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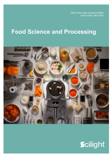

Review

Psyllium (*Plantago ovata*) in Meat Product Reformulation: Technological, Nutritional, and Functional Perspectives

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Abstract: This review summarizes current knowledge on the technological, nutritional, and functional applications of psyllium (*Plantago ovata*) in meat products. It discusses the structural and compositional characteristics of psyllium that underlie its hydrocolloid behavior, including water-binding, emulsifying, and gelling capacities, and examines its impact on emulsion stability, texture, oxidative stability, and sensory quality across different meat matrices. The review also explores psyllium's nutritional contributions as a source of soluble dietary fiber and its potential to reduce fat, sodium, and phosphate content. Recent advances in its molecular interactions with myofibrillar proteins and biopolymers, and its use in emerging processing technologies, are critically evaluated. Research gaps and future perspectives are highlighted, emphasizing the need for mechanistic understanding, process optimization, and validation of bioactive effects in psyllium-enriched meats. Overall, this review positions psyllium as a multifunctional ingredient for developing healthier, cleaner-label, and more sustainable meat products.

Keywords: psyllium; meat products; dietary fiber; gel formation; fat replacement; clean-label

1. Introduction

Meat and meat products play a central role in human nutrition as important sources of high-quality proteins, essential amino acids, minerals, and B vitamins. Despite this nutritional relevance, conventional formulations often contain excessive levels of sodium chloride and saturated fats, components directly associated with hypertension, obesity, and cardiovascular diseases [1]. The growing demand for healthier foods has therefore encouraged the meat industry to reformulate traditional products to maintain sensory and technological quality while reducing these critical compounds [2].

Among the strategies proposed, the incorporation of functional ingredients from plant sources has gained particular relevance. Fibers and hydrocolloids derived from plants can modify the physicochemical behavior of meat matrices, influencing water retention, emulsification, and gel formation. Psyllium (*Plantago ovata*), in particular, has attracted increasing attention for its unique composition and multifunctional potential. The seed husk of psyllium is rich in soluble arabinoxylans and galacturonic acid residues, polysaccharides that provide high water-binding, swelling, and gel-forming capacity. When hydrated, psyllium forms a viscous mucilage capable of retaining several times its weight in water, generating a stable three-dimensional network that can partially replicate the functional role of fat or phosphate additives in processed meats [3,4].

Beyond its technological contributions, psyllium provides relevant nutritional and physiological benefits. Its soluble fiber forms viscous gels in the gastrointestinal tract that can reduce cholesterol absorption, moderate glucose release, improve intestinal function, and increase satiety. These properties, supported by numerous clinical studies, highlight psyllium's potential as a natural, clean-label ingredient that can add both technological value and health benefits to reformulated meat products [5,6].

Recent investigations have explored its incorporation into different meat product categories, including emulsified sausages [7–9], luncheon meats [9], fermented sausages [10], patties and nuggets [11–13]. Results indicate that psyllium can act as a fat replacer, stabilizer, antioxidant, and texturizing agent, improving yield, oxidative stability, and sensory quality when used in appropriate concentrations. Complementary studies at the molecular level suggest that psyllium interacts with myofibrillar proteins through hydrogen bonds and electrostatic associations, forming mixed protein–polysaccharide networks that enhance viscoelasticity and gel strength. This structural interaction provides a mechanistic explanation for the technological effects observed in complex meat systems.

Given the growing body of evidence, this review aims to integrate current knowledge on psyllium applications in meat products from technological, nutritional, and functional perspectives. It critically discusses its chemical composition, mechanisms of interaction with muscle proteins, impacts on physicochemical and sensory characteristics, and its potential contribution to cleaner and more sustainable meat formulations.

