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Pulses for Production of Meat Analogues by High-Moisture Thermoplastic Extrusion, Technological and Nutritional Challenges: A Short Review

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ABSTRACT
Meat analogs represent a promising alternative to animal-derived meats, driven by growing environmental, nutritional, and sustainability demands. Producing these alternatives involves complex interactions among plant-based ingredients, processing technologies, and sensory factors. Pulses such as soy, lentil, and pea flours or isolates are common due to their high protein content but require advanced processing techniques to enhance functionality and remove antinutritional compounds. Extrusion remains a key method to achieve a fibrous texture similar to animal meat, although it involves sophisticated equipment, significant energy consumption, and elevated maintenance costs. Consumer acceptance also depends significantly on sensory attributes, including flavor and juiciness. Enhancing these attributes typically involves incorporating ingredients like soy heme, mushroom extracts, and plant lipids, which consequently elevate production costs. Additionally, optimizing nutritional profiles to overcome inherent plant protein deficiencies, particularly in essential amino acids, is crucial. Fortification strategies, incorporating iron, vitamin B12, and other micronutrients, are effective yet further increase costs. Despite economic and technological challenges, meat analogs provide significant environmental benefits, such as reduced greenhouse gas emissions and lower resource consumption compared to conventional livestock farming. Continuous growth in this sector, alongside technological advancements, promises cost reduction, potentially increasing consumer accessibility and affordability. Thus, meat analog production demonstrates a dynamic balance among technological feasibility, nutritional enhancement, cost management, and environmental sustainability, highlighting its potential to reshape dietary habits and transform the protein food industry.

Keyword: food extrusion, pulses, enrichment, meat analogues, nutritional implications, quality criteria.

INTRODUCTION
As the global population grows and living conditions improve in emerging nations, there has been a notable increase in meat consumption worldwide, which has more than doubled over the past five decades. This rising demand has driven a significant expansion in industrial

livestock farming, prompting important discussions regarding the environmental, ethical, and health-related implications of such extensive meat consumption.

The environmental consequences of this surge in production are clear and troubling, including increased greenhouse gas emissions like methane and nitrous oxide, as well as water contamination and deforestation. These harmful effects pose serious threats to the planet's well-being and its ability to support diverse forms of life.

From a health perspective, an overabundance of meat in one's diet can contribute to various issues, including heart disease and colorectal cancer, particularly associated with red meat consumption. It is vital to recognize the health risks entailed in eating meat and to work towards a more balanced nutritional approach.

There are also ethical dilemmas surrounding animal welfare and the significant use of crops meant for human consumption as feed for livestock. Notably, 44% of global cereal production and 33% of all cultivated land is allocated for animal feeding purposes. In fact, a total of 70% of the world's arable land is either directly or indirectly employed in the rearing of animals to provide food for humans (FAO, 2006).

The growing concern about the environmental impacts and sustainability of animal meat production has driven the demand for plant-based meat analogues. Among the processes used to obtain these products, high-moisture extrusion stands out, which allows the formation of a fibrous structure similar to meat. This review addresses the main aspects related to the raw materials, equipment configurations and process parameters involved in the production of these analogues.

The development of plant-based meat analogs using pulses has emerged as a significant innovation in food technology, driven by consumer demands for healthier, environmentally friendly, and sustainable dietary alternatives. Pulses, including beans, peas, lentils, and chickpeas, provide a nutritionally rich and technologically versatile raw material that can mimic animal-derived meat textures through advanced processing methods.

Protein isolation from pulses involves techniques such as aqueous extraction and isoelectric precipitation, ultrafiltration, and enzymatic extraction. These processes efficiently yield protein isolates and concentrates with high purity, suitable for the texturization processes required in meat analogs production (Lam et al., 2018). Ultrafiltration, in particular, is advantageous for preserving protein functionality, facilitating further processing into fibrous textures resembling animal muscle (Boye et al., 2010).

Extrusion cooking is the most commonly applied technology for pulse protein texturization. This technique utilizes high temperature, shear, and pressure to induce structural transformations in proteins, forming a fibrous and layered structure similar to muscle fibers. Parameters such as moisture content, barrel temperature, screw speed, and feed rate critically influence the textural attributes of the resulting analogs. Optimizing these parameters ensures the desired product consistency, chewiness, and resilience, essential for consumer acceptance (Chiang et al., 2019; Zhang, et al, 2022).

