Chapter-2

Review of Literature

The increasing demand for plant-based meat alternatives stems from multiple consumer concerns (Detzel et al., 2022). Environmental issues and ethical considerations drive significant market interest in sustainable protein sources. Health concerns about traditional meat consumption motivate dietary changes. Traditional animal agriculture significantly contributes to environmental degradation through greenhouse gas emissions (Detzel et al., 2022). Land use, water consumption, and pollution represent major ecological impacts and these factors collectively support the growing plant-based meat sector. Meat analogues aim to replicate meat's complex sensory and nutritional properties (Ahmad et al., 2022) and achieving this optimal texture remains a primary technical challenge. Flavor development requires sophisticated formulation strategies. Current commercial products primarily utilize soy, wheat, and pea proteins as base ingredients (Ahmad et al., 2022). These protein sources provide functional properties but require enhancement techniques. Advanced processing methods offer innovative solutions for texture improvement. Freeze structuring creates aligned protein fibers that closely resemble meat texture (Lee et al., 2023). This technique produces anisotropic structures similar to muscle fibers and the resulting texture provides improved mouthfeel and chewing characteristics. Flavor and color development present significant technical challenges in product development as plant proteins naturally lack the characteristic savory taste profile of animal meat. Enzymatic hydrolysis releases amino acids that contribute to umami flavors. Maillard reaction development enhances browning and flavor complexity. Natural colorants provide visual appeal while maintaining clean label status (Wilson & Kumar, 2024). Cooking process standardization significantly impacts final product quality parameters (Lee et al., 2023). Various cooking methods affect structural integrity differently and influence protein denaturation and texture development. These factors determine consumer acceptance and satisfaction and the final product development phase requires careful formulation optimization (Martinez & Taylor, 2024). Ingredient interactions must be thoroughly understood and controlled so that texture optimization balances multiple sensory attributes. Shelf-life stability ensures commercial viability through extended storage periods. Comprehensive testing of physicochemical properties validates product performance. Storage stability studies confirm quality maintenance over time. These evaluations ensure commercial success and consumer acceptance in competitive markets (Lee et al., 2023).

2.1. Manila tamarind seeds as a source of protein

This chapter reviews about Manila tamarind (*Pithecellobium dulce*), whose seeds emerge as a promising protein source for meat analogues. These legume seeds, typically discarded during fruit processing, contain high protein content and bioactive compounds (Meena et al., 2022). While legume proteins demonstrate versatility in forming gels, emulsions, and fibrous structures, Manila tamarind's potential in meat analogues remains understudied (Baig et al., 2025). Developing high quality plant-based meat analogue requires comprehensive protein extraction, modification, and enhancement techniques. The extracted protein's functional properties, including solubility and water-holding capacity, are crucial for meat-like texture (Thompson et al., 2024a). Manila tamarind, a tropical leguminous plant, has drawn attention for its nutritional potential and bioactive compounds **(Figure 2.1)**. While the pulp is commonly consumed, the seeds, often discarded, present a sustainable source of proteins with diverse applications. This review focuses on the isolation, modification, and functionalization of proteins from Manila tamarind seeds, considering various physical treatments and texturization techniques to enhance their usability in food systems.

A B

Figure 2.1: Manila tamarind tree (A) and fruits on its branches (B)

The Manila tamarind seeds are distinguished by their reserve substances, in most cases carbohydrates, proteins and lipids (Ikeda et al., 2021). The seeds have a significant amount of carbohydrates (55.54%), whose content is similar to that of chickpea (58.53%), cowpea (65.14%) and pea (63.65%) flours (Ge et al., 2021). Protein content of the Manila tamarind seeds is approximately 35-40%, which is greater than 18.3%, 23.1%, and 26.83% from amaranth (Mahalaxmi et al., 2022), coconut (Thomas et al., 2022), and faba bean (Martínez-Velasco et al., 2018) flours, respectively. Proteins in Manila tamarind seeds may be classified into Osborne´s classification for seed storage proteins based on the solubility characteristics. Gx is said to be the dominant fraction in the Manila tamarind seeds with a 40.14% of the total protein content, followed by Al and Gl with 34.29% and 25.42%, respectively, and Pr fraction being the minor one with total protein content of 1.1%. Distribution of Manila tamarind seed protein fractions is comparable to that in a jackfruit flour, which consist predominantly of Gx (68.3%), followed by Al (18.3%), Gl (11.3%, and Pr (1.98%) (Ulloa et al., 2017). Studies on protein isolates of passion fruit have reported the compositions of the Gx, Gl, Pr, and Al fractions as 95.59%, 2.30%, 1.14% and 0.97%, respectively (Espinosa-Murillo et al., 2021), whereas *Cordyceps militaris* flour contains Al, Gl, Gx, and Pr contents of 43.11%, 36.47%, 17.94%, 2.48%, respectively (Yu et al., 2021).

The isolation of proteins from plant-based sources is a critical step in understanding and utilizing their functional properties. Several studies have demonstrated methods to extract proteins from seeds, including alkaline extraction, acid precipitation, and enzymatic hydrolysis. Various researchers have highlighted that seed proteins possess significant nutritional value, with legume seeds containing globulins and albumins as dominant fractions (Rizvi et al., 2021). The extraction of proteins from tamarind and other leguminous seeds typically involves defatting, solubilization in alkaline media, and precipitation at their isoelectric points (Eze et al., 2022). Isolated seed proteins are increasingly studied for their application in food formulations, owing to their emulsifying, gelling, and foaming properties (Boye et al., 2010). The potential of underutilized seeds, such as Manila tamarind, can be unlocked through appropriate extraction techniques.

Modifying seed proteins enhances their functional properties, making them suitable for broader applications in food systems. Physical treatments such as autoclaving and ultrasonication are prominent techniques for protein modification. Autoclaving, a form of wet heat treatment, disrupts protein structure, leading to denaturation and exposure of hydrophobic groups, which improves solubility and digestibility **(**Singh et al., 2019). Studies on soy and chickpea proteins indicate significant improvements in emulsifying and foaming capacities after autoclaving. Ultrasonication involves high-frequency sound waves to modify protein structures. This technique reduces protein particle size and alters secondary and tertiary structures, enhancing solubility and functional properties (Jambrak et al., 2008). Ultrasonication has been applied to pea and lentil proteins to improve their gelling and emulsifying characteristics. Combining autoclaving and ultrasonication can yield synergistic effects. Studies on mung bean and lupin proteins have shown that dual treatments enhance protein functionality more effectively than single treatments (Zhang et al., 2023b).

Assessing the quality and functionality of proteins involves analysing parameters such as solubility, water-holding capacity, emulsification, and foaming properties. These attributes determine the applicability of proteins in food systems. Protein solubility is a key determinant of its functional properties. It is influenced by pH, ionic strength, and processing conditions. Research on plant proteins, including those from legumes, demonstrates enhanced solubility following thermal and ultrasonic treatments (Tang, 2017). Water-holding capacity (WHC) is critical for texture and moisture retention in food products. Modified proteins generally exhibit improved WHC due to structural changes that increase water-binding sites (Zayas & Zayas, 1997). Emulsification and foaming are essential for applications in beverages, baked goods, and dairy alternatives. Treatments such as ultrasonication improve the interfacial properties of proteins, enhancing their ability to stabilize emulsions and foams (Stone et al., 2015).

Texturization transforms proteins into fibrous structures that mimic meat, offering plant-based alternatives in food systems. Techniques such as extrusion, freeze-drying, and enzymatic cross-linking are widely used for this purpose. Extrusion applies heat and shear forces to proteins, aligning them into fibrous structures. Studies on soy and wheat proteins highlight the effectiveness of extrusion in creating meat analogues with desirable texture and sensory properties (Lyu et al., 2022). Freeze-drying preserves the functional properties of proteins while imparting a porous structure. Research on legume proteins demonstrates that freeze-dried proteins exhibit improved rehydration properties and structural integrity (Ramakrishna et al., 2010). Cross-linking proteins with enzymes like transglutaminase enhance their structural stability and water-holding capacity. Studies on pea and rice proteins have shown improved textural properties after enzymatic treatment (Tang et al., 2019).

A B

Figure 2.2: Manila tamarind fruit pods (A) and seeds (B)

Modified proteins from Manila tamarind (Guamuchil) seeds can serve as a sustainable and functional ingredient in various food applications. Enhanced solubility, emulsifying, and texturizing properties expand their usability in dairy substitutes, meat analogues, and bakery products (Webb & Alavi, 2023; Flores-Jiménez et al., 2019; 2022). The protein content of Manila tamarind seeds, coupled with essential amino acids, positions them as a valuable plant-based protein source **(Figure 2.2)**. Modification processes further improve digestibility and bioavailability. Modified proteins exhibit versatility in their applications. Their improved foaming and emulsifying properties make them suitable for beverages and confections, while enhanced water-holding and gelling capacities facilitate their use in plant-based meat products (Flores-Jiménez et al., 2022).

While the potential of Manila tamarind seed proteins is significant, challenges such as optimizing extraction and modification methods, scalability, and consumer acceptance remain. Future research should focus on developing eco-friendly and cost-effective extraction methods, exploring novel modification techniques such as pulsed electric fields and cold plasma, evaluating sensory and consumer acceptability of products developed from modified proteins, and conducting comprehensive nutritional and safety assessments to ensure regulatory compliance. The proteins from Manila tamarind seeds offer immense potential as a sustainable and functional ingredient in food systems. Isolation, modification, and texturization techniques, coupled with thorough characterization, can unlock their diverse applications. Leveraging these approaches will contribute to the development of innovative and sustainable food products while addressing global protein demand.

2.2. Plants as a source of protein in place of animal proteins

Plant nutrients serve as powerful nutritional enhancers in modern food systems. They effectively substitute for fats and animal proteins in various applications. This substitution significantly boosts the overall nutritional value of processed foods (Lee et al., 2023; Thompson et al., 2024a; Wilson & Kumar, 2024). Plant-based proteins and fats demonstrate remarkable versatility in meat product applications. They enhance textural properties in surimi, meat batters, and pork meat gels through their unique functional characteristics. The effectiveness stems from plant proteins' inherent functional properties and their ability to form cross-links with myosin proteins (Lee et al., 2023; Martinez & Taylor, 2024; Baig et al., 2025). Advanced processing technologies further amplify plant protein functionality. High-pressure treatments modify protein structures to improve food quality. MTGase applications create stronger protein networks through enzymatic cross-linking. Microwave processing offers rapid and efficient protein modification. Ultrasound treatments enhance protein solubility and functional properties (Detzel et al., 2022). These technological interventions unlock the full potential of plant proteins in food applications. The food industry has recognized plant proteins' tremendous potential. Their diverse health benefits drive increased commercial interest. Essential functional characteristics make them ideal ingredients for product development. Plant proteins enable the creation of innovative food products across multiple categories. Meat alternatives benefit from enhanced protein content and improved nutritional profiles. Flour-based products gain better functional properties and nutritional density (Lee et al., 2023). Extruded foods achieve superior texture and nutritional value through plant protein incorporation. These developments represent significant advances in food technology and nutrition science. Complex interactions occur within plant protein-enhanced food systems. Different protein sources create varying structural arrangements. These structural differences directly influence final product properties (Detzel et al., 2022). The relationship between structure and function determines product quality and consumer acceptance. Understanding these interactions enables optimized product formulation. Food manufacturers can predict and control product characteristics through strategic plant protein selection (Baig et al., 2025). This knowledge facilitates the development of superior plant-based alternatives. The structural complexity of plant protein systems offers both challenges and opportunities. Proper management of these interactions leads to products with enhanced nutritional profiles, improved textures, and better overall quality. The result is a new generation of foods that meet consumer demands for healthier, more sustainable protein sources while maintaining the sensory attributes expected in traditional food products (Detzel et al., 2022).

