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PROCESSING OF CHICKPEAS FOR THE PRODUCTION OF MEAT-ALTERNATIVE PLANT-BASED FOODS

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Abstract

The growing demand for sustainable, nutritious, and ethical food systems has accelerated the development of plant-based meat alternatives. Chickpeas (Cicer arietinum L.) represent a promising raw material for such products due to their high protein content, favorable amino acid profile, functional starch, and widespread availability. Beyond nutritional and environmental considerations, consumer acceptance of meat alternatives is strongly driven by sensory attributes, including texture, juiciness, flavor, and appearance. This paper reviews and synthesizes current knowledge on the processing of chickpeas to obtain plant-based products with sensory, nutritional, and structural properties similar to meat. Particular emphasis is placed on how processing conditions and formulation strategies influence texture perception, flavor development, and overall sensory quality. Challenges and future research directions related to sensory optimization, digestibility, and consumer acceptance are also highlighted.

Key words*: chickpea, extrusion, meat alternatives, plant-based meat, protein extraction, sensory quality, texturization.*

INTRODUCTION

Global food systems face increasing pressure from population growth, climate change, and resource limitations (FAO, 2019). Livestock production contributes significantly to greenhouse gas emissions, land use, and water consumption (Poore & Nemecek, 2018). Consequently, plant-based meat analogs have emerged as viable alternatives to conventional meat products (Tso & Forde, 2021). Legumes are among the most studied protein sources for these applications, and chickpeas have attracted attention for their agronomic resilience, nutritional quality, and relatively neutral flavor profile (Boye, Zare, & Pletch, 2010). Chickpeas are traditionally consumed as whole seeds or in minimally processed products such as flour, hummus, and cooked seeds. However, advanced processing technologies now enable the transformation of chickpeas into structured, fibrous products that mimic the texture, appearance, and sensory attributes of meat (Dekkers et al., 2018). This paper focuses on the processing strategies required to convert chickpeas into meat-like plant-based foods.

MATERIALS AND METHODS

A systematic literature review was conducted to identify scientific studies addressing the processing of chickpeas (*Cicer arietinum* L.) for the development of plant-based meat alternatives. The literature search was performed using the Web of Science Core Collection database, which is widely used for indexing peer-reviewed publications in food science and technology. The search strategy included combinations of keywords related to chickpeas and plant-based meat analogues. The following search query was used:
(*"chickpea" OR "Cicer arietinum"*) *AND* (*"meat alternative" OR "meat analogue" OR "meat analog*" OR "plant-based meat").
The search was restricted to publications from 2016 to 2026 to capture the most recent technological developments in plant-based meat substitutes.
To ensure the relevance and quality of the reviewed literature, the following inclusion criteria were applied: peer-reviewed scientific articles and review papers; publications written in English; studies classified within the Food

Science and Technology research area; studies focusing on chickpea processing, chickpea protein extraction, functional properties, or applications in plant-based meat analogues.

The following exclusion criteria were applied: studies not related to food applications of chickpeas; publications focusing exclusively on agronomy, crop genetics, or animal feed; conference abstracts, editorials, and non-peer-reviewed sources; studies not addressing protein functionality, processing technologies, or meat analogue applications.

The initial search generated 14,949 records in the Web of Science Core Collection database. After applying filters for publication year (2016-2026), document type (article or review), research area (Food Science and Technology), and language (English), the dataset was reduced to 2,844 records. Further screening was performed by refining the search using Citation Topics Meso categories related to food science, resulting in 1,791 publications. To focus specifically on studies relevant to chickpea-based ingredients and their technological applications, an additional keyword filter ("chickpea flour") was applied, resulting in 1,325 references. Titles and abstracts were subsequently screened to identify publications directly related to: chickpea protein composition and functional properties, processing technologies (e.g., extrusion, fermentation, fractionation), and formulation of plant-based meat analogues using chickpea ingredients. Studies meeting these criteria were included in the qualitative synthesis presented in this review.

Relevant information was extracted from the selected publications, including chickpea composition and protein functionality; processing technologies used for the development of plant-based meat analogues; effects of processing on structural, nutritional, and sensory properties; and formulation strategies for chickpea-based meat substitutes.

The collected information was then organized into thematic categories covering processing technologies, functional properties, product formulation, sensory characteristics, and sustainability considerations. These categories were used to synthesize current knowledge on the potential of chickpeas as a raw material for plant-based meat alternatives.