The binding quality and texture conferred by pulse-derived proteins are primarily due to their water and fat retention capacity, gelling, and emulsifying properties. Proteins from chickpeas and lentils have shown superior gel-forming and binding capacities, enabling effective simulation of meat juiciness and tenderness (Joshi et al., 2012). Additionally, combining different pulses enhances the complementary functionality of proteins, improving the overall textural and sensory qualities.

Flavor development remains a considerable challenge in pulse-based meat analogs, as pulses typically have distinct earthy and beany notes. Masking or modifying these flavors through fermentation, enzymatic treatments, or the use of flavor masking agents has proven effective. Furthermore, the Maillard reaction during extrusion cooking contributes positively by generating meat-like flavors, enhancing product palatability (Sha & Xiong, 2020).

Nutritionally, pulses significantly enhance meat analog formulations by providing high-quality plant proteins, dietary fibers, vitamins, and minerals. They also contribute to reducing cholesterol and saturated fat intake compared to animal meats, thereby addressing consumer health concerns and supporting cardiovascular health (Boukid, 2021).

Consequently, the integration of pulses in the formulation of meat analogs leverages their nutritional, functional, and environmental benefits. Continued research into optimizing isolation and processing methods is essential for advancing these products' sensory and nutritional profiles.

RAW MATERIALS FOR HIGH-MOISTURE MEAT ANALOGUES

The ingredients used in the formulation of high-moisture meat analogues play a crucial role in obtaining adequate texture and sensory properties. To be considered suitable for the formulation of meat analogues by thermoplastic extrusion, the raw materials must present the following intrinsic characteristics:

- High capacity for protein network formation: Plant proteins, such as soy, pea and wheat, must present a structure capable of forming a three-dimensional network during processing to confer a fibrous texture to the final product.
- Adequate solubility and dispersibility: protein solubility directly influences the interaction between the components of the formulation and the stability of the mixture inside the extruder.
- Water and oil retention capacity: ingredients that can retain moisture and fats help improve the juiciness and palatability of the meat analogue.
- Shear resistance and extrusion conditions: raw materials must withstand high temperatures and mechanical forces without completely denaturing or compromising the desired texture.
- Compatibility with other ingredients: the interaction between proteins, polysaccharides and emulsifiers is essential to ensure stability and appropriate texture.

- Neutral or easily maskable flavor: Proteins with strong flavors may require additional processing to remove undesirable notes and use of flavorings to simulate the flavor of meat.
- Balanced nutritional properties: The amino acid profile of vegetable proteins must be complemented to ensure a nutritional value similar to that of animal meat. - Minimum protein content of 65%: For the texturing phenomenon to occur during the extrusion process, the protein concentration in the raw materials must be high, ideally above 65%. This condition allows the formation of a three-dimensional protein structure, which is essential for obtaining a final product with characteristics similar to those of animal meat.

Table 1: Main functional properties of different vegetable protein sources used in the formulation of meat analogues

Protein Source	Protein Content (%)	Protein Functionality	Dispersibility	Impact on Meat Analogues	Solubility Oil	Absorption Capacity	Peculiar Characteristics
Chickpeas	65-70	Good foaming capacity, moderate water absorption	Moderate	Improves texture and mouthfeel, suitable for fish analogues	Good	Good	High in fiber, mild flavor
Lentils	70-75	Moderate emulsifying and gelation capabilities	Good	Contributes to tenderness and texture in beef-like analogues	High	High	High in iron, good emulsification
Peas	80-85	High solubility, good water-holding capacity	Good	Enhances juiciness and tenderness, promotes texture similar to chicken	High	High	Balanced amino acid profile
Black Beans	65-70	Moderate water retention, good emulsifying capacity	Moderate	Provides cohesive structure, useful in chicken and fish analogues	Moderate	Moderate	Rich in antioxidants, strong flavor
Fava Beans	70-80	High emulsification and gelation properties	Good	Ideal for creating dense, meat-like textures suitable for beef analogues	High	High	Soft texture, neutral flavor

Source: (Warsame et al. 2018, Mojica & González 2015, Kohajdová et al. 2011, Joshi, et al. 2012, Boy & Pletch 2010, Osen et al. 2014, Tulbek et al. 2016).