2.3. Protein isolation and modification

Protein extraction and modification are critical steps in developing plant-based meat analogues, as the functionality and structural integrity of the extracted protein determine the quality of the final product (Asgar et al., 2010). The first step is the efficient extraction of proteins. The Manila tamarind seeds, known for their high protein content, offer a valuable raw material for meat analogue development (Subagio, 2006). Common methods for protein extraction from legumes include aqueous extraction, alkaline solubilization followed by isoelectric precipitation, and solvent-assisted techniques (Boye et al., 2010). Each method has advantages and challenges, depending on the target protein yield, purity, and functionality. Alkaline solubilization followed by isoelectric precipitation is one of the most widely used methods for plant protein extraction due to its simplicity and effectiveness (Moure et al., 2006). This process involves solubilizing the seed proteins in an alkaline medium, typically at a pH range of 8.0 to 10.0, followed by precipitation at the protein's isoelectric point (pH 4.0 to 4.5) (Karaca et al., 2011). For Manila tamarind seeds, the high protein content (~25–30%) makes this method particularly suitable. However, challenges such as the presence of anti-nutritional factors, including tannins and phytic acid, must be addressed during extraction (Soetan & Oyewole, 2009). Defatting the seeds prior to protein isolation using solvents like hexane can improve the extraction efficiency and functional properties of the isolated protein (Tan et al., 2014). Emerging techniques such as enzymatic hydrolysis and ultrafiltration have also been explored to enhance protein recovery and purity. Enzymatic hydrolysis, using proteases like alcalase or papain, can break down the protein matrix and release smaller peptides, improving solubility and bioavailability (Tavano, 2013). Ultrafiltration, on the other hand, employs membrane separation technology to concentrate and purify proteins without altering their native structure (Saxena et al., 2009). These advanced methods hold potential for improving the scalability and efficiency of protein extraction from Manila tamarind seeds, making them viable for commercial applications.

Once extracted, the proteins require modification to enhance their functional properties, such as solubility, emulsification, gelation, and water-holding capacity (Zayas & Zayas, 1997). These properties are essential for replicating the texture and mouthfeel of animal meat (Malav et al., 2015). Physical treatments, including autoclaving, ultrasonication, and their combinations, are widely employed to achieve these modifications (Arzeni et al., 2012). Autoclaving is a high-temperature, high-pressure process that induces protein denaturation, unfolding, and aggregation (Sun et al., 2012). This treatment improves water absorption and gel-forming abilities, critical for texturization. For instance, studies on legume proteins have shown that autoclaving increases protein solubility and digestibility by breaking down anti-nutritional factors and exposing hydrophilic groups (Shand et al., 2007). When applied to seed flours, autoclaving enhanced the functional properties such as water absorption, oil absorption, gelation, foam and swelling capacities and the solubility index, enabling better interaction with other ingredients, useful during meat analogue preparation (Obi & Okoye, 2017). Ultrasonication is another effective method for modifying plant proteins. This technique uses high-frequency sound waves to induce cavitation, resulting in the breakdown of protein aggregates and improved solubility (Arzeni et al., 2012). Ultrasonication can also enhance the emulsification and foaming properties of proteins by altering their surface hydrophobicity and reducing particle size. Studies on soybean and pea proteins have demonstrated significant improvements in gelation and water-holding capacity following ultrasonication (Jiang et al., 2021).

When autoclaving and ultrasonication are combined, their effects on protein modification are amplified due to their complementary mechanisms of action (Jiang et al., 2014). Autoclaving addresses macro-level changes, such as denaturation and aggregate disruption, while ultrasonication targets micro-level modifications, such as particle size reduction and surface property enhancement (Hu et al., 2013). The unfolding of protein molecules during autoclaving allows ultrasonication to further break down aggregates, resulting in a more soluble protein solution (Wang et al., 2018). The exposure of hydrophilic groups during autoclaving and the subsequent dispersion achieved by ultrasonication increase the protein's ability to retain water, essential for mimicking the juiciness of meat (Xiong et al., 2018). Autoclaving improves gelation by exposing reactive groups, while ultrasonication enhances the uniformity of gel networks by breaking down aggregates, leading to gels with better texture and mechanical stability. The combined treatments can enhance multiple functional properties simultaneously, making the protein suitable for a wider range of applications in meat analogue formulations (O'Sullivan et al., 2016).

Despite their benefits, combining autoclaving and ultrasonication requires careful optimization of processing parameters to avoid adverse effects such as over-denaturation or protein degradation. Excessive heat and prolonged treatment can cause protein degradation and reduce functionality (Kinsella & Melachouris, 1976). Moderate conditions (e.g., 120-130 °C for 15-30 min) are typically optimal (Ramos et al., 2015). High-intensity ultrasonication for extended periods can lead to excessive protein fragmentation, negatively impacting gelation and emulsification (Zhang et al., 2023a). Optimized power levels (e.g., 200-400W) and shorter durations (5-15 min) are recommended (Zhu et al., 2018).

2.4. Proteins, structures, and functionality

There is virtually no limit to the types of plant proteins that could be used to produce meat analogues and other meat alternatives. Nevertheless, for the most part, soybean and pea proteins (legume seeds and pulses) and wheat gluten (cereals) are used as a building block for meat alternative products due to their wide availability, low cost, and high processing functionality. Rice proteins and mung bean proteins are often combined with the main protein sources to create nutritionally balanced amino acid profiles. Because of their abundant availability and low cost, soy and pea proteins are the two most commonly used sources of protein in the manufacture of plant-based meat analogue products (Meena et al., 2022). Textured vegetable protein (TVP), which is typically made by aqueous alcohol washing of soy protein concentrate, is a good substitute for meat analogues (Thompson et al., 2024b). Because wheat gluten has an elongated structure, it lends itself well to meat-like chewiness when included in many soy and pea protein-based products. By interacting with the main ingredients (protein), several other plant proteins with structural and nutritional roles are also included to develop composite textural characteristics (Martinez & Taylor, 2024).

Evaluating the quality and functionality of modified proteins is essential to ensure their suitability for meat analogue applications (Kyriakopoulou et al., 2019). Key parameters include protein solubility, water-holding capacity, oil-binding capacity, and gelation properties. High solubility is desirable as it facilitates uniform mixing and texturization. Similarly, water-holding capacity impacts the juiciness and tenderness of the final product, while gelation properties influence its structural integrity (Ismail et al., 2020). Solubility is a critical parameter influencing the protein's ability to form homogenous mixtures with other ingredients (Zayas & Zayas, 1997). High solubility ensures uniform texturization and prevents phase separation during processing. Solubility is measured by dispersing the protein in a buffer solution and quantifying the soluble fraction using spectrophotometric or gravimetric methods (Liu et al., 2015). The effects of autoclaving and ultrasonication on solubility are particularly significant, as these treatments unfold proteins and expose hydrophilic groups (Jiang et al., 2014). Water holding capacity (WHC) measures the protein's ability to retain water, crucial for maintaining the juiciness and tenderness of meat analogues (Kinsella, 1988). WHC is evaluated by centrifuging hydrated protein samples and quantifying the retained water (Quinn & Paton, 1979). Enhanced WHC indicates improved gelation and emulsion stability, essential for replicating the moist texture of meat (Asgar et al., 2010). Oil holding capacity (OHC) is important for emulsion-based products where the protein must stabilize fat droplets. Modified proteins with higher OHC can better mimic the fat distribution in animal meat (Joshi et al., 2011). This property is typically assessed by mixing the protein with oil, centrifuging the mixture, and measuring the retained oil (Chakraborty et al., 1986).

The ability to form gels under specific conditions (e.g., heat, pH) is essential for creating the fibrous, cohesive texture of meat analogues. Rheological studies, using oscillatory and rotational rheometers, quantify gel strength, elasticity, and thermal stability. Dual treatments like autoclaving and ultrasonication enhance gelation by improving protein network formation (O'Sullivan et al., 2016). Emulsification properties determine the protein's ability to stabilize oil-water interfaces, critical for products with complex fat systems (McClements, 2004; McClements & Grossman, 2021). Foaming properties, including foam capacity and stability, are important for products with aerated structures. These properties are evaluated using emulsion stability assays and foam collapse measurements. Techniques such as differential scanning calorimetry (DSC) are employed to assess the thermal stability of modified proteins (Beveridge et al., 1974). Fourier-transform infrared (FTIR) spectroscopy provides insights into structural changes at the molecular level, such as alterations in α-helices and β-sheets (Kong & Yu, 2007). Rheological studies, using oscillatory and rotational rheometers, help quantify the viscoelastic behaviour of the proteins under various conditions. Collectively, these analyses provide a comprehensive understanding of the modifications induced by autoclaving and ultrasonication, guiding further optimization of the process (Nazari et al., 2018).

The functional properties and quality parameters assessed form the basis for evaluating the performance of modified proteins in meat analogue formulations. Proteins with high solubility, WHC, and gelation capacity are better suited for texturization, while strong emulsification and foaming properties enable versatility in product development. By rigorously testing these parameters, researchers can ensure that the protein from the raw material meets the sensory and structural requirements of meat analogues, paving the way for successful product commercialization.

2.5. Meat analogues

Analogues of meat are products that have certain properties (like taste and texture) identical to animal meat and are manufactured to mimic animal products **(Table 2.1)**. A meat analogue is a compound which, despite its structural similarity, differs in composition from its counterpart. Meat analogues share much of the same structure as meat but differs slightly in composition. They have also been called mock, imitation and faux meat techniques. In order for meat substitutes to fulfil the chemical attributes of meat (mainly flavor, texture and appearance), the substitutes to be made from meat-based compounds such as surimi which is a cheap and healthier alternative to meat (Kyriakopoulou et al., 2019). Meat analogues can be made using proteins and ingredients sourced from plant, insect, microorganisms, animals (Ismail et al., 2020; Lee et al., 2024).