2. Chemical Composition and Functional Properties of Psyllium

Psyllium is derived from the husk surrounding the seeds, which accounts for roughly 25–30% of the total seed mass and contains the compounds responsible for its distinctive functionality. The husk is composed mainly of soluble polysaccharides, predominantly arabinoxylans, along with minor proportions of L-arabinose, D-xylose, rhamnose, and galacturonic acid residues. Structurally, these polymers consist of β-(1→4)-linked D-xylopyranose units partially substituted with α-L-arabinofuranose side chains, conferring a high degree of branching and hydrophilicity. This molecular configuration explains psyllium's strong affinity for water and its ability to form viscous, stable gels even at low concentrations [4,14].

When dispersed in water, psyllium mucilage swells and develops a three-dimensional network stabilized by hydrogen bonding. This network exhibits exceptional water-retention capacity, conferring the material high water-holding capacity and viscosity, both essential for its function as a hydrocolloid in food processing [15,16]. The gel strength and viscosity depend on particle size, concentration, temperature, and ionic strength, which must be optimized to ensure consistent behavior in meat matrices [17]. Within meat systems, psyllium behaves similarly to other natural hydrocolloids, enhancing thickness, emulsion stability, fat and water binding, and overall texture.

Beyond its rheological properties, psyllium provides relevant nutritional and bioactive benefits. It's soluble fiber forms viscous gels in the gastrointestinal tract, reducing cholesterol absorption, moderating glucose release, and promoting colonic fermentation, producing short-chain fatty acids that contribute to intestinal health [18]. The husk also contains small amounts of phenolic and flavonoid compounds that exhibit antioxidant activity [19], which can delay lipid oxidation in processed meats, an effect particularly advantageous in phosphate-free formulations.

Arabinoxylans in psyllium interact with myofibrillar proteins through hydroxyl and carboxyl groups, forming hydrogen and ionic bonds that strengthen emulsification and gelation. These interactions enhance water and fat retention, reduce cooking losses, and improve viscoelastic properties [3]. Consequently, psyllium can compensate for the functional loss that typically occurs in low-salt, low-fat, or phosphate-reduced formulations. Its light color and neutral flavor facilitate its inclusion in various processed meats without negatively affecting appearance or taste at concentrations around 1–2%. However, higher levels may increase firmness or alter color due to dense gel formation [9].

Overall, psyllium's technological performance stems from its complex polysaccharide composition, strong hydrophilicity, and ability to form stable gels. These characteristics, combined with its physiological effects, make psyllium a multifunctional ingredient that can improve both product stability and nutritional value. In the context of meat reformulation, it represents a promising tool for developing clean-label, fiber-enriched products that meet modern expectations for health and sustainability.

3. Mechanisms of Interaction between Psyllium and Myofibrillar Proteins

The technological functionality of psyllium in meat products is largely determined by its molecular interactions with myofibrillar proteins, mainly myosin and actin, which are responsible for the gelling, emulsifying, and water-binding properties that define texture and stability in processed meats. Understanding how these biopolymers interact is crucial for explaining psyllium's ability to reinforce the structural and rheological characteristics of reduced-fat, low-salt, or phosphate-free formulations.

Arabinoxylans, the predominant polysaccharides in psyllium, contain hydroxyl and carboxyl functional groups capable of establishing hydrogen bonds, ionic bridges, and hydrophobic associations with amino acid residues on myofibrillar proteins. These bonds can subtly alter protein conformation, promoting partial unfolding that exposes hydrophobic regions and sulfhydryl groups, thereby favoring crosslinking and gel network formation [20,21]. The proposed molecular mechanism of these psyllium–protein–water interactions, illustrating hydrogen bonding and interfacial network formation within the meat matrix, is schematically represented in Figure 1. When properly balanced, these interactions create a more homogeneous, cohesive gel structure, thereby enhancing elasticity and water retention. However, excessive polysaccharide addition may lead to steric hindrance or phase separation, impairing protein–protein contact and weakening gel strength [22].