The selection and proportion of these protein sources directly influence the formation of the desired fibrous structure, affecting the sensory and technological properties of the final product.

HIGH-MOISTURE EXTRUSION PROCESS

High-moisture extrusion is a process widely used for the production of meat analogues, characterized by moisture contents above 50%. The main factors involved in the process include:

- Extruder configuration: The use of twin-screw extruders allows for better process control and uniform distribution of the ingredients.

The screw configuration in twin-screw extruders (Fig. 1) plays a key role in determining the shear rate applied to the material during the extrusion process, directly influencing the texturing of vegetable proteins in the production of high-moisture meat analogues. The shear rate is crucial to promote structural changes in proteins, resulting in a fibrous texture similar to that of meat.

Screw Elements and Shear Rate

Extruder screws are composed of several modular elements, such as transport, mixing and restriction segments (Fig. 2). The arrangement and type of these elements affect the intensity of shear. These can be: transport segments, which are responsible for moving the material along the barrel, generally apply low shear; mixing elements, designed to homogenize the mass, apply moderate to high shear, depending on their geometry; and restriction or blocking elements, which create resistance to flow, significantly increasing shear and pressure, essential for protein texturing.

The proper configuration of these elements allows precise control of the shear rate, essential for obtaining the desired texture in the final products.

Contributions from Extruder Manufacturers

Renowned manufacturers, such as Wenger Manufacturing, emphasize the importance of screw configuration in modulating the shear rate. According to Wenger, the specific assembly of the screw elements allows the extruder to operate at low, medium or high shear conditions, depending on the requirements of the product and the raw materials used.

Practical Considerations

When configuring the extruder screws for the production of high-moisture meat analogues, it is essential to consider:

- Raw material characteristics: Proteins with different solubilities and water and oil absorption capacities may require specific adjustments to the screw configuration to achieve optimal texturization.
- Process parameters: Factors such as temperature, humidity and screw speed must be harmonized with the chosen configuration to ensure consistency and quality of the final product.

Therefore, the extruder screw configuration is a determining factor in applying the necessary shear rate for the adequate texturization of vegetable proteins. Careful selection and arrangement of the screw elements, aligned with the raw material properties and product objectives, are essential for the successful production of meat analogues with the desired characteristics.

Figure 1: Partial view of the extrusion system and elements of a twin-screw extruder.
Source: https://www.indiamart.com/proddetail/extruder-screw-manufacturers-with-profile-ground-23177313048.html.

Figure 2: Different elements to change the screw configuration according to the need for low, medium or high shear rate.

Source: https://pt.made-in-china.com/co_njkairong/product_Extruder-Screw-Barrel-in-Plastic-Extrusion-Bimetallic-Screw-Barrel_rrhsiueig.html.

- Process parameters: Temperature profile in the extruder barrel, feed rate, shear rate, screw speed, and moisture content of the material entering the extrusion system, residence time, number and shape of dies are all determining factors in obtaining an adequate fibrous structure.
- Accessories: The use of specific dies and cooling systems (Figure 3). Directly influences the orientation of the protein fibers and, consequently, the final texture of the product.

Figure 3: Cooling accessory in the production of meat analogues.
Source: https://img.foodprocessing.com/files/base/ebm/foodprocessing/image/2022/08/1660318457818-clextralmeatanalogprocessing.png?auto=format,compress&fit=max&q=45.

STRUCTURE AND SENSORY QUALITY OF MEAT ANALOGUES.

Consumer acceptance of meat analogues depends heavily on the product's ability to imitate the texture, flavor and juiciness of animal meat. Different technologies are used to achieve this.

Theories on Fiber Formation in Plant-Based Meat Analogues via Extrusion

During high-moisture extrusion of vegetable protein concentrates (e.g., soy, pea, faba bean), the formation of a fibrous, meat-**like** structure is a complex process that relies on several thermodynamic, rheological, and molecular phenomena. Below are the main theories and mechanisms proposed to explain fiber formation:

1. Phase Separation Theory (Thermodynamic Incompatibility): This theory suggests that incompatible biopolymers, such as different protein fractions (globulins vs. albumins) or protein–carbohydrate mixtures tend to phase-separate under shear and heat, forming aligned domains. When extruded under high-moisture conditions, this alignment results in anisotropic fibrous structures, (Manski et al. (2007). Application, especially relevant for mixtures of soy with wheat gluten or polysaccharides.
2. Protein Alignment and Shear-Induced Structuring: Under intense shear and thermal conditions inside the extruder, denatured proteins unfold and align in the direction of

flow. As the molten mass passes through the long cooling die, the proteins begin to aggregate and solidify in aligned configurations, resulting in longitudinally oriented fibers. The forces involved are hydrophobic interactions, hydrogen bonding, and disulfide bond formation (mainly in sulfur-containing proteins like soy), Schreuders, et al., 2019.