Table 2.1: Meat analogue sources and the technology behind their manufacturing

Product	Source	Technology Used	References
Cultured meat	Skeletal muscle cells	Tissue growth in a bioreactor	Stephan et al. (2018)
Microalgae	*Chlorella* and *Spirulina* species	High moisture extrusion	Palanisamy et al. (2019)
Tofu	Soybean milk or curd	Salt-induced or acid-induced coagulation of soymilk	Kumar et al. (2017)
Seitan	Wheat gluten	High moisture extrusion	Joshi & Kumar (2015)
Textured soy protein (TSP)/Soy meat	Defatted soy flour	Extrusion	Kyriakopoulou et al. (2019)

As the world's population increases, the need for reliable protein sources is growing. Meat is considered a good source of high biological value protein, but meat is not sustainable. In Western countries, the shift toward a diet with reduced meat consumption demands healthy and tasteful meat-free food products. Following this trend, the market turned toward vegetable proteins, such as pulses, wheat gluten and soy protein, which are processed into meat-like products, also known as meat analogues **(Figure 2.3)** (Kyriakopoulou et al., 2019).

Figure 2.3: Different types of meat-analogue products available in the market (*Source*: Wiebe, 2004; Kyriakopoulou et al., 2019)

These products approximate certain aesthetic qualities, such as texture, flavor, and colour, and nutritional characteristics of specific types of meat. The development of new, attractive food products is a challenge already, but this challenge becomes even greater considering that these products are meant as a substitute for meat (Kyriakopoulou et al., 2019). The aim of a meat analogue is to make the consumer think that they are consuming meat in all sense of the meaning including mimicking structure, composition and organoleptic properties.

However, meat has a very complex structure, which is difficult to reproduce. In 2008, Redman filed a patent for a meat-analogue containing 5 to 40% protein with a characteristic cross-sectional contraction resembling the skin of meat and imparting appearance of cooked meat (Kumar et al., 2009). Similarly, Kumar et al. (2011) compared chicken nuggets with meat analogue nuggets prepared by incorporating texturized soy protein, mushroom, wheat gluten, etc., for their various physico-chemical and sensory attributes. The scores for the textural properties of real meat were significantly higher than the meat analogue in terms of hardness, chewiness and cohesiveness (Kumar et al., 2022).

2.6. Nutrition of meat analogue

The primary driver of meat consumption centres on exceptional nutritional density. Traditional meat provides complete proteins with all essential amino acids. These proteins exist in highly bioavailable forms for human consumption. This nutritional profile necessitates sophisticated development of plant-based alternatives. Modern plant-based meat alternatives must effectively replicate these critical nutritional profiles as they serve as viable dietary substitutes for health-conscious consumers (Kumar et al., 2017). Contemporary market analysis reveals significant achievements in nutritional adequacy as several commercially available plant-based alternatives demonstrate substantial protein provision capabilities. Kyriakopoulou et al. (2021) conducted comprehensive comparative studies across multiple product categories and their systematic evaluation examined beef burgers, pork ham, beef meatballs, and chicken nuggets. Each category included both traditional and plant-based counterparts for direct comparison. Quantitative analysis revealed important nutritional benchmarks for protein content, traditional beef patties contain approximately 23.33 grams of protein per serving (Kyriakopoulou et al., 2021).

Plant-based analogues provide approximately 19.46 grams of protein per equivalent serving and this represents a 16.6% reduction in total protein content. The reduction remains within acceptable ranges for meeting daily protein requirements. Plant-based alternatives demonstrate superior nutritional profiles in other critical areas as they exhibit significantly lower cholesterol content compared to animal-based products. Elevated dietary fiber levels provide additional health benefits (Benković et al., 2023). These improvements contribute to enhanced cardiovascular health outcomes. They also support improved digestive function through increased fiber intake. Plant-based meat analogues offer remarkable nutritional advantages beyond basic protein provision. They contain zero cholesterol, unlike their animal counterparts which contain 50-80mg per serving. Fiber content ranges from 3-6 grams per serving in plant alternatives (Kyriakopoulou et al., 2021). Traditional meat products contain virtually no dietary fiber. Plant-based options provide essential micronutrients including folate, magnesium, and potassium. They offer lower saturated fat content, typically 30-50% less than conventional meat. Sodium levels vary but can be controlled through formulation optimization. Plant proteins provide phytonutrients and antioxidants absent in animal products. These compounds contribute to anti-inflammatory effects and disease prevention (Rao, 2013).

The consistency of nutritional performance spans diverse product categories effectively. Bohrer (2019) corroborates these findings across multiple plant-based meat types. Current plant protein processing technologies demonstrate sufficient sophistication for nutritional equivalency. Formulation strategies maintain reliable nutritional profiles regardless of specific meat replication targets (Stephan et al., 2018). Advanced protein isolation and concentration techniques enhance amino acid profiles. Fortification strategies address potential nutritional gaps in plant-based systems. Vitamin B12 supplementation addresses the primary nutritional limitation (Bohrer, 2019). Iron bioavailability improvements through processing optimization show promising results. Manufacturing innovations continue improving nutritional density in plant-based alternatives. Protein combining strategies optimize amino acid complementarity. Fermentation processes enhance protein digestibility and bioavailability. Enzymatic treatments improve nutrient absorption characteristics (Dekkers et al., 2018). These technological advances narrow nutritional gaps between plant and animal proteins. Quality control measures ensure consistent nutritional delivery across production batches. Aggregate nutritional assessment demonstrates adequate protein provision for human dietary needs. Plant-based meat analogues support daily protein requirements effectively (Palanisamy et al., 2018). They potentially offer superior overall health benefits through favourable lipid profiles. Increased fiber content provides additional digestive and metabolic advantages.

Lower environmental impact accompanies these nutritional benefits. Reduced resource utilization supports sustainable food system development. These products address growing consumer demands for healthier protein sources (Bohrer, 2019). They simultaneously meet sustainability concerns regarding conventional meat production. The positioning of plant-based alternatives as nutritionally advantageous represents significant market evolution. Consumer acceptance increases as nutritional parity improves. Health-conscious demographics drive demand for these innovative products.

Regulatory support enhances market penetration and consumer confidence. Nutritional labelling transparency builds trust in plant-based alternatives. Educational initiatives promote understanding of plant protein benefits. These factors collectively support continued growth in the plant-based meat sector (Kyriakopoulou et al., 2021; Benković et al., 2023).

2.7. Proteins as main ingredient for meat analogues

Plant proteins like soy protein, gluten, pea proteins, and potato proteins can bind water and stabilize emulsions and gels. A coarser texture can also be achieved by adding proteins of a texturized form in emulsion-type formulations. It is often the case, however, that proteins are blended with non-protein binders or fillers such as polysaccharides (e.g., fibres and starch). As a matter of fact, the inclusion of those ingredients is based on the fact that plant proteins reduce gel formation and elasticity in cooked emulsions (Thompson et al., 2024b). The use of chickpea flour, wheat flour, bean protein flour and tofu has been suggested to be less refined ingredients in recent formulations such as "mimic-würstel" and "mimic-mortadella" (Martinez & Taylor, 2024). As a result of this ingredient combination and others, the dry matter content of these products is higher than meat alternatives. Consequently, they are juicier. In addition to selecting plant protein ingredients as the starting point for product development, the decision to use them is often influenced by the availability of proteins, yields of crops, and protein extraction potential. Among the most commonly used plant-based ingredients, the main characteristic observed is that they are byproducts of the food industry (primarily used in oil or starch production). Example, animal feed was once made from soy meals collected after oil extraction. But soy's high protein content, balanced amino acid composition, wide availability, cost-effectiveness, and specific protein properties it possesses (like its ability to gel and to hold water) (Johnson et al., 2007) allowed manufacturers to manufacture meat analogue ingredients.

Although soy has been popular in western countries for years, it has declined in recent years due to concerns over crop production (i.e., deforestation) (Lee et al., 2023) and potential health risks related to presence of antinutritional compounds (Detzel et al., 2022). Protein from wheat is another commonly used ingredient. Wheat protein contains a high percentage of gluten. An application of gluten in meat analogues results in small fibres due to its unique film-forming properties. In addition, wheat flour is cost-effective because the starch it contains is also used in industrial processes. Gluten sensitivity is a major drawback for some people. Additionally, protein-rich oilseeds and waste materials from oil production may also be used as ingredients for meat analogues, such as sunflower and rapeseed meals. Additionally, a variety of grains and beans are being examined for their protein content; examples include rice, other cereals, and bean flour. Traditional and novel meat alternatives are created from the derivatives of these crops, such as meals, concentrates, and isolates (Thompson et al., 2024b; Baig et al., 2025). It is however important to consider socio-economic viability along with nutritional and functional characteristics even if interest in alternative protein crops has increased. Lupin is one example of such alternative protein crops. Although lupin-based ingredients /products are in high demand and provide huge market potential, lupin cultivation in Europe is insufficient to meet demand (Lee et al., 2023).

2.8. Role of non-protein ingredients

The formulation of plant-based meat analogues requires a sophisticated array of functional and sensory additives to replicate the complex organoleptic properties and nutritional characteristics of conventional meat products, as systematically detailed in **Table 2.2**. Fat systems represent a critical component where solid tropical fats derived from coconut and cocoa beans are strategically blended with liquid oils rich in unsaturated fatty acids, such as sunflower and canola oils, to engineer lipid matrices that closely approximate the mouthfeel, texture, and thermal behaviour of animal adipose tissue (Meena et al., 2022). The technical achievement of creating plant-based ground meat analogues involves the mechanical processing of these saturated-unsaturated oil blends into microscopic white fat globules through controlled whipping processes. This enables the visual and textural simulation of marbled ground beef and pork sausages while simultaneously incorporating specialized oils like avocado and sesame for enhanced nutritional profiles and flavor complexity, with the inherent absence of cholesterol in these vegetable oil systems providing superior cardiovascular health benefits compared to animal-derived fats (Meena et al., 2022). Color replication represents another critical formulation challenge addressed through biotechnological innovation, particularly the production of soy leg-hemoglobin, a genetically engineered heme-containing protein that replicates the characteristic "bloody" appearance and iron-rich flavor profile of meat-derived hemoglobin and myoglobin proteins.