RESULTS AND DISCUSSIONS

Composition and Functional Properties of Chickpeas

Chickpeas typically contain 18-24% protein, 40-50% carbohydrates (mainly starch), 5-7% lipids, and significant amounts of dietary fiber, vitamins, and minerals (Wood & Grusak, 2007; Jukanti et al., 2012). The protein fraction is rich in globulins (legumin and vicilin), which play a critical role in gelation, emulsification, and water-holding capacity, key properties for meat analog formulation (Kaur & Singh, 2007).

Functional properties of chickpea proteins include water and oil holding capacity, emulsifying ability, and gelation behavior (Grasso et al., 2022). These properties contribute to juiciness, fat stabilization, and texture formation in meat analogue systems. Native chickpea proteins, like most plant-derived proteins, are globulins that exist in a spherical (globular) shape rather than the elongated, fibrous structure found in animal muscle tissue. While they offer similar nutritional benefits and functional properties, such as emulsification and gelation, their natural structure lacks the anisotropy needed to mimic the chewy, fibrous texture of meat (Gulzar et al., 2025).

Processing of Chickpeas for Meat-Alternative Applications

Processing begins with cleaning, dehulling, and milling of chickpeas. Dehulling reduces fiber content and antinutritional factors while improving protein extractability (Khattab & Arntfield, 2009). Milling produces chickpea flour, which serves as the base material for further fractionation or direct texturization.

Based on the literature analysis, several key processing techniques are employed to convert chickpeas into meat-alternative structures: extrusion, fermentation, milling/fractionation, thermal processing, enzymatic hydrolysis, emulsion/gelation, and other emerging technologies.

Extrusion

High-Moisture Extrusion (Figure 1) is used to create "whole-muscle" meat analogues with a fibrous texture similar to chicken or beef. It typically uses moisture levels above 40%.

High-moisture extrusion is the most widely used technology for producing meat analogues (Cheftel et al., 1992). During extrusion, chickpea protein-rich material is subjected to heat, pressure, and shear, leading to protein denaturation, unfolding, and alignment (Akdogan, 1999). In high moisture extrusion, fibrous products are produced with moisture contents above 50 wt.%. The proteins are plasticized/molten inside the barrel by a combination of heating, hydration, and mechanical deformation. When this protein 'melt' flows into the die, it becomes aligned by the (inhomogeneous) laminar flow and is cooled to prevent expansion (Dekkers et al., 2018). Plant-based protein ingredients (such as flours, concentrates, or blends) are fed into the extruder barrel and are mixed with water. With help of high pressure and increasing temperature, friction and shear forces are achieved. Together with a cooling die, these conditions lead to the formation of fibrous structures in the plant proteins. The result is a meat-free product that mimic the texture and bite of meat.

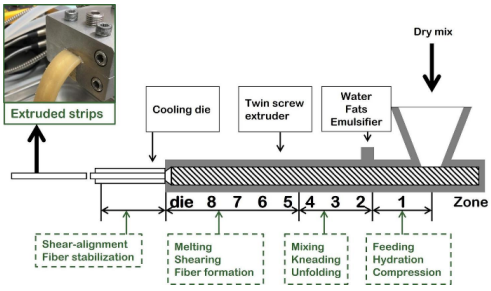

Figure 1. High moisture extrusion equipment (source: https://futurefoodsbv.com/high-moisture-extrusion)

Low-Moisture Extrusion (Figure 2) can also be used to produce texturized vegetable protein, which requires rehydration before incorporation into final products (Singh et al., 2007). The produced textured vegetable protein is often used as a meat extender or in "ground" meat products like burgers (Zahari et al., 2023; Yagci et al., 2020; Kaur et al., 2023). Plant protein powders (such as flours, concentrates, or blends) are loaded into the extruder barrel and are mixed with water. With increasing pressure and temperature, the material undergoes friction and shearing. In combination with a specific die, these conditions lead to fiber formation of the plant proteins. This technology yields a meat-free product with a texture and bite similar to meat. After extrusion, the products are dried to extend their shelf life to approximately 6-12 months.