3. About the molecular cross-linking and network formation, the proteins unfold and interact, covalent and non-covalent bonds are formed, and disulfide bonds, especially in cysteine-rich proteins (soy), hydrophobic interactions, and drive protein–protein association in low-polarity zones, ionic interactions and hydrogen bonds: contribute to local stabilization. These interactions result in the formation of a cross-linked network, which becomes organized under flow into fibrous matrices (Dekkers, et al, 2018).
4. Whit reference at rheological and flow behavior within the cooling die, the geometry of the cooling die plays a crucial role. As the protein melt is cooled under controlled shear, differential viscosity and elongational flow contribute to the formation of layers and strands. The laminar flow and temperature gradient stabilize the anisotropy necessary for fibrous texture. Cooling profile and die length are optimized to promote fiber retention (Lin, et al., 2002).

Table 2: Summary of Bonding Mechanisms

Interaction Type	Role in Fiber Formation
Disulfide bonds	Stabilize aligned protein chains (soy > pea)
Hydrogen bonds	Reversible bonding for network reinforcement
Hydrophobic interactions	Main driver of alignment and aggregation
Ionic interactions	Moderate effect depending on protein and salts

Source: Schmid, et al, 2022.

Consequently, fiber formation depends not only on protein type and composition, but also on extrusion parameters such as moisture (>50 %), temperature (~120–160 °C), screw speed, and cooling die design.

Blending proteins (e.g., soy + wheat gluten) or adding structuring aids (e.g., methylcellulose) can enhance alignment and texture. High-Moisture Extrusion (HME) is essential for mimicking muscle-like structures due to the need for melt plastification and controlled solidification (Dekkers, et al, 2018).

5. Sustainability and Future Prospects: Plant-based meat analogues offer considerable environmental advantages over animal meat, including lower greenhouse gas emissions, reduced water consumption and less use of arable land. Minimum protein content of 65%: For the texturization phenomenon to occur during the extrusion process, the protein concentration in the raw materials must be high, ideally above 65%. This condition allows the formation of a three-dimensional protein structure, essential for obtaining a final product with characteristics similar to those of animal meat.

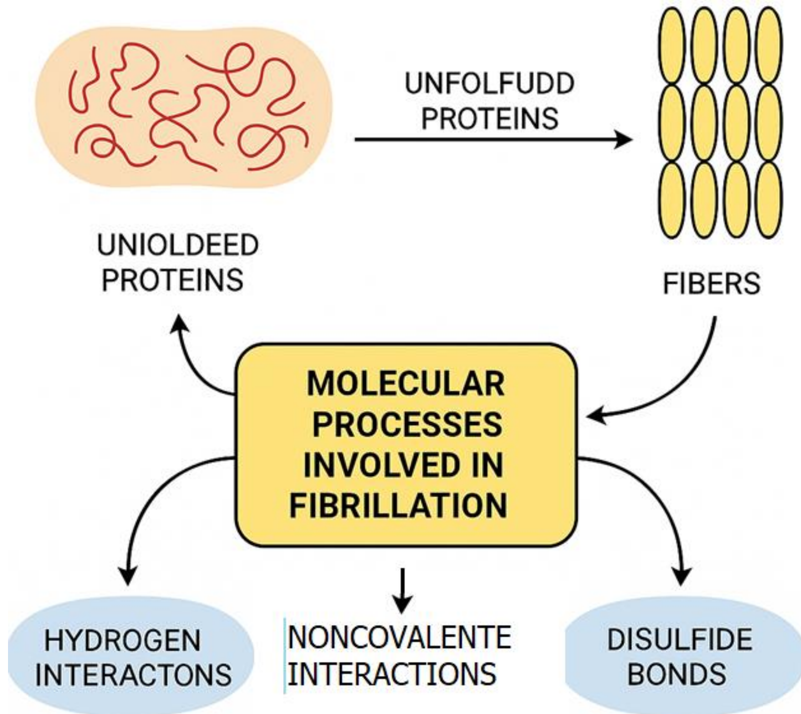

Figure 4: A diagram illustrating the variations in the conformational changes of proteins (fibrillation) related to meat substitutes produced by food extruders.
Source: Schmid, et al., 2022.