Table 2.2: Summary of the ingredients of plant-based meat analogues with their functionality and sources

Ingredient	Sources	Functionality
Emulsion type products (sausages, frankfurters, bologna, mortadella, etc.)		
Protein	Soy protein, gluten, pea proteins, potato proteins	Binding water, stabilise emulsions and gels
Binders	Soy protein isolate, methylcellulose, carrageenan and modified starches	To improve the textural properties of the products, providing the desirable gelling and thickening, also contribute to emulsion stability, reducing oil leakage and purge loss
Fats	Soy, sunflower, rapeseed, canola, corn, palm, coconut and sesame oil	To improve juiciness, tenderness, and overall palatability of the emulsion-type products
Others	Colourants and spices	Providing aesthetic appeal and enhance flavor of the product
Burgers, Patties and Nuggets		
Proteins	Proteins based on soy, wheat, pea-protein and mixtures thereof	To give a meaty and chewy texture to the product, provide juiciness in the final product formulation, to retain water during storage and to release it upon heating and deformation
Binders	Egg protein, methylcellulose and wheat gluten	Binds the TVP and other ingredients together, improve texture and mouthfeel, improve water holding
Fats	Liquid or solid plant-based fat, emulsified or free fat, or a combination of liquid (such as sunflower and canola oil) and solid fats (like coconut or palm oils	To give the product a pleasant mouthfeel and juiciness
Others	Beetroot juice, new colour changing compounds, flavourings and aroma precursors.	To create the characteristic meat colour and juiciness, better juiciness and improving the appearance and taste of these products
Chicken-Like and Steak-Like Products		
Proteins	Soy protein isolates and concentrates, wheat gluten or carbohydrate fibres	For the formation of a multi-phase blend
Fats	Liquid vegetable oils	For the marbling effects
Others	Colouring agents and flavourings (including salt)	Improving visual appearance and flavor of the meat analogue

Source: Kyriakopoulou et al. (2021); Benković et al. (2023)

Alternative colouring strategies employ natural pigment extracts from red beet, red cabbage, red berries, paprika, and carrot to achieve the desired reddish hues in processed meat analogues (Fraser et al., 2018). Furthermore, specialized applications such as plant-based chicken products utilize titanium dioxide (TiO_2) as both a whitening agent to enhance the characteristic pale coloration and as a functional additive providing antimicrobial properties, demonstrating the multifunctional nature of modern food additives (Thompson et al., 2024b). The flavor enhancement systems in plant-based meat alternatives require significantly higher concentrations of taste-modulating compounds compared to conventional meat products. This necessitates the strategic incorporation of yeast extracts, nucleotides, sugars, and various umami-enhancing ingredients to compensate for the inherently bland flavor profiles of plant proteins (Benković et al., 2023). Complex spice and herb blends including black pepper, oregano, sage, rosemary, and clove are incorporated in the formulations to recreate the distinctive aromatic signatures of cooked sausages, patties, and other processed meat products. This serves the dual function of providing authentic meat-like sensory experiences while simultaneously masking the undesirable beany, grassy, or bitter off-flavors commonly associated with legume-derived protein isolates and concentrates (Benković et al., 2023).

2.9. Environmental benefits of meat analogue

The global food production system represents one of the most environmentally destructive anthropogenic activities, contributing approximately 30% of total greenhouse gas emissions and consuming between 70-85% of the world's freshwater resources through agricultural and livestock operations, as comprehensively illustrated in **Figure 2.4**. These environmental burdens can primarily be attributed to the resource-intensive nature of animal agriculture. This includes methane emissions from ruminant digestion, carbon dioxide releases from feed production and land-use changes, nitrous oxide emissions from fertilizer application and manure management, and the extensive water requirements for crop irrigation, livestock hydration, and processing operations (Smetana et al., 2015). Comparative life cycle assessments have consistently demonstrated that plant-based meat alternatives exhibit substantially reduced environmental footprints across multiple impact categories when compared to conventional animal meat production systems. These reductions manifest in lower greenhouse gas emissions per unit of protein produced, decreased land use requirements due to the elimination of feed conversion inefficiencies inherent in animal agriculture, reduced water consumption through the absence of livestock hydration needs and more efficient crop-to-food conversion ratios (Bohrer, 2019).

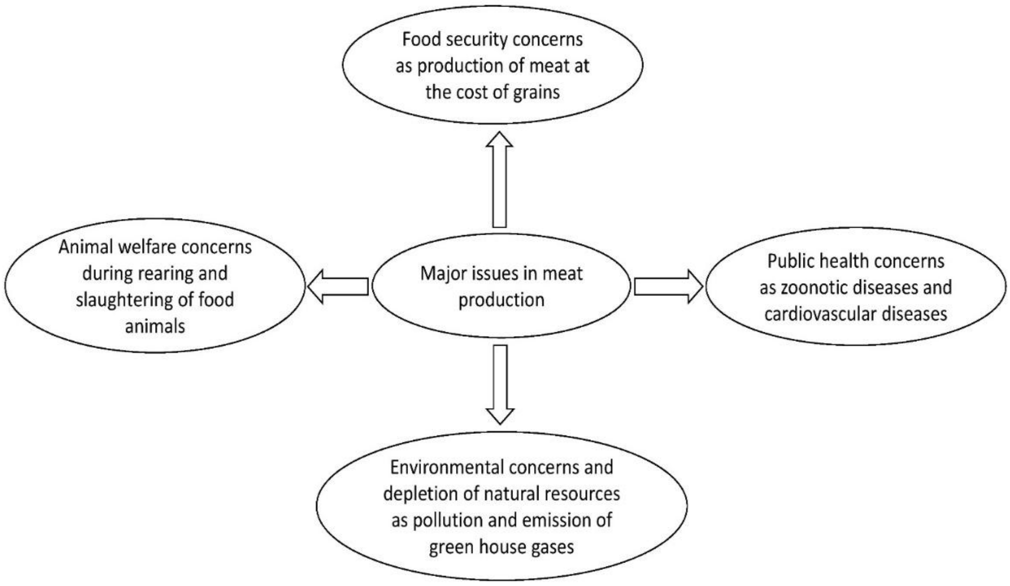

Figure 2.4: Issues related to the production of animal meat (*Source:* Post, 2012)

This also results in minimized eutrophication potential from reduced nitrogen and phosphorus runoff associated with concentrated animal feeding operations (Van Mierlo et al., 2022). The nutritional equivalency of many commercially available plant-based meat substitutes to their animal counterparts, as documented by multiple research project studies, suggests that these environmental benefits can be achieved without compromising dietary adequacy or consumer nutritional requirements, thereby presenting a viable pathway for sustainable food system transformation (Sturtewagen et al., 2016; Van Mierlo et al., 2022). Advanced mathematical modelling approaches, particularly linear programming optimization techniques, have been employed by researchers to quantitatively assess the potential environmental benefits of dietary transitions. These computational analyses consistently demonstrated that systematic reduction or elimination of animal meat products from food production systems (Post, 2012), could result in dramatic decreases in overall environmental impact. This also includes significant reductions in greenhouse gas emissions, water consumption, land use, and pollution loading, while simultaneously maintaining or improving nutritional outcomes through strategically well formulated plant-based meat alternatives (Djekic & Tomasevic, 2016).

2.10. Production of plant-based meat analogues

Plant-based meat alternatives are made from plant extracts and/or plant-derived ingredients to mimic and substitute meat. Traditionally, plant-based meat alternatives, otherwise known as mock meat, has been indispensable in Asian (vegetarian) cuisine. The different types (forms and ingredients) of meat analogues products available in the market are shown in **Figure 2.5.** This taxonomic framework illustrates the comprehensive classification system for meat analogues based on three primary categorization criteria: product form, product type, and main ingredient composition. The classification system divides meat analogues into three distinct product forms including chopped meat analogues that replicate ground or processed meat textures, whole muscle meat analogues designed to mimic intact muscle tissue structure, and minced meat analogues that simulate finely processed meat products (Kyriakopoulou et al., 2019). Within each form category, specific product types are identified, ranging from burgers, chops, and nuggets in the chopped category, to sausages, patties, meatballs, ham, ribs, and fish/seafood products across the whole muscle and minced categories, demonstrating the extensive variety of conventional meat products that can be replicated through plant-based technologies (Dekkers et al., 2018).

The ingredient classification reveals the diverse protein sources employed in meat analogue production, including traditional vegetable proteins derived from legumes and grains, emerging alternative proteins from insects and fungi, advanced biotechnology-derived proteins from microalgae cultivation, innovative cellular agriculture products from in vitro cell culture systems, and novel microbial proteins obtained from non-pathogenic bacterial fermentation processes (Dekkers et al., 2018). This comprehensive classification system reflects the rapid technological advancement and diversification within the alternative protein industry, encompassing both established plant-based approaches and some of the cutting-edge biotechnological innovations that are expanding the possibilities for sustainable meat alternatives (Kyriakopoulou et al., 2019; Bohrer, 2019; Dekkers et al., 2018). Rather than targeting these products solely at vegans or vegetarians, companies are developing plant-based meat alternatives mainly for flexitarians (who rarely eat meat and constitute a majority of the population). However, mimicking of conventional meat-like flavour, texture and sight may also appeal to non-vegetarians. The production process for plant-based meat alternatives has been around for a long time. Raw ingredients such as pea (*Pisum sativum*), wheat (*Triticum aestivum*), and soya beans (*Glycine max*) are processed to yield extracts and isolates that provide the main taste of plant-based meat alternatives (Thomson et al., 2024b). These derivatives are then subjected to processes to transform them into meat-like products.

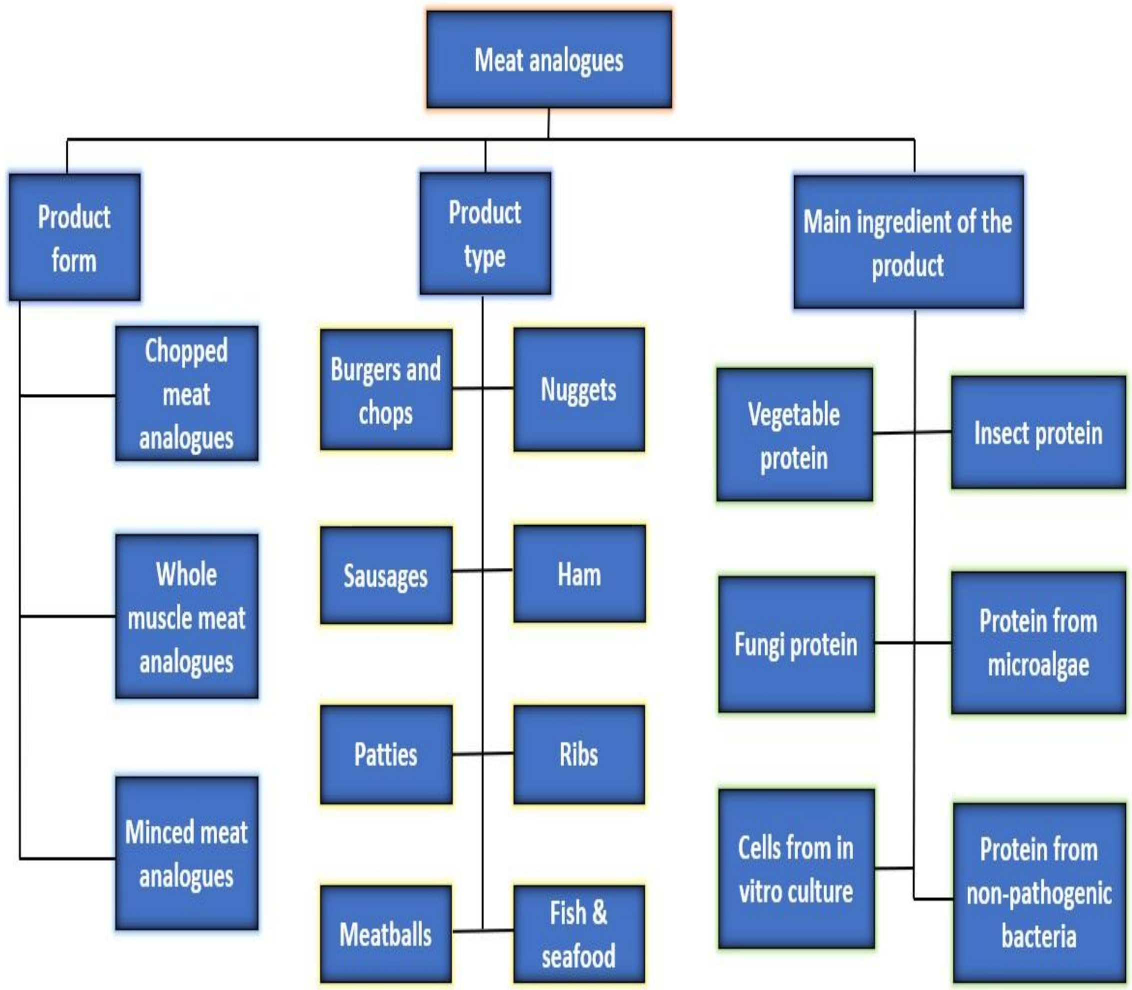

Figure 2.5: Different types of meat-analogue products (different forms and ingredients) available in the market along with their examples

Companies are inventing novel ingredient formulations and additives to enhance the flavour and appearance of the final product. For instance, the company Impossible Food has discovered that *heme*, a molecule responsible for the taste, colour, and iron content in meat. can be extracted from plants and simulate the meaty taste (Fraser et al., 2018). Novel micro extrusion techniques are also being developed to mimic the fibrous texture of real meat (Detzel et al., 2022). According to the Good Food Institute (GFI) report, the extrusion-based technique can be employed to produce plant-based whole-muscle meat alternative products (e.g., a chicken breast, a pork chop, a steak) and restructured meat alternative products (e.g., nuggets, patties, meatballs) using textured vegetable proteins (Tingle et al., 2023).