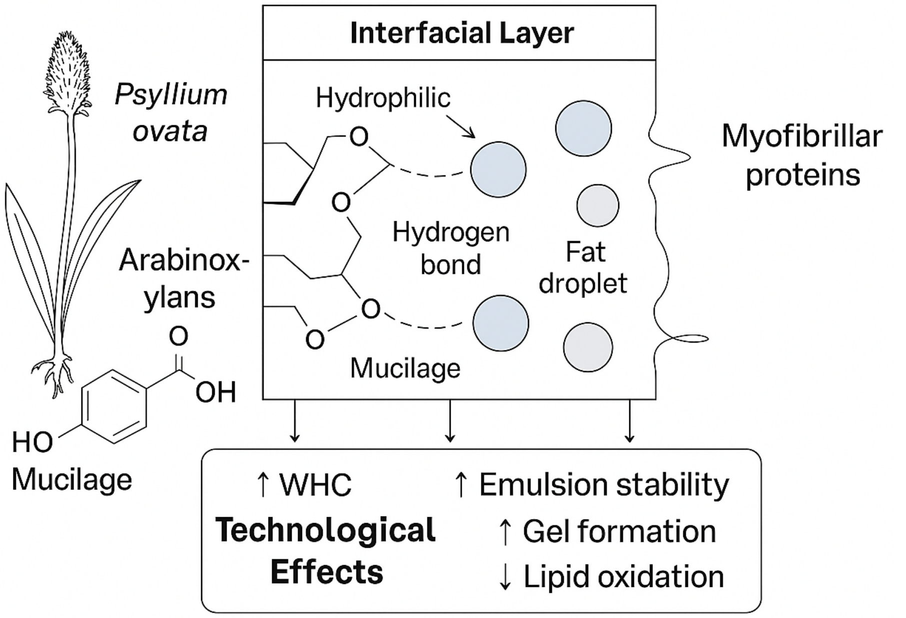

Figure 1. Mechanistic representation of psyllium-protein-water interactions in meat matrices supported by evidence from spectroscopy, rheology, and microscopic analyses.

Spectroscopic and rheological evidence support the hypothesis that psyllium increases the storage modulus (G′) and decreases tan δ of myofibrillar protein gels, indicating stronger viscoelasticity and elasticity [20]. These effects are associated with a denser and more continuous protein–polysaccharide network reinforced by hydrogen bonding. Microscopic analyses further show that psyllium addition promotes a fine, compact gel matrix with smaller pores, effectively trapping water and reducing syneresis, thereby improving cooking yield and textural uniformity [21].

Processing conditions strongly influence the strength and nature of these interactions. pH, ionic strength, temperature, and shear intensity can all determine the degree of protein–polysaccharide association. Under moderate salt concentrations, electrostatic interactions favor complex formation, whereas high ionic strength tends to mask charges and weaken the effect. Interestingly, combining psyllium with emerging technologies such as ultrasound or high-pressure treatment has been shown to enhance its functional efficiency. Bi et al. [21] observed that ultrasound-assisted gelation of goose myofibrillar proteins increased solubility, exposed reactive sites, and generated stronger protein-polysaccharide crosslinks, yielding gels with superior water-holding capacity and gel strength compared to non-sonicated controls. Such synergistic effects open the door to integrating psyllium into modern processing strategies to improve texture and stability in reformulated meats.

From a mechanistic standpoint, current evidence supports a conceptual model in which psyllium arabinoxylans interact primarily with myosin tails and head domains through hydrogen bonding and electrostatic forces during thermal denaturation. These interactions moderate protein aggregation and facilitate the formation of flexible three-dimensional networks that retain both water and lipids. At moderate inclusion levels (around 1–2%), the resulting gels exhibit optimal elasticity and hydration, whereas concentrations above 3% may lead to over-viscous systems and undesirable rigidity.

In summary, psyllium contributes to the structural organization of meat matrices through molecular and physicochemical interactions that modify protein conformation, enhance gelation dynamics, and strengthen network integrity. The improvements in gel strength, emulsion stability, and water-holding capacity observed across various meat systems can be attributed to this synergistic behavior between myofibrillar proteins and polysaccharides. Further investigation using advanced techniques such as molecular docking, small-angle X-ray scattering, and atomic force microscopy could help clarify the kinetics of these interactions and guide optimized application of psyllium in next-generation meat formulations.