Challenge of Vitamin Presence in Meat Analogues

Animal meat is a rich and natural source of several essential vitamins, especially the B complex, including B12 (cobalamin), B6 (pyridoxine), B3 (niacin) and B2 (riboflavin). These vitamins play key roles in energy metabolism, neurological function and red blood cell formation. However, plant-based meat analogues do not naturally contain (Table 3) many of these vitamins, requiring a fortification process to ensure their adequate nutritional value (CHEAH, et al., 2020).

The main challenges include:

- Lack of Vitamin B12, this vitamin B12 is exclusively of microbial origin and found in animal sources, being essential for DNA synthesis and neurological health. In meat analogues, supplementation with synthetic B12 or derived from bacterial fermentation is necessary.
- Lower Availability of B6 and B2, these vitamins, essential for the metabolism of proteins and fats, are in lower concentrations in plant proteins and require fortification.
- Ingredient Interaction and Stability: Some B vitamins are sensitive to heat and moisture and may degrade during thermal processing of meat analogues, requiring careful consideration of vitamin forms and methods of addition to the extrusion system.
- Nutritional Balance and Bioavailability: In addition to B vitamins, meat analogues may be limited in other essential micronutrients, such as zinc and selenium, requiring balanced formulations and strategic fortifications.

Table 3: Comparison of vitamin content between animal meat and plant analogues

Nutrient	Animal Meat (100g)	Plant-Based Meat Analogues (100g)	Fortification Strategy
Vitamin B12	2.4 mcg	0 mcg	Supplementation with cyanocobalamin or methylcobalamin
Vitamin B6	0.5mg	0.1 mg	Addition of pyridoxine to formulations
Niacin (B3)	5.5 mg	1.2 mg	Enrichment with natural or synthetic sources
Riboflavin (B2)	0.3 mg	0.05 mg	Fortification in combination with other micronutrients

Source: Yang, 2023; Sadler, 2004; Costa-Catala, 2023; Cole, et al., 2022. Bryngelsson, et al., 2022; Cheah, et al. 2020)

Fortification in Combination with other Micronutrients

Fortification with B vitamins and other essential micronutrients can ensure that meat analogues are a nutritionally complete alternative to conventional meat, meeting the needs of health-conscious and sustainability-conscious consumers.

The Challenge of Heme Iron in Meat Analogues

The iron present in animal meat is predominantly in the form of heme iron (Fe^{2+}), which is highly bioavailable and readily absorbed by the human body. In plant-based meat analogues, the main source of iron is non-heme iron (Fe^{3+}), found in legumes and cereals. However, non-heme iron has lower bioavailability due to the presence of antinutritional factors such as phytates and tannins, which inhibit its absorption. The challenges associated with fortifying meat analogues with iron include:

- Poor bioavailability, because, non-heme iron has a reduced absorption rate compared to heme iron.
- Interference from antinutritional compounds are phytates, oxalates and polyphenols present in vegetables can further reduce iron absorption.
- Taste and color change, the addition of iron in bioavailable forms can affect the flavor and appearance of the product, requiring microencapsulation technologies.
- Need for cofactors, because, the absorption of non-heme iron can be increased with the addition of vitamin C and reduction of inhibitory compounds.
- Fortification of meat analogues with synthetic heme iron or biotechnological derivatives is a promising approach to mitigate these limitations, ensuring a more nutritionally complete product that is more acceptable to consumers.

Challenge of the Absence of Collagen in Meat Analogues

There are two situations regarding the collagen present in animal meat, the first is related to its function in providing texture and tenderness to animal meat, the second to its nutritional role in human nutrition. Collagen is a fundamental structural protein present in the connective tissues of animal meat, and is responsible for providing firmness, elasticity and juiciness to meat products. Furthermore, collagen directly influences the texture of cooked meat, promoting tenderness when properly processed. In plant-based meat analogues, the absence of collagen poses a challenge in replicating the texture and juiciness of traditional meat.