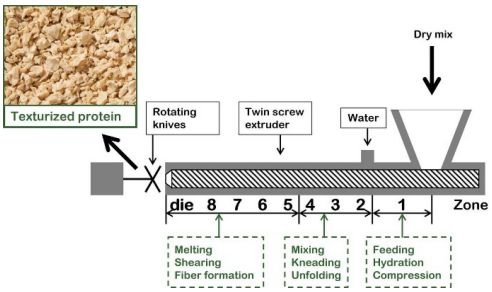

Figure 2. Low moisture extrusion equipment (source: https://futurefoodsbv.com/low-moisture-extrusion)

High-moisture extrusion is widely recognized as the most effective technology for producing fibrous meat analogues; however, significant variability exists across studies regarding its efficiency and product quality. For example, Dekkers et al. (2018) report that high-moisture extrusion (>50% water) enables strong anisotropic fiber formation due to phase separation and protein alignment. In contrast, Osen et al. (2014) observed that the formation of well-defined fibrous structures is highly dependent on protein source and composition, with legume proteins (including chickpea) often requiring blending with gluten or other structuring agents to achieve comparable textures.

This highlights a key limitation: chickpea proteins alone may not consistently produce optimal fibrous structures, due to their globular nature and lower elasticity compared to wheat gluten. Supporting this, Zahari et al. (2023) demonstrated improved texture only when chickpea proteins were co-extruded with wheat gluten, suggesting that protein-protein interactions are critical but not fully understood.

Moreover, while extrusion is industrially scalable, studies such as Akdogan (1999) emphasize its high energy consumption and process complexity, which may limit sustainability advantages when compared to less intensive structuring methods. Therefore,

although extrusion is considered the benchmark technology, its efficiency is formulation-dependent and may contradict claims of universal applicability across plant proteins.

Fermentation

Fermentation is increasingly applied to chickpea-based meat analogues to overcome the inherent limitations of plant proteins, such as "beany" off-flavors, low digestibility, and poor texture. Fermentation helps break down cell wall components and protein structures, creating more fibrous, meat-like textures. It increases the protein's water- and oil-holding capacity, enhancing juiciness. Fermentation reduces anti-nutritional factors (such as phytic acid) and increases the bioavailability of nutrients, amino acids, and phenolic compounds in chickpeas. It serves as a sustainable and natural processing method to enhance the nutritional value, sensory quality, and structural integrity of chickpea-based alternatives.

Fermentation, particularly with lactic acid bacteria like *Lactobacillus plantarum*, reduces green/beany notes by decreasing aldehydes (e.g., n-hexanal) and creating aromatic compounds (acids, alcohols, and esters) that mask off-flavors.

Homolactic fermentation (e.g., *Lactobacillus acidophilus*) can be used to improve protein digestibility, reduce antinutritional factors, and enhance flavor profiles (Hurtado-Murillo et al., 2025).

The use of fungi, such as *Rhizopus oryzae* or *Aspergillus oryzae*, can create a fibrous texture similar to muscle tissue, enhancing the savory, umami flavor of chickpea-based burgers.

Studies show that microbial fermentation (e.g., 24-hour lactic acid fermentation) causes profound structural changes in chickpea proteins. These include protein degradation, where complex, compact structures are broken down into smaller, more digestible peptides, and structural reconfiguration, characterized by decreased β-sheet content, increased α-helix content, and greater exposure of hydrophobic groups. These changes enhance protein solubility and improve its functionality for use in meat substitutes (Milcarz & Harasym, 2025).

Chiacchio et al. (2025) showed that submerged chickpea flour fermentation for 24 hours at 30-37°C with *Lacticaseibacillus casei*, *Lactiplantibacillus plantarum*, *Leuconostoc mesenteroides*, and *L. plantarum* reduced phytic acid.

Solid state fermentation of chickpea at 30-37°C, 48 hours with *A. oryzae*, *A. niger*, and *L. plantarum* determined a reduction of *in vitro* protein digestibility from 87% to 74-82% (Stone et al., 2024; Coronel-León et al., 2025).

Fermentation (Figure 3) enables the creation of "clean-label" products, minimizing the need for artificial additives to improve flavor and texture.

To mimic the fibrous structure of meat, fermented chickpeas are often combined with other technologies, such as high-moisture extrusion or 3D printing (Tao et al., 2022).