4. Technological Applications of Psyllium in Meat Products

The integration of psyllium into meat formulations has progressed from simple fiber enrichment to a multifaceted technological approach that can improve emulsion stability, gel formation, cooking yield, and oxidative stability. Its functional impact depends on product type, concentration, and interaction with proteins, lipids, and salts, which together determine its overall performance in the matrix. A summary of the main technological outcomes reported for different product types is presented in Table 1.

In emulsified cooked sausages, such as frankfurters, mortadella, and luncheon meats, psyllium has demonstrated strong potential as a water-binding and stabilizing agent. Studies have shown that adding 3–5% psyllium fiber to boiled sausages increases water and fat retention, enhances cooking yield, and reduces lipid oxidation without compromising sensory attributes [7]. Zhao et al. [9] reported that 0.75–1.5% psyllium could successfully replace phosphate salts in luncheon meat, reducing cooking losses by about 10–15% while maintaining firmness and improving oxidative stability. These findings suggest that psyllium's high hydration capacity and mucilage structure mimic the water-binding effect of phosphates through physical rather than ionic mechanisms.

In fermented sausages, psyllium's gel-forming ability allows partial replacement of animal fat while maintaining the structural integrity essential for sliceability and flavor development. Jovanovichs et al. [10] replaced 15–30% of pork back fat in salamis with psyllium–linseed gels and observed a 25–30% reduction in total fat along with improved lipid profiles and acceptable sensory quality. Lower substitution levels maintained cohesiveness and moisture stability, while higher ones led to excessive oxidation and firmness, emphasizing the need for formulation balance.

Applications in restructured meats, burgers, and nuggets have also yielded positive results. Kausar et al. [11,13] found that adding 1–3% psyllium to meat patties reduced fat by up to 39%, improved water-holding capacity, and extended shelf life through lower lipid oxidation. The resulting products were described as juicier and more cohesive. Similar behavior was observed in nuggets, where psyllium produced low-fat matrices with textural properties similar to those of traditional counterparts [12].

As clean-label formulations gain momentum, psyllium has emerged as a viable natural alternative to synthetic phosphates and carrageenan. Osheba et al. [23] demonstrated that psyllium provided stabilizing effects comparable to those of carrageenan and guar gum in beef sausages, while Zhao et al. [9] confirmed that 1.5% psyllium replicated phosphate functionality in emulsions. In addition, its mild antioxidant effect supports product stability during refrigerated storage.

Although most studies have focused on traditional meat products, psyllium's hydrocolloid behavior also positions it as a valuable structuring component in plant-based or hybrid meat formulations. Gao et al. [24] highlighted its compatibility with plant proteins and its ability to enhance water retention and textural uniformity in meat analogues that often suffer from dryness or fragmentation.

Taken together, these studies reveal that psyllium can act simultaneously as an emulsifier, stabilizer, fat mimetic, and antioxidant, allowing manufacturers to design healthier, additive-free meat products without compromising sensory quality. Optimal inclusion levels typically range from 1–2% in emulsified systems to up to 15% in gel-based fat replacers. However, excessive addition can increase viscosity or hardness, which must be controlled through proper hydration and process optimization. In this context, psyllium represents a versatile ingredient capable of bridging technological and nutritional objectives in the reformulation of modern meat products.

Table 1. Technological effects of psyllium addition in different meat products.

Meat Product	Psyllium Form/Level	Main Technological Effects	Oxidative Stability	Sensory Impact	References
Boiled sausage	Psyllium husk fiber, 3–5%	↑ Cooking yield, ↑ water-holding capacity, improved texture, and sliceability	↓ TBARS values during storage	No significant changes in flavor or color	[7]
Phosphate-free luncheon meat	Psyllium husk powder, 0.75–1.5%	↑ Emulsion stability, ↓ cooking loss (~10–15%), improved firmness	Comparable to phosphate control	Similar sensory quality to phosphate-containing samples	[9]