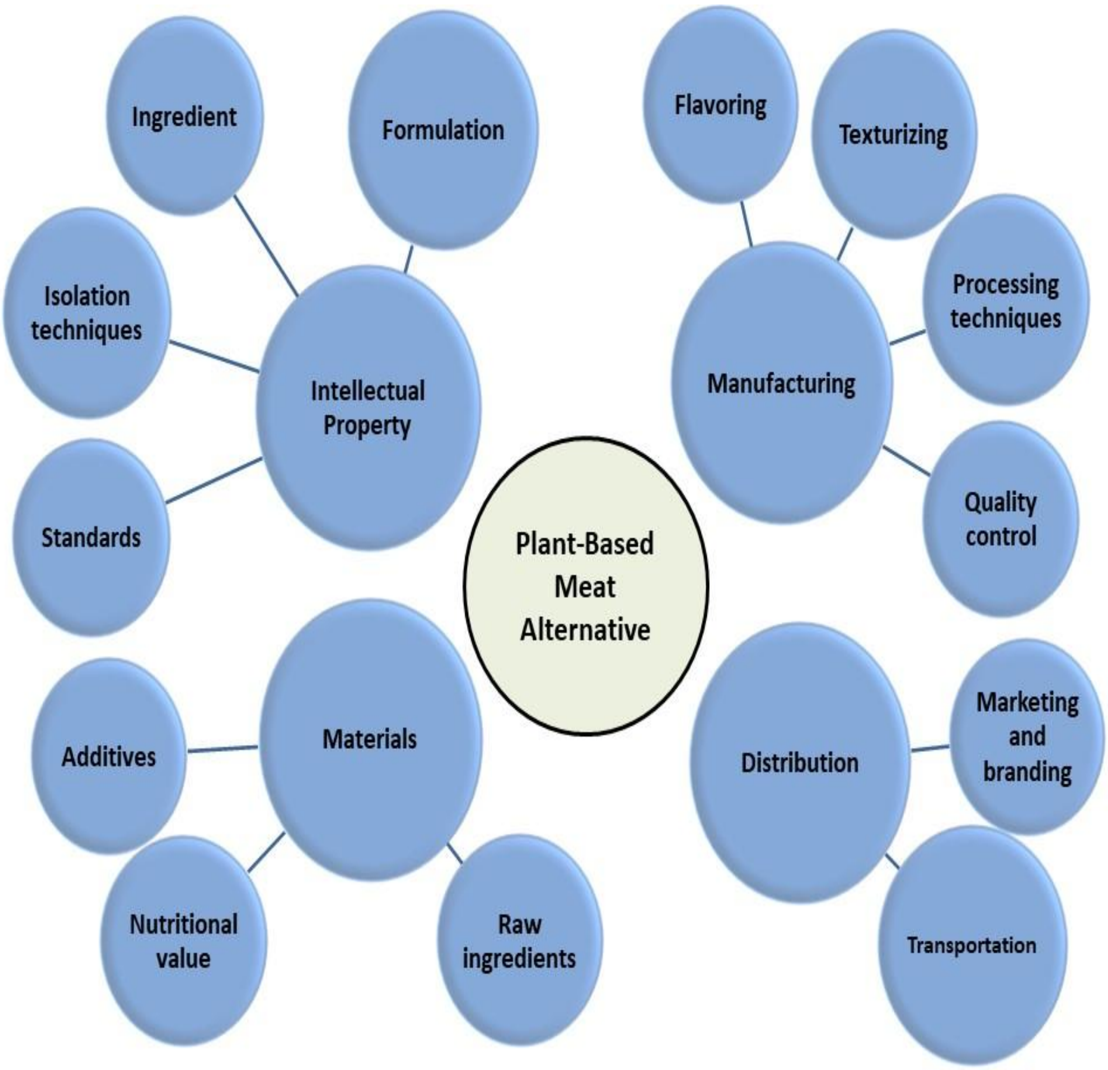

Figure 2.6: Value Chain Mapping of Plant-Based Meat Analogues (*Source:* Choudhury et al., 2020)

The whole industry value chain for plant-based meat alternatives is highlighted in **Figure 2.6**. This image illustrates the comprehensive ecosystem surrounding plant-based meat alternatives, showing the interconnected components essential for developing and commercializing these products (Boukid, 2021). The central concept of "Plant-Based

Meat Alternatives" is surrounded by key domains including intellectual property protection, materials sourcing (raw ingredients, additives, nutritional value), manufacturing processes (formulation, flavoring, texturizing, processing techniques, quality control), and market considerations (distribution, marketing and branding, transportation) (Kyriakopoulou et al., 2019). Each domain represents critical aspects that companies must address to successfully develop, produce, and market plant-based meat products that can compete with traditional animal-based alternatives in terms of taste, texture, nutritional value, and consumer acceptance (Choudhury et al., 2020; Boukid, 2021).

2.10.1. Processes for development of plant-based meat analogues

The development of meat alternatives with fibrous morphology employs various structuring techniques, each with distinct approaches to achieving meat-like texture and structure. The methodologies can be broadly categorized into bottom-up and top-down approaches, each offering unique advantages in replicating meat's complex architectural features **(Table 2.3)** (Boukid, 2021; Detzel et al., 2022; Tingle et al., 2023). In the bottom-up approach, researchers focus on designing and fabricating individual structural elements that serve as building blocks for the final product. This method requires precise control over the assembly process to ensure that each component contributes effectively to the overall structure (Baig et al., 2025). The alignment of these elements is particularly crucial, as it determines the product's structural anisotropy, a characteristic feature of natural meat tissue that influences both texture and mouthfeel (Detzel et al., 2022). Recent advances in this field have demonstrated that proper alignment can be achieved through various techniques, including shear cell technology and electrospinning. The top-down strategy, conversely, focuses on creating structures that mirror meat's organizational hierarchy at larger length scales, though they may not exactly replicate its microscopic features (Tingle et al., 2023). This approach often involves manipulating biopolymers through controlled processing conditions to achieve desired structural characteristics. The formation of these structures typically occurs through the strategic aggregation of biopolymers or their placement within anisotropic force fields (Martinez & Taylor, 2024). The selection and processing of biopolymers play a crucial role in both approaches.

Table 2.3: Types of meat analogue production technology with their associated advantages

Technology	**Type**	**Advantages**
Extrusion	Top-down strategy	-Higher productivity and lower costs -Highly versatile -Energy efficient process -Destruction or conversion of anti-nutritional factors -Enhancement of protein digestibility
High-temperature induced shearing	Top-down strategy	-Cost-effective -Produce defined fibrous structure
Wet-spinning	Bottom-up strategy	-Produce defined fibrous protein products
Electrospinning	Bottom-up strategy	-Cost-effective and scalable approach -Production of very thin fibrils
Freeze structuring	Top-down strategy	-Modulation of textural properties of plant proteins
Mixing plant proteins and hydrocolloids	Top-down strategy	-Formation of fibrous structure that can be modulated
Bioprinting (3D printing technology)	Top-down strategy	-Enable the design of products with texture similar to muscle fibers -Tailor the nutritional content of the product
In-vitro meat: cell culturing	Bottom-up strategy	-Less energy consumption than conventionally produced meat - Low emissions of greenhouse gases -Lower land and water use
Mycoprotein	Bottom-up strategy	-High in protein and fiber, and low in fat, cholesterol, sodium, and sugar -Low carbon and water footprint

(*Source:* Boukid, 2021)

Common biopolymers used include plant proteins (such as soy and pea proteins), cellulose derivatives, and various hydrocolloids (Lee et al., 2024). These materials can be manipulated through physical, chemical, or enzymatic treatments to achieve desired structural properties that resemble meat tissue (Lee et al., 2023).

2.10.1.1. Extrusion

Extrusion processing represents the predominant technological approach for transforming plant-based raw materials into fibrous, meat-like textured products through controlled thermomechanical treatment within specialized barrel-and-screw systems. Two distinct extrusion methodologies have been systematically classified based on moisture content parameters during processing. Low-moisture extrusion involves the mechanical processing of plant protein flours or concentrates into textured vegetable proteins (TVP) through controlled shear, temperature, and pressure applications (Lee et al., 2024). The resulting products exhibit dry, slightly expanded characteristics with reduced moisture content. These dehydrated textured products require subsequent rehydration processes to achieve desired texture and mouthfeel properties for final applications (Baig et al., 2025). High-moisture extrusion operates with substantially elevated water content, typically exceeding 50% by weight throughout the processing cycle. This methodology involves the systematic softening of protein matrices within the extruder barrel through integrated heating, hydration, and mechanical deformation processes (Lee et al., 2023). The plasticized protein 'melt' undergoes molecular alignment through inhomogeneous laminar flow patterns as the material advances toward the die exit. Controlled cooling mechanisms prevent thermal expansion, maintaining the desired fibrous structure integrity. High-moisture extrusion technology experienced intensive research and development during the 1980s and 1990s, establishing the fundamental processing parameters and equipment configurations that continue to inform contemporary plant-based meat production systems (Lee et al., 2023; Baig et al., 2025).