Figure 3. Converting chickpeas into meat-like plant-based foods based on fermentation (created with https://biorender.com)

Even if fermentation is frequently reported as an effective strategy to improve flavor and nutritional quality of chickpea-based products, findings across studies are not entirely consistent. For instance, Chiacchio et al. (2025) and Hurtado-Murillo et al. (2025) demonstrate that lactic acid fermentation significantly reduces antinutritional factors and enhances digestibility. Similarly, Tao et al. (2022)

highlight its role in reducing off-flavors through aldehyde degradation.

In contrast, Stone et al. (2024) reported a decrease in *in vitro* protein digestibility (from 87% to 74-82%) following solid-state fermentation, which contradicts the commonly reported improvement in digestibility. This discrepancy may be attributed to differences in microbial strains, fermentation conditions, and substrate composition, suggesting that fermentation outcomes are highly process-specific.

The long processing time and variability in microbial activity represent important limitations for industrial scalability of fermentation (Milcarz & Harasym, 2025). Therefore, although fermentation is promising, its effects are not universally beneficial and require precise optimization to avoid negative impacts on nutritional quality.

Milling/Fractionation

Wet and dry fractionation techniques present a clear trade-off between purity and sustainability. Wet-milling is a process used to obtain high-purity chickpea protein isolates by separating proteins from starch and fiber in a liquid medium.

Wet-milling is a high-purity liquid medium extraction process used to isolate chickpea protein (up to 94.2% purity) by separating it from starch and fiber. The process involves soaking chickpea seeds (often in a solution like sulphur dioxide to break down protein-starch interactions), grinding them into a slurry, and using centrifugal force to separate the components based on density.

Key aspects of the wet-milling process:

- Mechanism: The process utilizes high-speed grinding or homogenization to break down the tissue, followed by filtration, centrifugation, and drying to isolate the protein.
- Separation: It relies on the sedimentation rates of different components, where starch settles out, and protein remains in an aqueous suspension for further purification.
- Advantages: This method offers high protein purity (ranging from 49% to over 94%), high yields (up to 49%), and low fat content in the final product.
- Limitations: It is resource-intensive, requiring high amounts of water and energy, and can lead to the loss of certain functional properties or amino acids, such as sulfur-containing ones.
- Applications: The resulting protein isolates are used in various food and nutraceutical applications (Patil et al., 2024).

Wet-milling, compared with dry fractionation (Figure 4), produces higher-purity protein (usually> 70% pure), though it uses significantly more energy and water. While wet-milling can offer higher purity, it may yield lower yields than alkaline extraction followed by isoelectric precipitation (Patil et al., 2024).

Air Classification (Dry Fractionation) is a sustainable alternative to wet processing that uses air to separate protein-rich and starch-rich fractions based on particle size and density (Espinosa-Ramírez & Serna-Saldívar, 2019).

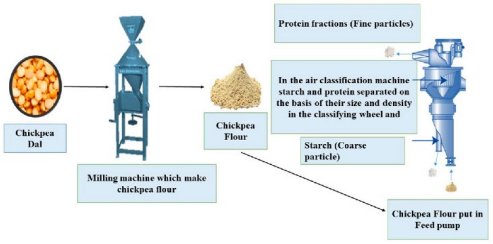

Figure 4. Chickpea protein extraction using the air classification method (source: Patil et al., 2024, https://doi.org/10.3390/foods13091398)

Comparing wet-milling processes and dry fractionation (air classification), we can conclude that dry fractionation is more sustainable (Espinosa-Ramírez & Serna-Saldívar, 2019) but it produces protein fractions with lower purity and higher starch content, which can negatively affect texturization efficiency during extrusion. On the other hand, wet milling is advantageous for controlled structuring applications. Both methods are resource-intensive, requiring large amounts of water and energy, and may lead to loss of functional properties, particularly of sulfur-containing amino acids. A notable contradiction in the literature concerns protein yield versus functionality: while wet extraction yields higher purity, some studies suggest that less refined protein fractions may retain better functional properties due to reduced denaturation (Lima et al., 2023). This indicates that higher purity does not necessarily translate into better performance in meat analog

applications, underscoring the need to balance processing intensity and functionality.

Thermal Processing

Thermal processing is widely used to improve protein functionality (Huang et al., 2023; Nosworthy et al., 2020; Xu et al., 2017; Avilés-Gaxiola et al., 2018); however, its effects depend heavily on processing conditions. Nosworthy et al. (2020) showed that excessive heat treatment can reduce protein quality, whereas moderate heating can enhance digestibility and functionality. This suggests a narrow optimal processing window, beyond which protein denaturation becomes detrimental.