Table 1. *Cont.*

Meat Product	Psyllium Form/Level	Main Technological Effects	Oxidative Stability	Sensory Impact	References
Chicken sausage	Psyllium flour, 10–15%	↑ Water retention, improved color stability, and juiciness	↓ Lipid oxidation due to phenolics	Enhanced juiciness and overall acceptability	[25]
Salami (dry-cured)	Gel of psyllium or psyllium + linseed oil (15–30%)	Partial fat replacement; maintained fermentation and cohesiveness	↑ PUFA/SFA ratio; no oxidation increase at 15%	Acceptable up to 15%; slight rancidity at 30%	[10]
Goat meat patties/nuggets	Psyllium husk (1–3%) or combined with fenugreek	↓ Fat content (~30–40%), ↑ water binding, improved texture	↓ Lipid oxidation	High acceptance; better tenderness and juiciness	[11–13]
Meat patties	Psyllium husk powder, 1–2%	↑ Water-holding capacity and yield	ND	Slightly firmer texture at >2%	[20]
Goose myofibrillar protein gels	Psyllium husk + ultrasound	↑ Gel strength, viscoelasticity, WHC	ND	ND	[21]
Beef sausage	Psyllium husk among vegetal colloids	Improved texture and moisture retention	ND	Comparable to carrageenan and guar gum	[23]

Abbreviations: ↑ increase; ↓ decrease; WHC = water-holding capacity; ND = not determined; PUFA = polyunsaturated fatty acids; SFA = saturated fatty acids; TBARS = thiobarbituric acid reactive substances.

5. Nutritional and Functional Benefits of Psyllium-Enriched Meat Products

The incorporation of psyllium husk into meat formulations not only improves technological performance but also adds considerable nutritional and physiological value. Owing to its exceptionally high soluble fiber content, psyllium is one of the richest natural sources of viscous arabinoxylans, containing roughly 70–85% soluble polysaccharides [26]. When ingested, these fibers form highly viscous gels in the gastrointestinal tract, slowing nutrient absorption and modulating lipid and glucose metabolism. Thus, reformulated meat products containing psyllium are not merely lower in fat or sodium but also become functional foods that can actively support cardiometabolic health. The main nutritional and functional outcomes reported for psyllium-enriched meat products are summarized in Table 2.

One of the most immediate nutritional effects of psyllium inclusion is the substantial increase in total dietary fiber. Formulations enriched with 3–5% psyllium can provide up to 4 g of soluble fiber per 100 g of product, sufficient to meet labeling criteria for "source of fiber" in most jurisdictions [7]. The same water-binding capacity that improves yield in processing also allows partial replacement of fat, reducing overall energy density while maintaining juiciness. In meat patties and nuggets, for instance, the addition of 1–3% psyllium reduced fat content by nearly 40%, decreased total cholesterol, and lowered caloric value without impairing consumer acceptance [12,13]. Similarly, salamis containing psyllium–linseed gels exhibited reductions of 25–30% in total fat and a more favorable lipid profile [10].

Table 2. Nutritional and functional effects of psyllium incorporation in meat products.

Meat Product	Psyllium Level	Nutritional Impact	Functional/Health Benefit	References
Boiled sausage	3–5%	+4–6 g total dietary fiber/100 g; ↓ fat content	Meets "source of fiber" claim; potential satiety effect	[7]
Goat patties	1–3%	↓ total fat (~39%), ↓ cholesterol, ↓ calories	Weight management potential; improved lipid profile	[11,13]
Salami	15–30% fat replaced by psyllium–linseed gel	↓ total fat (25–30%), ↑ omega-3 PUFA, improved lipid ratio	Cardioprotective fatty acid profile	[10]
Chicken sausage	10–15%	↑ fiber content, ↓ oxidation	Antioxidant activity; clean-label formulation	[25]
Luncheon meat	1.5%	Comparable protein and fat; ↑ fiber; phosphate-free	Functional ingredient replacing synthetic additives	[9]
Review of psyllium fiber	—	Demonstrated cholesterol and glucose reduction	Cardiometabolic health benefits when regularly consumed	[26] *

* Refer to review data extrapolated to contextualize the potential health implications of psyllium-enriched meat products. PUFA = polyunsaturated fatty acids.