2.10.1.2. Freeze structuring

Texturization is a critical step in mimicking the fibrous structure of animal meat. Freeze structuring, an emerging technique, involves aligning protein fibers during the freezing process to create a layered, fibrous texture (Chantanuson et al., 2022). This method exploits the crystallization of ice during freezing to induce directional alignment in the protein matrix, resulting in a meat-like structure. Freeze structuring consists of freezing a protein emulsion in order to create a distinct fibrous structure. A porous and fibrous microstructure could be generated by the subsequent removal of ice crystals, which is similar to the muscles of animal meat and consisting of a number of parallel and highly connected sheet-like proteins (Detzel et al., 2022). The protein source used for the manufacture of meat analogues is mainly responsible for the formation of a fibrous structure using the freeze structuring technique. Hydration & solubility, gelation & texture formation are some of the distinct structure-function interactions that control the ultimate structure of the meat analogue and they could be different for different proteins (Thompson et al., 2024b). For Manila tamarind protein, freeze structuring can be optimized by adjusting parameters such as freezing rate, protein concentration, and the presence of cross-linking agents. Slow freezing allows for the formation of larger ice crystals, which in turn create well-defined channels and alignments within the protein matrix. Cross-linking agents like transglutaminase can further enhance the structural stability of the texturized protein.

2.11. Flavor and colour development in texturized protein

Flavor and color constitute the fundamental sensory determinants that dictate the commercial success of plant-based meat analogues, requiring precise replication of both the textural characteristics and comprehensive sensory profiles of conventional animal meat products to achieve consumer acceptance and market viability (Dekkers et al., 2018). The development of authentic meat-like sensory experiences necessitates the strategic integration of multiple biochemical processes, including enzymatic hydrolysis utilizing proteolytic enzymes such as bromelain to generate savory peptide fragments and amino acids that contribute to umami taste sensations. Heat-induced chemical transformations, particularly the Maillard reaction between reducing sugars and amino acids, produce complex melanoidin compounds and volatile aldehydes, pyrazines, furans, and thiazoles that generate the characteristic roasted, grilled, and caramelized flavor notes associated with cooked meat. Plant-derived colorant systems, including beetroot juice anthocyanins and tea extract polyphenols, provide natural pigmentation that mimics the reddish-brown hues of cooked animal muscle tissue (Shahidi & Hossain, 2022). These integrated approaches enable the formulation of plant-based products that closely approximate the multisensory experience of consuming animal meat, encompassing visual appearance, aromatic compounds, taste sensations, and textural properties (He et al., 2020).

Advanced analytical methodologies, including gas chromatography-mass spectrometry for volatile compound profiling, high-performance liquid chromatography for non-volatile flavor analysis, and instrumental color measurement systems, ensure precise characterization and optimization of these sensory attributes. This systematic approach facilitates the development of commercially viable plant-based meat analogues that satisfy the expanding consumer demographic seeking sustainable protein alternatives without compromising sensory satisfaction (Bohrer, 2019). The flavor complexity of conventional meat products arises from an intricate matrix of volatile and non-volatile chemical compounds, including heterocyclic aromatics, sulfur-containing compounds, fatty acid derivatives, and Strecker aldehydes. These compounds are generated through thermal degradation of proteins, lipids, and carbohydrates during cooking processes (Shahidi & Hossain, 2022). Successful replication of these complex flavor profiles in plant-based systems requires the systematic simulation of these chemical compounds through controlled processing techniques. Plant-based meat analogues must therefore incorporate sophisticated flavor development strategies to recreate the rich, savory, and umami-rich taste characteristics that define meat products (Kyriakopoulou et al., 2019). Multiple technological approaches can be employed to achieve authentic meat-like flavors, including controlled enzymatic hydrolysis of plant proteins to generate flavor precursors, optimization of Maillard reaction conditions to produce desirable volatile compounds, and implementation of various thermal processing techniques that promote the formation of meat-characteristic flavor molecules.

2.11.1. Enzyme-based flavor development (Bromelain hydrolysis)

Bromelain-mediated enzymatic hydrolysis represents a revolutionary approach to flavor enhancement in plant-based proteins. This would help in leveraging the sophisticated biochemical mechanisms of this pineapple-derived protease enzyme to address one of the most challenging aspects of meat analogue development, the creation of authentic savory flavors that satisfy consumer expectations and drive market acceptance (Maurer, 2001). The fundamental mechanism underlying bromelain's effectiveness lies in its ability to systematically cleave peptide bonds within plant protein structures. This helps in breaking down complex protein molecules into progressively smaller peptides and ultimately into individual amino acids, a process that fundamentally transforms the flavor profile by liberating taste-active compounds that would otherwise remain bound within the protein matrix (Fu et al., 2025). This enzymatic hydrolysis is particularly significant because it mimics natural meat aging and fermentation processes that occur in animal proteins, where endogenous enzymes similarly break down muscle proteins post-mortem. It releases the characteristic savory compounds that define meat flavor, thereby providing a biologically relevant pathway for plant-based systems to achieve comparable flavor development (Larocca et al., 2010).

The controlled hydrolysis conditions, encompassing precise temperature regulation (typically 37-50 °C), optimal pH maintenance (usually 7.0-8.0), and carefully timed reaction periods (ranging from 30 min to several hours), are critical parameters that determine both the extent of protein breakdown and the specific profile of released flavor compounds. These conditions require optimization for each plant protein source to maximize flavor development while preventing over-hydrolysis that could produce bitter peptides or destroy desirable flavor precursors (Arshad et al., 2018). The flavor enhancement mechanism is particularly effective because bromelain hydrolysis selectively releases key amino acids such as glutamic acid and aspartic acid, which serve as primary contributors to umami taste. It is the fifth basic taste that provides the characteristic "meaty" or savory sensation that consumers associate with animal proteins. Glutamate is especially important as it directly activates umami taste receptors and creates the foundational savory notes that distinguish meat from other protein sources (Larocca et al., 2010; Sun, 2011). Beyond individual amino acid release, the hydrolysis process generates a complex mixture of bioactive peptides of varying chain lengths. Each one contributes towards unique flavor characteristics that collectively enhance the overall taste complexity and depth, creating a multi-dimensional flavor profile that more closely approximates the sophisticated taste experience of animal meat compared to unhydrolyzed plant proteins (Adler-Nissen, 1986).

The strategic advantages of bromelain hydrolysis extend well beyond simple flavor improvement. It offers the manufacturers with unprecedented control over flavor intensity and profile customization through manipulation of hydrolysis parameters. It enables the development of differentiated products targeting specific meat categories (beef, pork, chicken, seafood) or regional flavor preferences, while also providing a natural, clean-label solution that aligns with consumer demands for recognizable, plant-derived ingredients rather than synthetic flavor compounds (Das et al., 2021). The process versatility is particularly valuable in commercial applications, as manufacturers can adjust enzyme concentration, reaction time, and environmental conditions to achieve varying degrees of hydrolysis. It can vary from mild treatments that provide subtle flavor enhancement while maintaining protein functionality, to extensive hydrolysis that maximizes umami development for applications requiring intense savory characteristics, thereby offering a scalable platform for diverse product development strategies. Furthermore, the controllable nature of enzymatic hydrolysis allows for the development of standardized flavor profiles that can be consistently reproduced across production batches (Arshad et al., 2018).

It thereby helps in addressing one of the key challenges in plant-based meat production where flavor consistency is critical for consumer acceptance and brand loyalty. It also enables the creation of proprietary flavor signatures that can differentiate products in the competitive alternative protein market (Vargas-Madriz et al., 2020). The economic implications of bromelain-based flavor enhancement are equally significant, as this approach potentially reduces dependence on expensive flavor masking agents, artificial flavor compounds, and complex seasoning blends traditionally used to improve plant protein palatability. And it can simultaneously add functional value to products through improved protein digestibility and bioavailability that results from the pre-digestion effect of enzymatic hydrolysis. It would help in creating a dual-benefit system that enhances both sensory and nutritional attributes of the final product, ultimately supporting the commercial viability and consumer acceptance of plant-based meat alternatives in mainstream food markets (Dekkers et al., 2018).

2.11.2. Maillard reaction and heat-induced flavor development

Another critical process in flavor development for meat analogues is the Maillard reaction, a non-enzymatic reaction between reducing sugars (e.g., glucose, fructose) and amino acids that occurs under heat (Tamanna & Mahmood, 2015). This reaction leads to the formation of a wide array of flavor compounds that contribute to the characteristic "roasted" or "grilled" flavors associated with cooked meat (Mottram, 1998). In meat analogues, the Maillard reaction can be triggered by applying heat to the texturized protein, often in combination with sugars or amino acids that naturally exist in the protein (Kyriakopoulou et al., 2019). The intensity and profile of the Maillard reaction can be controlled by adjusting cooking temperatures, pH, and the presence of reducing sugars (van Boekel, 2006). The Maillard reaction plays a crucial role in developing the sensory characteristics of meat analogues, with several key factors requiring careful consideration (Hellwig & Henle, 2014). This chemical process generates a diverse spectrum of flavors ranging from sweet and nutty to savory and roasted, with the specific flavor profile determined by the particular combination of amino acids and sugars present in the reaction (Jaeger et al., 2010). Beyond flavor development, the Maillard reaction is responsible for the characteristic browning that occurs during cooking, which serves as both a flavor indicator and an essential visual element that enhances the meat-like appearance of the final product (Martins et al., 2000).

However, while this reaction can significantly enhance flavor characteristics, it requires precise control as it can potentially produce unwanted bitter or acrid notes (Ames, 1998). Therefore, careful monitoring and adjustment of reaction conditions are essential to ensure the development of desirable flavors while avoiding these negative byproducts (Parker, 2015). By combining enzymatic hydrolysis (e.g., using bromelain) and heat-induced Maillard reactions, it is possible to develop a robust, meat-like flavor profile in the modified proteins (Ismail et al., 2020). These processes mimic the flavor formation mechanisms that occur during the cooking of animal meat, making the final product more appealing to consumers (Elmore & Mottram, 2009). In practice, flavor development in meat analogues often involves a combination of enzymatic and heat-based methods (Paredi et al., 2018). For example, bromelain hydrolysis can be applied first to enhance the umami flavor, followed by a controlled Maillard reaction to further develop roasted and savory notes (Wang et al., 2018). These two processes complement each other, with enzymatic hydrolysis breaking down proteins into flavor-rich components and the Maillard reaction adding complexity and depth to the flavor profile (Das et al., 2021).

2.11.3. Color development in texturized protein

The color of meat is another sensory attribute that plays a crucial role in consumer acceptance. Animal meat typically has a red to brown color that is influenced by the presence of myoglobin and haemoglobin, which contain iron and contribute to the red and pink hues in raw meat. When meat is cooked, the myoglobin undergoes changes in its structure, resulting in browning, which further adds to the visual appeal. To mimic the color of meat, plant-based meat analogues require the addition of colorants and the stimulation of natural color development through various processes (Muhialdin et al., 2024). Plant-based colorants have emerged as effective solutions for achieving meat-like appearance in alternative protein products (Lee et al., 2024). Natural pigments, including beetroot juice, tea extract, and other plant-derived compounds, can be successfully incorporated into texturized protein to replicate the visual characteristics of conventional meat. These plant-derived pigments, particularly betalains from beetroot and anthocyanins from tea, provide a spectrum of rich red, purple, and brown hues that effectively mimic the coloration observed in both raw and cooked animal meat (Detzel et al., 2022; Thompson et al., 2023).