Similarly, enzymatic hydrolysis is often reported to improve solubility and emulsification (Ghosh et al., 2025), yet excessive hydrolysis can lead to loss of gelation capacity and weakened texture, which is critical for meat analog structure. This creates a technological contradiction: improved interfacial properties *vs*. reduced structural integrity. Therefore, both approaches require careful control, as functional improvements in one property may compromise others, particularly texture.

Enzymatic Hydrolysis

Moderate proteolytic hydrolysis is used to create amphiphilic polypeptides that improve the emulsifying and foaming properties of chickpea proteins (Ghosh et al., 2025). Moderate proteolytic hydrolysis (typically 5-15% degree of hydrolysis) breaks down chickpea proteins into smaller, amphiphilic peptides, which improves their functional properties by increasing surface hydrophobicity and solubility. Enzymes like trypsin and alcalase expose hydrophobic groups, enabling better adsorption at oil-water interfaces and enhancing emulsion stability and foaming capacity.

Moderate hydrolysis improves protein solubility (especially at pH 4.0), increases surface hydrophobicity, and improves water/oil holding capacities. Trypsin and alcalase are effective in producing amphiphilic peptides, with trypsin specifically generating higher surface hydrophobicity and better functional improvements. The process reduces molecular weight, enabling smaller peptides to form more stable emulsions and foams than raw chickpea protein. Optimal results are often found at low degrees of hydrolysis (e.g., 6% to 15% DH) using controlled pH and temperature conditions (Ghosh et al., 2025). This enzymatic modification produces plant-based, functional ingredients suitable for food applications that require superior foaming and emulsification.

Emulsion/Gelation

Chickpeas can be used to produce thick pastes that are suitable for new spreads or pâte-like products. The chickpea pastes exhibit a lumpy texture (Durage et al., 2025; Viadel et al., 2024; Mazumder et al., 2023). While fat in animal tissue is embedded within the collagen scaffolds of adipose tissues, in meat analogues, it is typically present in a free, unbound form. Some of the negative textural sensory qualities of plant-based meat substitutes, such as their lack of hardness, chewiness, juiciness, and oil binding, are partly caused by the absence of adipose tissue. Chickpea flour minimizes oil loss without compromising texture, and an ideal gel consisting of 6% pea starch, 4% chickpea flour, and 40% oil (7:3 coconut: sunflower oil) gel was created (Czapalay et al., 2025).

Emerging Technologies

Emerging technologies such as shear cell processing, wet spinning, and 3D food printing have been explored for chickpea- and legume-based systems (Krintiras et al., 2015; Nieuwland et al., 2014). Shear cell processing of chickpeas (Figure 5) is an emerging thermomechanical method for creating fibrous, meat-like textures from plant proteins. Unlike traditional high-moisture extrusion, it uses a well-defined shear flow to align protein molecules into anisotropic structures under more moderate conditions. The process typically uses either a conical shear cell (cone-cone device) or a cylindrical Couette cell (concentric cylinders). Protein molecules are unfolded and aligned within the narrow gap between the rotating parts. This creates a layered, fibrous "meat-like" matrix. It requires lower energy input and lower shear forces than extrusion, enabling better control over the final texture and structure.

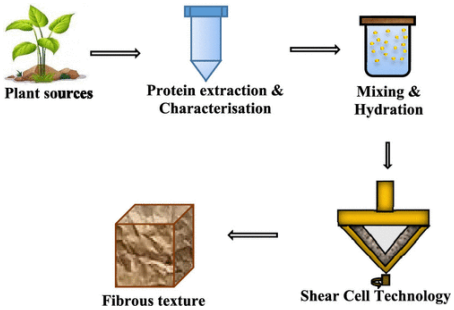

Figure 5. Shear Cell Technology on the production of plant-based meat analog (source: Ajay et al., 2025 https://pubs.acs.org/doi/10.1021/acsfoodscitech.5c00416)

The production of chickpea-based fibrous structures follows three main unit operations:

- Mixing and hydration: Combining chickpea protein concentrates or isolates with water and other ingredients (like hydrocolloids or lipids) to form a consistent dough;
- Thermo-mechanical treatment: Applying heat and shear forces simultaneously to promote protein-protein interactions and alignment;
- Cooling and Resting: The material is cooled and allowed to "rest" to stabilize the newly formed fibrous network before being removed from the cell (Cornet et al., 2022).