The main technological challenges and solutions for replacing collagen include: Use of gums and hydrocolloids, ingredients such as xanthan gum, guar gum and carrageenan can act as structuring agents, helping to provide viscosity and elasticity to meat analogues. Some plant proteins, such as pea and soy protein isolates, have functional properties that allow the formation of structural networks similar to collagen. On the other hand, plant fibers such as cellulose and bamboo fibers, can contribute to the replication of collagen texture by providing structural support to the final product. In addition, gelling agents and water retention agents, such as pectin, alginates and modified starches can help to maintain the moisture content of the product and provide a chewy sensation similar to that of meat.

Biotechnological alternatives, with the intention of developing synthetic collagen through microbial fermentation, are a promising approach, which may offer a solution closer to animal collagen.

Nutritional Aspect of Collagen Replacement

In addition to its structural function, collagen plays a crucial role in human nutrition, especially in maintaining healthy skin, joints and connective tissues. Collagen is rich in amino acids such as glycine, proline and hydroxyproline, which are essential for protein synthesis in the body.

To meet this nutritional need in meat analogues, some strategies could be considered, such as supplementation with plant collagen peptides, such as genetically modified algae and yeast, which can produce peptides similar to animal collagen. The use of specific amino acids, such as the addition of glycine, proline and lysine in the formulation, can stimulate the endogenous production of collagen in the human body.

Fortification with Vitamins and Minerals Cofactors: The natural synthesis of collagen depends on micronutrients such as vitamin C, zinc and copper, and their inclusion is necessary to improve the bioavailability and absorption of these components.

Plant Proteins with Similar Structures: Some plant proteins, such as those found in legumes and seeds, contain significant levels of structural amino acids that can help nutritionally replace collagen.

Collagen Challenge in Meat Analogues

Collagen is a fundamental structural protein present in the connective tissues of animal meat, responsible for providing firmness, elasticity and juiciness to meat products. In addition, collagen directly influences the texture of cooked meat, promoting tenderness when properly processed. In plant-based meat analogues, the absence of collagen represents a challenge in replicating the texture and juiciness of traditional meat. The main challenges and solutions for replacing collagen include:

- Use of gums and hydrocolloids, ingredients such as xanthan gum, guar gum and carrageenan can act as structuring agents, helping to provide viscosity and elasticity to meat analogues.
- Structured plant proteins, some plant proteins, such as pea and soy protein isolate, have functional properties that allow the formation of structural networks similar to collagen.

- Plant fibers, such as cellulose and bamboo fibers, can contribute to the replication of collagen texture by providing structural support to the final product. Gelling agents and water-binding agents such as pectin, alginates and modified starches can help maintain product moisture and provide a chewy sensation similar to meat.
- Biotechnological alternatives, the development of synthetic collagen through microbial fermentation is a promising approach that may offer a solution closer to animal collagen. Table 4 below presents some nutritional supplementation options for replacing collagen in meat analogues.

Table 4: Some nutritional supplementation options for replacing collagen in meat analogues.

Nutritional Replacement	Function	Application in Meat Analogues
Plant collagen peptides	Tissue regeneration	Direct supplementation or microbial fermentation
Glycine and proline	Essential amino acids for collagen	Added to the protein formulation
Vitamin C	Essential cofactor for collagen synthesis	Product fortification
Zinc and copper	Enzymatic regulators of collagen production	Inclusion in the formulation

Source: Sha, L., & Xiong, 2020; Lam, Et Al., 2018; Bohrer, 2017; Wang, Et Al, 2011; Lin, 2002.

The combination of these approaches can ensure that meat analogues not only reproduce the texture of collagen, but also provide the essential nutritional benefits to the human body. Fortification with B vitamins, synthetic heme iron and structural and nutritional replacement of collagen are essential approaches to ensure that meat analogues are nutritionally and sensorially equivalent to animal meat. The use of structured vegetable proteins, fibers, hydrocolloids and advanced biotechnological technologies allows the production of products with improved characteristics, meeting the demands of the market and consumers concerned about health and sustainability.