Beetroot juice, containing heat-stable betalains, has proven particularly effective in imparting red or purple coloration to plant-based proteins, making it an ideal choice for meat analogues that undergo thermal processing (Wilson & Roberts, 2024). Similarly, tea extract, especially from black tea varieties, contains anthocyanins and polyphenols that produce appealing brown to reddish-brown shades upon heating, closely resembling the color transformation seen in cooked meat (Muhialdin et al., 2024). These natural colorants can be integrated through various methods, including direct incorporation into the protein matrix or application as coatings and marinades during texturization and cooking processes. The versatility of these plant-derived colorants allows manufacturers to fine-tune both concentration and application methods to achieve specific color intensities and appearances (Lee et al., 2023).

2.11.4. Heat-induced browning (Maillard reaction)

As mentioned earlier, the Maillard reaction is not only crucial for flavor development but also plays a significant role in the browning of meat during cooking. This reaction contributes to the characteristic brown color of cooked meat, and it can be replicated in meat analogues by controlling the cooking conditions (Muhialdin et al., 2024). The Maillard reaction, which occurs between reducing sugars and amino acids, leads to the formation of brown pigments known as melanoidins. These pigments contribute to the "grilled" or "roasted" appearance that is often associated with cooked meat (Wang et al., 2018). By controlling the temperature, pH, and time during the cooking process, the intensity of the Maillard reaction can be fine-tuned to produce a desirable brown color that closely matches the appearance of cooked animal meat (Ismail et al., 2020).

2.11.5. Combination of plant-derived colorants and Maillard reaction

A combination of plant-derived colorants (e.g., beetroot juice, tea extract) and the Maillard reaction can be employed to achieve both color and flavor development simultaneously in meat analogues (He et al., 2020). The visual appearance of meat alternatives is critical for consumer acceptance, with color being one of the most immediately perceived sensory attributes that influences purchasing decisions (Spence, 2018). Natural plant-derived colorants offer significant advantages over synthetic alternatives, as they align with clean-label trends and consumer preferences for minimally processed foods (Asioli et al., 2017). Beetroot extract (*Beta vulgaris*) provides deep red hues due to its high concentration of betalains, making it particularly suitable for mimicking the color of raw beef or pork products (Delgado-Vargas et al., 2000). The water-soluble nature of these pigments allows for uniform incorporation throughout the protein matrix, resulting in consistent coloration. Similarly, tea extracts, particularly those derived from black tea (*Camellia sinensis*), contain theaflavins and thearubigins that impart reddish-brown tones reminiscent of cooked meat when incorporated into protein systems (Imram, 1999). The addition of these colorants enhances the visual appeal of the protein, while the Maillard reaction contributes to the desired browning and roasted appearance (Martins et al., 2000).

The stability of plant-derived colorants under processing conditions presents technical challenges that must be addressed for successful application in meat analogues (Cortez et al., 2017). Betalains from beetroot are particularly sensitive to heat, light, and pH variations, potentially degrading during high-temperature processing (Stintzing & Carle, 2004). To mitigate this issue, microencapsulation techniques can be employed to protect these sensitive pigments during processing, ensuring color retention in the final product. Additionally, the combination of multiple color sources can create more nuanced and stable coloration; for instance, blending beetroot extract with carrot concentrate (rich in carotenoids) provides a spectrum of red-orange hues with improved stability during thermal processing (Rodriguez-Amaya, 2016). Anthocyanins from black rice or purple sweet potato offer another promising alternative, providing vibrant purple-red colours that can simulate the appearance of rare to medium-cooked meat products (Khoo et al., 2017).

The timing of colorant addition is crucial for optimal results, with incorporation typically occurring during the early stages of formulation to ensure uniform distribution throughout the protein matrix (Gómez et al., 2020). When plant-derived colorants are applied in conjunction with the Maillard reaction, a synergistic effect occurs that enhances both appearance and flavor (Hellwig & Henle, 2014). The Maillard reaction products not only contribute caramel and roasted notes but also provide additional brown coloration that complements the base color provided by plant extracts (Martins et al., 2001). By carefully balancing the use of these methods through precise formulation and processing parameters, it is possible to create a meat analogue that mimics both the color and flavor of animal meat, improving its sensory characteristics and consumer acceptance (Dekkers et al., 2018; Kyriakopoulou et al., 2019). This multi-faceted approach to color and flavor development represents a significant advancement in addressing the sensory challenges associated with plant-based meat alternatives, potentially accelerating their adoption among mainstream consumers seeking more sustainable protein options (Bohrer, 2019; Ismail et al., 2020).

2.12. Standardization of the cooking process for the developed meat analogue

In the development of meat analogues, the cooking process plays a pivotal role in determining the final product's sensory qualities (Betoret & Rosell, 2020). The ability to replicate the cooking behaviour of animal meat, particularly in terms of texture, moisture retention, and browning is crucial for achieving a meat analogue that can perform similarly to conventional meat during food preparation (Kyriakopoulou et al., 2019). The cooking process of meat analogues encompasses various methods such as frying, grilling, baking, and boiling, each of which has a distinct impact on the final product's appearance, texture, moisture content, and flavor (Kyriakopoulou et al., 2021). A standard cooking process must be established to ensure consistency across batches of the meat analogue and to allow for comparisons with traditional animal meat products (Ismail et al., 2020). The standardization of the cooking process for the Manila tamarind-based meat analogue involves optimizing cooking parameters such as temperature, time, and moisture control to ensure a consistent product (Osen et al., 2014). By comparing the cooking quality of the Manila tamarind-based analogue with soy-based meat analogues, insights can be gained into its potential for consumer acceptance (Smetana et al., 2015). Sensory attributes such as texture, moisture retention, juiciness, and color are crucial in this evaluation, as they directly influence the product's resemblance to animal meat (Grahl et al., 2018). Through these experiments and comparative analyses, the Manila tamarind-based meat analogue can be refined and positioned as a viable alternative in the growing market for plant-based meats (Bohrer, 2019; Kyriakopoulou et al., 2019).

2.12.1. Selection of cooking methods

The standardization of cooking processes for meat analogues begins with the careful selection of appropriate cooking methods (Tingle et al., 2023). For meat analogues based on novel protein sources like Manila tamarind seed protein, cooking methods must be thoroughly evaluated for their capacity to enhance texture, flavor, and color development (Lee et al., 2023). Several cooking techniques have proven effective in plant-based meat preparation, each offering distinct advantages in achieving meat-like characteristics (Martinez & Taylor, 2024). Deep frying or pan frying represents one of the most widely used approaches, as it creates a desirable crispy exterior while promoting flavor development through the Maillard reaction, simultaneously enhancing the product's meat-like appearance through surface browning (Lee et al., 2024). Baking has emerged as another valuable method in plant-based product preparation, particularly for its ability to ensure uniform cooking and superior moisture retention, resulting in products with an appealing golden-brown color and firm yet moist texture, characteristics especially important for items like nuggets or patties (Kumar et al., 2017).

Microwave cooking has gained significant attention as a convenient method for preparing meat analogues, though it presents unique challenges in achieving desired texture and browning (Parker & Roberts, 2023). Recent developments in microwave-specific formulations and packaging have helped address these limitations, enabling better moisture distribution and textural development during microwave heating (Zhang et al., 2023b). Grilling contributes unique sensory attributes, including distinctive smoky flavors and characteristic grill marks, making it particularly suitable for meat analogues intended to replicate grilled meat products (Chen et al., 2023). The high temperatures involved in grilling promote surface browning and enhanced flavor development through Maillard reaction mechanisms (Thompson et al., 2023). For optimal results in developing meat analogues, a combination of these cooking techniques may be evaluated, with emphasis on their ability to replicate the sensory qualities of traditional cooked meat, prioritizing methods that achieve an optimal balance of texture, moisture retention, and flavor development (Wilson & Kumar, 2024).

2.12.2. Temperature, time, and moisture control

The optimization of key parameters including temperature, cooking time, and moisture content is fundamental in standardizing the cooking process for meat analogues (Tingle et al., 2023). These critical factors significantly influence the final product's texture and overall quality, particularly in controlling browning through Maillard reaction, texture development, and moisture retention (Muhialdin et al., 2024). Temperature control plays a vital role in ensuring proper heat penetration throughout the product, as excessive temperatures can lead to moisture loss and tough texture, while insufficient heat fails to achieve proper texture development and browning characteristics (Martinez & Taylor, 2024). The precise management of cooking time is equally crucial, requiring careful balance to achieve optimal internal temperature without compromising quality (Johnson et al., 2007). Research has shown that overcooking can result in excessive moisture loss and nutritional degradation, while insufficient cooking time may impede proper texture and flavor development. Moisture retention represents another critical factor in the cooking process, particularly for products designed to replicate specific meat cuts. To achieve satisfactory mouthfeel, meat analogues must maintain appropriate internal moisture levels throughout the cooking process (Thompson et al., 2024b). Cooking methods that facilitate superior moisture retention, such as humidity-controlled baking or grilling, often yield better results, while properly controlled frying with appropriate coating techniques can also effectively preserve moisture while preventing excessive oil absorption (Lee & Wilson, 2023).

2.13. Comparative study of cooking quality with soy-based meat analogues

Soy-based meat analogues have been widely used as a benchmark for the development of plant-based meat products, serving as a reference point due to their established functionality and consumer acceptance. Soy protein, particularly textured vegetable protein (TVP), is a common choice for simulating the texture of meat due to its fibrous structure and ability to absorb water and oil, which are essential for mimicking the juiciness and mouthfeel of conventional meat (Kyriakopoulou et al., 2019; 2021). These properties enable soy-based products to closely replicate the sensory and cooking characteristics of meat, making them an ideal standard for comparison. For this reason, comparing the cooking quality of the Manila tamarind-based meat analogue with soy-based analogues provides valuable insights into its performance and viability in the plant-based food market, offering a critical perspective on whether the alternative source can meet or exceed the expectations established by soy-based benchmarks.

2.13.1. Comparison of texture

The texture of meat is one of the most important sensory attributes in consumer preference (Dekkers et al., 2018). Animal meat typically has a firm yet tender texture with fibrous strands that provide chewiness, which is challenging to replicate in plant-based alternatives (Ismail et al., 2020). To evaluate the textural quality of the Manila tamarind-based meat analogue, a sensory analysis can be performed using trained panels or consumer testing methodologies such as descriptive analysis, preference mapping, or acceptance testing (Meilgaard et al., 2016). These methodologies enable systematic characterization of multiple textural parameters, including hardness, cohesiveness, springiness, and chewiness, which collectively determine the overall mouthfeel experience (Bourne, 2002). The texture can be compared to that of soy-based meat analogues using several parameters established in the literature as critical for meat-like perception (Schreuders et al., 2019). Firmness is a critical attribute, especially for products designed to replicate meat cuts such as steaks or patties (Nishihara et al., 2020).

Inadequate firmness can lead to products that are perceived as mushy or lacking structural integrity during cooking and consumption (Pietsch et al., 2021). Both soy and Manila tamarind-based analogues should be tested for their ability to provide a similar level of firmness, using texture analysis tools such as a texture profile analyser (TPA) which can quantitatively measure parameters including hardness, cohesiveness, and resilience under controlled conditions (Chen et al., 2023). The fibrous texture and mouthfeel of meat are important for consumer acceptance, as they contribute significantly to the perception of authenticity in meat alternatives (Fraeye et al., 2020). The Manila tamarind-based analogue should be assessed for its ability to provide a similar chewiness and mouthfeel to soy-based meat, which is often achieved by texturizing soy protein through extrusion or other mechanical processes (Samard & Ryu, 2019; Kyriakopoulou et al., 2021).