Chickpea is highly suitable for this technology because of its specific functional properties: high thermal stability: chickpea protein has high thermal expansion and stability, which helps maintain the integrity of the fibrous structure during heating; textural versatility: researchers use shear cell processing to develop chickpea-based meat analogs, such as emulsion gel meat substitutes, by aligning chickpea protein with oils like flaxseed. Cornet et al. (2022) suggest that shear cell technology provides better control over fiber alignment under milder conditions. However, its low throughput and limited scalability currently restrict commercial application.

3D food printing (Figure 6) is an emerging technology utilized to create sustainable, plant-based meat alternatives by using chickpea-based "inks" to mimic the texture, flavor, and nutritional profile of conventional meat. Chickpeas are particularly valued for this application due to their high protein content, digestibility, and rich mineral profile.


Figure 6. 3D food printing for creating plant-based meat alternatives (source: Dang Hui L 2024. https://www.foodnavigator-asia.com/Article/2024/02/07/3d-food-printing-vital-for-creating-plant-based-alternatives-with-buckwheat-being-most-promising-ingredient/)

The key aspects of 3D printed chickpea meat alternatives are:

- ink formulation**:** chickpea flour is blended with ingredients like water, oils, and binding agents to create a printable paste;
- textural optimization**:** research indicates that extruded chickpea flour has better printability at a water content of around 72%, while non-extruded flour is better at lower moisture levels (around 36%);
- process efficiency**:** extrusion-based 3D printers can create complex geometries, mimicking the fiber-like structure of meat. The process also allows for the integration of other ingredients to enhance texture and juiciness, such as mushrooms or omega-3-rich oils;
- aquafaba application**:** the liquid leftover from cooking chickpeas, known as aquafaba, is used in 3D food printing as a functional plant-based ingredient (like an egg substitute) due to its high viscosity and foaming capacity, which helps with structural retention.

This technology has many advantages: it is sustainable - chickpeas are an environmentally friendly crop, making them a sustainable source of protein for meat alternatives; it allows personalisation of products with tailored nutritional content to meet specific dietary requirements, such as high-fiber or low-fat diets; it enables the use of upcycled ingredients and precise ingredient portioning to minimize waste (Auyeskhan et al., 2024; Rodríguez-Herrera et al., 2024; Hena et al., 2024). The challenges of this technology are: the technical limitations- achieving the precise, fibrous

mouthfeel of meat remains difficult; cost and scalability- the technology is currently expensive and generally limited to, or focused on, high-end food service or specialized products; rheological properties -the "ink" must be viscous enough to hold its shape, yet fluid enough to be extruded, which requires precise control over temperature and formulation (Bhuiyan et al., 2025; Qiu et al., 2025). In contrast to extrusion, which is already industrialized, these technologies remain largely at the prototype or pilot scale, highlighting a gap between innovation and practical implementation.

Protein Extraction and Fractionation

Protein ingredients can be obtained through dry or wet fractionation methods (Pelgrom et al., 2013). Dry fractionation involves milling followed by air classification to separate protein-rich fractions and is considered more sustainable due to lower water and energy requirements. Wet fractionation typically includes alkaline solubilization, isoelectric precipitation, washing, and drying, yielding chickpea protein isolates with protein contents exceeding 80% (Lima et al., 2023). To enhance functionality, chickpea proteins may be subjected to physical, chemical, or enzymatic modifications (Nivala et al., 2021). Heat treatment, pH shifting, and enzymatic hydrolysis can improve solubility, reduce beany flavors, and promote protein-protein interactions during texturization (Osen et al., 2014).

Formulation of Meat-Analog Products

Processing technologies play a central role in developing meat-like texture in chickpea-based systems. Protein alignment and phase separation during processing contribute to the formation of fibrous structures that enhance chewiness and structural integrity. The incorporation of plant-based oils and structuring agents further improves mouthfeel by simulating intramuscular fat, which is critical for lubrication and flavor release during consumption. Chickpea-based meat analogs are commonly formulated with plant-based oils for fat mimicry, hydrocolloids such as methylcellulose for binding, and natural colorants to simulate meat appearance (Kyriakopoulou et al., 2021). Flavorings, salts, and umami compounds are carefully balanced to enhance overall palatability while maintaining clean-label considerations. Product formats include burgers, sausages, nuggets, and minced-meat analogs, each requiring tailored sensory and structural optimization. Table 1 presents examples of chickpea-based meat alternatives produced using various processing technologies.