Beyond its compositional impact, psyllium has well-documented physiological benefits in clinical nutrition. Its viscous gel binds bile acids and promotes their excretion, thereby reducing serum cholesterol, while also delaying glucose uptake and lowering postprandial glycemia. Regular intake of psyllium fiber has been associated with decreases of 5–10% in total cholesterol and up to 15% in LDL cholesterol [19]. When incorporated into meat products, these effects are expected to persist, as the food matrix provides an additional source of protein that further modulates glycemic response. Consequently, psyllium-fortified meats could help reduce cardiovascular risk factors, although controlled human studies are still required to confirm these effects under realistic consumption scenarios.

A further contribution of psyllium relates to intestinal health. The soluble arabinoxylans serve as fermentable substrates for beneficial gut bacteria, leading to the production of short-chain fatty acids—acetate, propionate, and butyrate—that enhance mucosal integrity and reduce intestinal inflammation [27,28]. Given that most consumers have low habitual fiber intake, using widely consumed foods such as meat as delivery vehicles for prebiotic fibers is a practical strategy for improving gut microbiota composition at the population level.

Psyllium also provides modest antioxidant protection owing to its phenolic and flavonoid content to the physical barrier formed by its viscous matrix, which limits oxygen diffusion into lipid-rich systems [29]. These properties help retard lipid oxidation in meat products and can enhance product shelf life [23]. When combined with other bioactive compounds such as plant extracts, psyllium helps retain antioxidants within the gel network, amplifying oxidative stability and reducing the need for synthetic additives.

From a nutritional policy perspective, psyllium-enriched meats align closely with global recommendations from the WHO and FAO to reduce saturated fat and sodium intake while increasing fiber intake. Such products could also support functional or health-claim labeling related to cholesterol reduction, improved glycemic control, or digestive health, depending on regulatory frameworks. Consumer studies have shown that moderate inclusion levels, typically 1–2% in emulsions or up to 15% in fat-replacement gels, maintain or even enhance sensory acceptability [7,13].

Overall, the nutritional and functional advantages of psyllium in meat systems encompass several dimensions: fiber enrichment, energy reduction, antioxidant protection, and modulation of lipid and glucose metabolism. These benefits can be achieved without detrimental effects on sensory quality, making psyllium an ideal candidate for the development of next-generation meat products that integrate technological functionality with tangible health value.

6. Sensory and Consumer Acceptance

The incorporation of psyllium into meat formulations inevitably influences sensory perception, as modifications in water-binding capacity, gel structure, and fat content can alter texture, appearance, and flavor. However, most evidence indicates that, when properly optimized, psyllium improves or at least preserves overall consumer acceptance. The key lies in balancing its technological benefits with palatability, as excessive inclusion can lead to excessive firmness or viscosity.

From a textural standpoint, moderate psyllium levels (around 1–2%) tend to increase cohesiveness and elasticity, producing a firmer but juicier mouthfeel that consumers associate with freshness and quality. In emulsified sausages, such as frankfurters and luncheon meats, psyllium reduced exudate formation during cooking and storage, yielding slices with a more compact and uniform structure [7,9]. The higher water retention contributes to juiciness, while the resulting gel network enhances sliceability. Conversely, inclusion levels above 3% often cause a rubbery or gummy sensation due to matrix overhydration [8,20]. These effects highlight the importance of controlling both hydration time and mixing intensity to ensure uniform dispersion within the emulsion.

Color attributes are only slightly affected by the incorporation of psyllium. Owing to its naturally beige hue and high hydration capacity, minor decreases in lightness (L*) and redness (a*) have been reported in sausages and patties, though the changes usually remain below the sensory detection threshold [7,30]. Interestingly, products containing psyllium often exhibit a glossier surface and a more hydrated appearance, which can enhance visual appeal in sliced or cooked items [9]. In salamis, psyllium gels did not interfere with pigment development or ripening color, confirming their compatibility with nitrite-curing systems [10].