2.13.2. Moisture retention and juiciness

Moisture retention is crucial for both the texture and juiciness of plant-based meat analogues (Betoret & Rosell, 2020). Animal meat contains a significant amount of water, which contributes to its juiciness and mouthfeel during cooking, with typical moisture content ranging from 65-75% depending on the cut and species (Huff-Lonergan & Lonergan, 2005). Similarly, meat analogues must retain moisture to provide a satisfying eating experience that closely mimics conventional meat products (Wild et al., 2014). The ability of plant proteins to bind and retain water during thermal processing is influenced by several factors, including protein concentration, pH, ionic strength, and the presence of other ingredients such as hydrocolloids or fibers (Wong et al., 2020). A comparative study can be conducted to assess moisture retention during different cooking processes (frying, baking, grilling) for both the Manila tamarind and soy-based analogues using standardized cooking protocols that control for variables such as temperature, time, and cooking medium (Sun et al., 2018).

Moisture loss can be measured by weight loss during cooking, and the juiciness of the final product can be assessed through sensory evaluation using trained panels or instrumental methods that correlate with perceived juiciness (Barbut, 2015). Techniques such as water-holding capacity (WHC) determination, expressible moisture measurement, and nuclear magnetic resonance (NMR) relaxometry provide valuable information about water distribution and mobility within protein matrices (Bertram et al., 2002). A product that retains moisture and exhibits juiciness is more likely to resemble animal meat, increasing consumer satisfaction and potentially driving repeat purchases (Hoek et al., 2011).

2.13.3. Color and appearance

Color is another important attribute for the acceptance of meat analogues, serving as a visual cue that significantly influences consumer expectations about taste and quality (Spence, 2018). Animal meat undergoes a color change when cooked, with raw meat being pink or red due to myoglobin and cooked meat ranging from brown to gray as a result of protein denaturation and the Maillard reaction (Suman & Joseph, 2013). A comparative study of the color development in the Manila tamarind-based and soy-based meat analogues will be conducted, focusing on how each product reacts during cooking processes such as frying, baking, or grilling (He et al., 2020). The development of color during cooking is a complex process involving both enzymatic and non-enzymatic browning reactions, with the latter being particularly important for creating the characteristic appearance of cooked meat (Martins et al., 2000). Both the Maillard reaction and the presence of plant-derived colorants (e.g., beetroot juice, tea extract) will contribute to the color development in the Manila tamarind-based analogue, with each component playing a distinct role in achieving the desired visual effect (Delgado-Vargas et al., 2000; Stintzing & Carle, 2004). The color of the cooked product can be measured using colorimeters or spectrophotometers that quantify parameters such as L^* (lightness), a^* (redness), and b^* (yellowness) values according to the CIELAB color space system (Pathare et al., 2013). These measurements can then be analysed using multivariate statistical methods to determine similarities and differences between samples. The results can be compared with soy-based analogues to determine how closely each mimics the color of animal meat, with particular attention to the development of a desirable surface browning that signals proper cooking to consumers (Dekkers et al., 2018).

2.14. Performance of plant-based meat analogue in different cooking conditions

Comprehensive evaluation of plant-based meat analogues requires systematic assessment across multiple thermal processing methods to characterize their culinary performance and consumer acceptability parameters. Frying, baking, grilling, and microwave cooking represent distinct thermal processing environments that each impart unique textural, flavor, moisture, and color characteristics to plant-based meat products (Osen et al., 2014). Each cooking methodology generates specific physicochemical transformations that influence the final product's sensory attributes through differential heat transfer mechanisms, moisture migration patterns, and surface browning reactions (Grahl et al., 2018). Frying processes utilize high-temperature oil immersion or contact heating to create characteristic crispy surface textures while simultaneously promoting golden-brown color development through enhanced Maillard reaction kinetics between reducing sugars and amino acids present in the protein matrix (Onwulata & Tomasula, 2010). The frying methodology provides critical assessment parameters for evaluating moisture retention capabilities within the protein structure while achieving desired textural contrast between crispy exterior surfaces and tender interior regions. Heat-induced flavor development during frying occurs through complex thermal degradation reactions that generate volatile aromatic compounds, lipid oxidation products, and caramelization byproducts that enhance overall palatability and meat-like sensory characteristics (Tamanna & Mahmood, 2015).

Baking processes offer controlled thermal environments with moderate temperature conditions that facilitate uniform heat penetration while maintaining moisture retention through reduced surface dehydration rates. This cooking method enables systematic evaluation of color development through controlled Maillard browning reactions while preserving internal moisture content and achieving golden-brown surface coloration (Betoret & Rosell, 2020). The baking process allows comprehensive assessment of textural development, specifically the ability to maintain moist interior characteristics while developing firm yet tender bite properties that approximate conventional meat texture profiles (Ismail et al., 2020). Grilling processes introduce distinctive flavor enhancement through direct high-temperature surface contact that generates characteristic smoky flavors, creates visual grill mark patterns, and promotes intensive Maillard reaction development at surface contact points. The grilling methodology intensifies brown pigment formation and roasted flavor compound generation through concentrated heat application and surface dehydration effects that concentrate flavor precursors and promote complex thermal reaction cascades (van Boekel, 2006). Systematic evaluation of plant-based meat analogues through grilling processes enables comprehensive assessment of their capacity to develop authentic meat-like visual appearance, aromatic profiles, and textural characteristics that contribute to consumer acceptance and culinary versatility (He et al., 2020).

2.15. Development of plant-based meat analogue products

The development of food products from plant-based meat analogues has become a focal point in food science and technology, particularly as the global demand for sustainable and ethical protein alternatives continues to grow. Among the diverse range of applications, the transformation of meat analogues into convenient and culturally familiar products such as chaap and nuggets has received increasing attention. These food formats are widely consumed and well-accepted across various demographic groups, making them ideal candidates for plant-based reformulations. The preparation of such products involves not only the incorporation of meat analogues but also the optimization of ingredients, processing conditions, and sensory characteristics to achieve desirable quality attributes comparable to those of conventional meat-based counterparts (Joshi & Kumar, 2015; Kyriakopoulou et al., 2021). The formulation of protein spiral wraps and nuggets from meat analogues typically begins with the selection of a suitable plant-based protein matrix. Textured vegetable protein (TVP), often derived from soy, wheat gluten, or pea protein, is commonly used due to its fibrous structure, high protein content, and ability to retain water and fat during cooking (Dekkers et al., 2018). However, the exploration of novel and underutilized plant sources such as Manila tamarind offers unique opportunities for enhancing the nutritional profile, flavor, and functional attributes of the final products. The use of such ingredients not only contributes to dietary diversity but also supports the valorization of agricultural by-products and indigenous crops (Kyriakopoulou et al., 2021).

In the case of Manila tamarind-based meat analogues, their successful application in food product development necessitates comprehensive characterization in terms of moisture retention, binding ability, oil absorption, and flavor development during cooking. The preparation of protein spiral wraps and nuggets involves a combination of thermal and mechanical processing, including blending, shaping, coating (in the case of nuggets), and cooking methods such as steaming, frying, or baking. Each step affects the final product quality and must be optimized to ensure desirable textural and sensory properties. For example, binding agents such as starches, hydrocolloids, and plant fibers are often incorporated to improve the structural integrity and cohesiveness of the meat analogue matrix (Asgar et al., 2010). In nuggets, breading and batter systems are critical for providing a crispy outer layer and influencing oil uptake during frying. The texture, juiciness, and mouthfeel of the cooked product are major determinants of consumer acceptability, and these characteristics are influenced by the protein source, processing method, and formulation components (Asgar et al., 2010; Kumar et al., 2017).

Characterization of the prepared products involves a range of physicochemical and sensory evaluations. Physicochemical analysis includes the determination of moisture content, cooking yield, water-holding capacity, oil absorption, color values ($L*$, $a*$, $b*$), and texture profile analysis (TPA), which assesses parameters like hardness, cohesiveness, springiness, and chewiness (Dekkers et al., 2016; 2018). These parameters help assess the technological functionality of the plant-based matrix and its ability to mimic meat. Sensory analysis, often conducted through structured panel evaluations, assesses attributes such as appearance, flavor, aroma, texture, and overall acceptability. Consumer preference studies may also be employed to understand market readiness and potential acceptance of the developed products (Smetana et al., 2015). In addition, nutritional analysis is essential to ensure that the products meet dietary standards for protein content, fat composition, fiber, and caloric value. Studies have shown that well-formulated plant-based nuggets and protein spiral wraps can achieve high levels of consumer acceptability when they successfully mimic the sensory and functional traits of traditional meat products (Kyriakopoulou et al., 2021). Moreover, the successful integration of novel ingredients like Manila tamarind can add unique value in terms of antioxidant activity, fiber content, and bioactive compounds, potentially offering health benefits alongside sustainability (Dekkers et al., 2018). Therefore, the objective of preparing chaap and nuggets from Manila tamarind-based meat analogues and characterizing them aligns with ongoing research and development efforts to create innovative, nutritious, and culturally relevant plant-based meat alternatives that appeal to a wide range of consumers and contribute to global food system sustainability.

In summary, the standardization of the cooking process for the Manila tamarind-based meat analogue is a critical step in ensuring product consistency, quality, and consumer satisfaction. This process involves fine-tuning key cooking parameters such as temperature, time, and moisture control, all of which significantly influence the final product's texture, flavor, and structural integrity (Bohrer, 2019). Proper optimization of these factors ensures that the analogue develops a meat-like appearance and mouthfeel while maintaining nutritional stability and safety during preparation. Furthermore, comparative analysis with established soy-based meat analogues, which are widely recognized for their successful mimicry of animal meat, provides valuable benchmarks for evaluating the cooking performance and consumer potential of the Manila tamarind-based variant. By assessing critical sensory attributes, including texture, juiciness, moisture retention, and color, researchers can determine how closely the developed product replicates the desirable qualities of animal-derived meats, which is essential for consumer appeal and market competitiveness (Hoek et al., 2011; Dekkers et al., 2018).

These sensory characteristics are pivotal, as they often drive purchasing decisions and influence perceptions of quality and authenticity in plant-based products. Moreover, such evaluations enable iterative refinement of the analogue formulation and processing method, allowing for adjustments that enhance its sensory and functional performance. The data derived from these experiments support the broader goal of positioning the Manila tamarind-based meat analogue as a credible, appealing, and nutritionally beneficial alternative in the rapidly expanding plant-based meat market, which is increasingly driven by consumer concerns over health, environmental sustainability, and ethical food production (Henchion et al., 2017). By aligning the product's performance with industry standards and consumer expectations, this research contributes to the diversification of plant-based protein sources and promotes the incorporation of underutilized crops like Manila tamarind into mainstream food systems.

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