to spoilage because their neutral pH, high protein content, and relatively high water activity favour the growth of spoilage microorganisms and foodborne pathogens [98, 99]. A study [97] by the Danish Meat Research Institute (DMRI) found that adding 10-15% plant protein to meat products increased bacterial counts beyond levels typically found in fresh meat. Changes in physicochemical properties, such as increased carbohydrate content and pH, may further influence microbial growth. However, research on meat sausages with higher carbohydrate content showed minimal impact on *Listeria monocytogenes* growth [100].

Several studies have assessed how plant ingredients affect the shelf life of HPM products. Minced meat with 25% and 50% vegetable inclusion had a 6% and 16% shorter shelf life, respectively [100]. In another study, emulsion sausages containing 15% and 25% soy protein isolate showed no significant change in total plate count over 28 days [66]. However, microbial growth varied depending on ingredient composition. For example, beef burgers made with buckwheat flour exhibited lower bacterial counts due to the flour's antimicrobial properties [61].

Processing methods play a crucial role in controlling microbial risks. High-temperature treatments used in extruding plant proteins effectively inactivate parasites, viruses, and most bacterial cells. However, plant starch content may encourage spoilage bacteria, leading to gas formation and sour off-flavours [97]. For canned HPM products, manufacturers must monitor spore-forming bacteria, as some anaerobic spores are highly heat-resistant and may survive autoclave treatments [97].

Beyond microbial concerns, HPM products may pose allergen risks, particularly from gluten, soy, or novel plant proteins. Limited research exists on the allergenic potential of these ingredients in hybrid formulations [22]. Future studies should focus on optimizing packaging and storage methods to extend shelf life, assessing microbial stability in different formulations, and investigating the allergenic and anti-nutritional effects of plant-based ingredients to ensure product quality and safety.

6. Sensory aspects of HPM products

Sensory evaluation is the systematic assessment of the sensory attributes of food products, including appearance, colour, texture, flavour, juiciness, aroma, and mouthfeel, using human panels to understand and optimise consumer acceptance [91]. Sensory attributes, particularly flavour and texture, play a crucial role in consumer acceptance of HPM products. For HPM products to succeed commercially, product development must align with consumer expectations. Understanding sensory preferences and optimizing ingredient formulation are essential for improving the acceptability and marketability of HPM products [73, 91]. Studies comparing sensorial properties between meat, hybrid, and meat-free products have shown that "meaty flavour" is the most influential factor driving consumer preference [34, 101]. Neville, Tarrega [101] found no significant difference in sensory acceptance between meat and HPM products, whereas meat-free alternatives were less favoured. However, achieving a balance between meat reduction and sensory appeal remains a challenge [35]. The incorporation of plant-based ingredients can introduce undesirable textural changes and off-flavours. For example, increasing lupin flour in beef sausages negatively impacted texture and overall acceptability [67]. Similarly, Broucke, Van Poucke[72] showed that replacing 20% of pork meat with low and high moisture extrudates in sausages resulted in structural flaws, including large cavities with jelly-like exudate, leading to rejection by panellists.

Despite these challenges, some studies have highlighted successful applications of plant-based ingredients in HPM products. Grasso, Smith [76] reported that hybrid meatballs with texturized soy protein (TSP) received higher acceptability scores than conventional meatballs, particularly when yeast was added. Baune, Broucke [91] also demonstrated that HPM products containing 30% pea-based TVP maintained strong consumer appeal.

To address sensory limitations, flavour-masking agents, natural meat flavour extracts, Maillard reaction precursors, and processing techniques are commonly used to enhance the meat-like sensory experience [55, 102]. For example, Kamani, Meera [35] found that replacing chicken with soy protein isolate was well-received, with no detectable beany flavour due to effective seasoning. Interestingly, Chin, Baier [103] also showed that HPM products may require a higher salt content to achieve a similar level of saltiness and flavour perception as meat products. Similarly, Flores, Hernán [71] showed that deodorizing texturized pea protein with ethanol reduced off-flavours, although this process altered texture by affecting protein solubility.

Future work that could combine sensory evaluation with that of instrumental measurement around the capture of changes during the distinct stages of oral processing [55], would provide a deeper understanding of texture perception and overall consumer experience of HPM products compared to meat products. To enhance the commercial viability of HPM products, it is also important to consider not only the specific attributes of the final product but also factors related to consumer preferences [73]. Integrating consumer preferences into the development process would assist in the creation of HPM products with improved formulation and higher acceptance [91].

7. Consumer acceptance of HPM products

Consumer surveys [8, 104] suggest that while traditional meat is generally perceived as more flavourful than alternative protein sources, there is growing openness toward HPM products [55, 105]. A study by Barone, Banovic [43], involving consumers from Denmark, the UK, and Spain, found that many preferred HPM products made with vegetables and legumes, especially if they were minimally processed, additive-free, and sourced from organic and ethical farming. Over-processing and unfamiliarity negatively impacted acceptance, while seasoning, reduced fat, and lower sodium content enhanced appeal. Similarly, an online survey of 501 Belgian consumers [8] revealed that many viewed HPM products as healthier, environmentally sustainable, and better for animal welfare, though concerns about price remained. Women generally exhibited greater acceptance than men, while consumers with a strong attachment to traditional meat were less receptive to hybrid options. Studies [34, 104] indicate that consumer perceptions of HPM products are highly influenced by product information. In blind taste tests, hybrid burgers with 70% beef were preferred over meat-free alternatives, but acceptance declined when ingredient details were disclosed [104]. A study by Grasso, Rondoni [34] found that UK consumers rated hybrid burgers higher in overall liking compared to both 100% beef and fully plant-based burgers.