Table 1. Chickpea-Based Meat Alternatives

Product Type	Processing Technology	Key Findings	Reference
Meat analogue	Freeze-alignment combined with emulsion/gelation	Chickpea protein–flaxseed oil emulsion gel created a fibrous structure with improved textural properties suitable for meat analogues	Durage et al., 2025
Sausage analogue	Emulsion gel formulation using chickpea and mung bean proteins	Chickpea incorporation improved rheological behavior, digestibility, and microstructural stability of plant-based sausages	Sivapragasam et al., 2025
Burger patty	Formulation with chickpea flour and textured vegetable protein	Higher chickpea concentrations improved protein content and influenced the texture and in vitro digestibility of plant-based burgers	Kea et al., 2025
Meat analogue	High-moisture extrusion with chickpea proteins and wheat gluten	Co-extrusion improved fibrous texture and sensory attributes in meat analogue products	Zahari et al., 2023
Sausage analogue	Emulsion-type gel system using chickpeas and grey oyster mushrooms	Chickpea flour contributed to emulsion stability and improved textural properties in plant-based sausages	Mazumder et al., 2023
Fermented burger	Solid-state fermentation with Aspergillus oryzae	Fermentation improved flavor profile, increased protein content, and reduced undesirable sensory notes	Mohamed & Ali, 2025

Flavor Development, Texture Perception, and Product Formulation

The success of chickpea-based meat analogues largely depends on their ability to replicate key meat sensory attributes, including fibrous texture, juiciness, cohesiveness, flavor intensity, and visual appearance (Tso & Forde, 2021). Texture is often identified as the most

critical factor, as consumers expect anisotropic, fibrous structures that resemble muscle tissue during chewing (Dekkers et al., 2018). Juiciness perception is influenced by water-holding capacity, fat distribution, and moisture release during mastication, all of which are affected by protein structure and formulation. Chickpeas contain volatile compounds associated with beany and grassy flavors derived mainly from lipid oxidation and enzymatic activity (Roland et al., 2017). These flavors can negatively impact consumer acceptance, particularly in products intended to mimic meat. Mitigation strategies include thermal processing, fermentation, enzymatic treatment, and the use of flavor-masking or flavor-generation systems, such as Maillard reaction precursors (Kyriakopoulou et al., 2019).

Nutritional and Sustainability Considerations

Chickpea-based meat analogs offer high protein content, dietary fiber, and cholesterol-free properties, while potentially reducing saturated fat intake (Loveday, 2020). From a sustainability perspective, chickpeas require less water and nitrogen fertilizer than many animal protein sources and contribute to soil fertility through biological nitrogen fixation (Merga & Haji, 2019). However, the environmental benefits may be influenced by processing intensity and ingredient complexity, underscoring the importance of life-cycle assessment in product development (Mari et al., 2025).

Challenges, Critical Synthesis and Future Perspectives

Despite technological advances, challenges remain in achieving full sensory equivalence to meat, particularly regarding juiciness, flavor release, and fibrousness (Sha & Xiong, 2020). The literature reveals that no single processing technology is sufficient to fully replicate the complex structure and sensory profile of meat. While extrusion provides the most advanced structuring capability, its dependence on formulation and high energy input represents a significant limitation. Fermentation and enzymatic treatments improve flavor and functionality but may introduce inconsistencies in digestibility and structural integrity. Similarly, fractionation techniques involve trade-offs between purity, sustainability, and functionality. These findings suggest a growing consensus toward hybrid processing strategies that combine multiple technologies to overcome individual limitations. However, the lack of standardized processing conditions across studies makes direct comparison difficult and highlights the need for systematic optimization and harmonized evaluation methods in future research. Future research should focus on improving protein functionality with minimal processing, enhancing digestibility, developing clean-label formulations, and scaling up novel structuring technologies.

CONCLUSIONS

Overall, the current literature demonstrates that while chickpeas are a promising raw material for plant-based meat analogues, their successful application depends on carefully balanced, multi-step processing strategies, and no single technology currently provides a complete solution, underscoring the need for integrated, interdisciplinary approaches in future research.

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