High-moisture Extrusion Process

High-moisture extrusion is a process widely used for the production of meat analogues, (Figure 4) characterized by moisture contents above 50%. The main factors involved in the process include:

- Extruder configuration: The use of twin-screw extruders allows for better process control and uniform distribution of the ingredients.
- Process parameters: Temperature, shear rate, residence time and moisture are decisive in obtaining an adequate fibrous structure.

Figure 5: Meat analogue produced by thermoplastic extrusion.

SUSTAINABILITY AND FUTURE PERSPECTIVES

Plant-based meat analogues offer considerable environmental advantages over animal meat, including lower greenhouse gas emissions, reduced water consumption and reduced use of arable land. Fortification with B vitamins and synthetic heme iron are essential approaches to ensuring that meat analogues are nutritionally equivalent to animal meat, meeting market and consumer demands.

The cost-benefit Issue in the Production of Meat Analogues

The growing demand for plant-based meat alternatives has driven research and development of analogue products that seek to reproduce the sensory and nutritional characteristics of animal meat. However, the economic viability of these products still represents a challenge, given the high cost involved in obtaining quality ingredients, employing technologically sophisticated processes and the need to meet consumer expectations in terms of texture, taste and nutritional value.

Regarding ingredients and raw materials, meat analogues often use flours with concentrated or isolated proteins from pulses, such as peas, soybeans, broad beans and lentils, which have a high protein content and good functional properties. However, these ingredients have a considerable cost due to the need for additional processing to remove antinutritional factors, concentrate the protein, improve solubility and increase the bioavailability of nutrients. In addition, obtaining vegetable lipids and natural additives to improve flavor and texture adds an additional cost component.

As for the technological process and infrastructure, the technology used in the production of meat analogues is another determining factor in the final cost. Thermoplastic extrusion, for example, is widely used to give a fibrous structure to vegetable proteins, simulating the texture of meat. This process requires specialized equipment, sophisticated process controls and high operating costs, including significant energy consumption. In addition, complementary processes, such as fermentation and encapsulation of aromatic compounds, may be necessary to improve the flavor and stability of the product. In this sense, the acceptance of meat analogues by the consumer market depends on their sensory similarity to animal meat. This includes aspects such as flavor, texture and juiciness, which often need to be adjusted with specific additives and processes, further increasing production costs. Ingredients such as soy heme and natural mushroom extracts are used to intensify umami, but they are expensive. Furthermore, concerns about consumer perception of artificial ingredients drive the search for natural solutions, which are not always economically advantageous.

As for nutritional and sustainability aspects, one of the main challenges in the formulation of meat analogues is ensuring a balanced nutritional profile. Although plant-based proteins are an alternative to meat, they often have deficiencies in essential amino acids, requiring a strategic combination of protein sources. In addition, the addition of vitamins and minerals, such as iron and vitamin B12, is essential to avoid nutritional deficiencies, but it increases the cost of the formulation. On the other hand, the sustainability of meat analogues is a competitive advantage; since they have, a smaller environmental footprint compared to conventional meat, and can add value to the product.

Therefore, the cost-benefit of producing meat analogues should be assessed considering not only the direct costs of raw materials and technology, but also the long-term gains in terms of sustainability, innovation and consumer satisfaction. Although the initial investments are high, advances in technology and increased production scale tend to reduce costs, making products more accessible and competitive in the market. Therefore, continuous innovation and production efficiency are essential for the success of this expanding sector.

CONCLUSION

The utilization of pulses in developing meat analogs offers notable advantages, including enhanced nutritional profiles, such as high-quality protein content, dietary fibers, and essential micronutrients, supporting healthier dietary patterns and cardiovascular benefits. Furthermore, pulse-based products significantly reduce environmental impact compared to conventional meat production, aligning with growing consumer demand for sustainability. Technologically, advanced methods such as protein isolation and extrusion allow pulses to mimic the desirable textures and sensory characteristics of meat. However, key challenges remain, particularly related to overcoming the inherent off-flavors and achieving flavor profiles acceptable to traditional meat consumers. Competitive pricing and scalability of pulse-based meat analogs are essential for broader market penetration. Additionally, regulatory frameworks must adapt swiftly to support innovation while ensuring product safety and transparency. Continued research and consumer education are critical for the widespread acceptance and market success of pulse-derived meat analogs.

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