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Additionally, product format and processing level influenced acceptance, with less processed formats generally preferred [104]. Furthermore, an online survey revealed that protein source was the most important factor influencing HPM product selection, followed by price, fat and packaging claims [106]. These findings highlight the importance of engaging with consumers during the development of HPM products to ensure greater acceptance.

While many HPM products are successfully on the market, occasionally products have struggled to gain traction, leading to product discontinuation. For instance, Tyson Foods' Raised & Rooted blended patties, containing pea protein isolate and beef, were launched in 2019 but withdrawn by late 2020, despite the company's continued investment in plant-based products [107]. Similarly, BrewDog [10] introduced a 50% Beyond Meat, 50% beef Hybrid Burger, which has since been removed from the market. Speculation as to the potential reasons for these failures relate to the lack of clear differentiation from either plant-based or meat products, and cost, among others [104]. Little firm data is available in this regard, and further consumer research is required to understand reasons why there may be rejection of certain HPM products, including market positioning, brand, cost, and potential environmental impact.

8. Regulatory considerations for incorporating plant-based ingredients

Manufacturers of plant-based meat face regulatory challenges worldwide, including restrictions on labelling, ingredient classification, and market access, with some regulations being contested or overturned in court [108]. In the United States, several states have enacted laws restricting the use of traditional meat-related terms on plant-based food labels. Kansas, for instance, allows such terms only if explicitly qualified as not containing conventional meat [108]. Similarly, to gain pre-market approval in the European market, standardized methods for plant protein extraction, including pre-treatment, production, and processing, must comply with relevant regulations and align with European Union (EU) policies [109]. The EU classifies proteins extracted from familiar plants as novel foods if processed using innovative techniques, potentially limiting market entry for products like cultured meat, algae, and insect-based proteins [110]. Additionally, countries like France and Belgium have introduced legislation prohibiting the use of meat-related terms for plant-based proteins [108, 110]. Japan has taken a different approach, with the Ministry of Agriculture introducing new standards for soy protein products, categorizing them based on their suitability for vegetarian and vegan diets [111]. However, as HPM product gains traction, global regulatory challenges persist, particularly regarding ingredient selection, processing methods, and labelling requirements [112].

Both plant-based meat analogues and HPM products face regulatory scrutiny over ingredient labelling and product naming. For HPM products, careful ingredient selection and processing are crucial, while clear, accurate labelling helps inform consumers about the nature and composition of these innovative food products. Additionally, as regulations continue to shift, manufacturers must navigate these complexities to ensure compliance while maintaining consumer trust.

9. Conclusion and looking forward

By combining conventional animal-based meat with plant-based ingredients, HPM products aim to meet consumer expectations for taste and nutrition while addressing the health, environmental, and ethical challenges associated with conventional meat consumption. When optimally formulated, HPM products can provide balanced nutrition, meat-like texture, enhanced sensory appeal, and economic viability, ultimately supporting a more sustainable and widely accepted dietary shift.

Despite these advantages, several challenges limit the large-scale adoption of HPM products. Consumer acceptance remains critical, as concerns about unpleasant taste, unfamiliar ingredients, and nutritional quality can reduce willingness to purchase. From a nutritional perspective, blending plant proteins with meat can lower protein quality due to reduced digestibility and the presence of anti-nutritional factors such as phytates, which further affects nutrient bioavailability. Textural differences also persist between meat products and HPM products, particularly at high levels of plant protein inclusion. Moreover, it remains challenging to achieve fibrous, meat-like textures in HPM products using co-extrusion technology.

To drive wider adoption, these challenges need to be addressed through careful ingredient selection and modification, innovations in processing technologies, and development of products aligned with consumer preferences to ensure both technical performance and market acceptance. Future research could focus on optimising plant protein functionality using technologies such as enzymatic hydrolysis, fermentation, and ultrasound to improve texture attributes of HPM products. Incorporating alternative protein sources, such as cultured meat, algae, and insects, could further enhance bioavailability, nutritional quality, and sustainability. Innovations in processing technologies, including plant fibre spinning, may also support the development of more fibrous HPM products. For industry, scaling up the production of HPM products will require clean label processing, consumer preferred formulations, and ensured food safety. In conclusion, as HPM products development continues to progress, HPM products have the potential to bridge the gap between conventional meat and plant-based alternatives, offering a sustainable and flexible approach to protein consumption.

Author contributions

Zuo Song: Conceptualization, Investigation, Writing - original draft. Ruth Hamill: Conceptualization, Supervision, Funding acquisition, Resources, Writing - review & editing. Joe Kerry: Conceptualization,

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Conflicts of interest

There are no conflicts to declare.

Data availability

No new data were created or analysed in this study.

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Data availability

No new data were created or analysed in this study.