Flavor perception is another critical factor for consumer acceptance, and psyllium performs well in this respect. It has a neutral taste and lacks volatile compounds that might mask characteristic meat notes. Studies on chicken, beef, and goat meat products consistently show no significant differences in flavor intensity or aroma between psyllium-containing and control samples at moderate inclusion levels [13,25]. In some cases, panelists even described enhanced juiciness and more balanced seasoning, likely due to the ingredient's ability to retain moisture and distribute flavor compounds more evenly. However, when psyllium is combined with unsaturated oils, as in linseed-based gels, off-flavors can appear from lipid oxidation unless antioxidants or protective packaging are used [10].

Regarding overall acceptability, consumers have shown high tolerance for psyllium-enriched products. Aleshkov et al. [7] reported that sausages with up to 5% psyllium received sensory scores statistically comparable to controls. Similar findings were observed by Kausar et al. [13], who noted improved tenderness and juiciness in goat meat patties containing 2–3% psyllium. Zhao et al. [9] also confirmed that luncheon meats with 1.5% psyllium achieved parity with phosphate-containing controls in both texture and flavor evaluation. Together, these data demonstrate that psyllium can be successfully incorporated without compromising sensory appeal when used within optimized limits.

From a marketing standpoint, psyllium offers advantages that extend beyond sensory neutrality. Consumers increasingly value "high-fiber", "reduced-fat", and "phosphate-free" labels, and products meeting these expectations benefit from health-oriented positioning. Psyllium allows manufacturers to achieve these claims while maintaining desirable sensory profiles, which supports consumer trust and repeat purchase intent. Future sensory studies should explore cross-cultural preferences and willingness to pay, as acceptance may vary among markets depending on dietary habits and awareness of functional ingredients.

In conclusion, psyllium's neutral flavor, moisture-retention ability, and contribution to cohesive texture make it a suitable ingredient for reformulated meat products that satisfy both health and sensory criteria. When properly dosed and hydrated, it maintains color, flavor, and texture at levels equivalent to those of conventional formulations, ensuring that the pursuit of cleaner, healthier labels does not come at the expense of eating quality.

7. Technological Challenges and Optimization Strategies

Although psyllium has proven to be a versatile ingredient in meat reformulation, its use presents several technological and formulation challenges that must be carefully managed to achieve consistent quality and scalability. These challenges arise mainly from its strong hydrophilicity, complex rheological behavior, and sensitivity to processing conditions. Achieving a balance between functionality and sensory quality requires precise control of hydration, dispersion, and interaction with other components in the matrix.

One of the main difficulties is controlling psyllium's water-binding capacity and viscosity. Its ability to absorb large amounts of water, while beneficial for yield and juiciness, can lead to over-gelation or excessive firmness if used at high levels or under inadequate hydration conditions. When psyllium absorbs water too rapidly, it may form localized agglomerates that hinder uniform protein extraction and emulsification, leading to a heterogeneous texture. Pre-hydration is therefore essential: allowing psyllium to swell in water for about ten to fifteen minutes before incorporation ensures more uniform dispersion and consistent gel formation. The use of fine or micronized psyllium particles can also minimize graininess and improve integration with the protein matrix.

Optimizing the psyllium concentration in the formulation is another key factor. In emulsified systems such as mortadella or frankfurters, optimal levels typically range from 0.75 to 2%, sufficient to improve emulsion stability without negatively affecting mouthfeel. In restructured or low-fat products, higher concentrations of up to 10–15% in preformed gels can be used to replace animal fat while maintaining desirable structure and cohesiveness. Exceeding these levels, however, tends to increase hardness and decrease cohesiveness due to excessive viscosity. Experimental modeling techniques, such as response surface methodology, have proven useful for defining optimal ratios of psyllium, protein, and fat and for understanding synergistic interactions with other hydrocolloids or plant proteins.

Compatibility with other ingredients also plays an important role. The performance of psyllium is influenced by salt concentration, pH, and ionic strength, all of which affect the electrostatic balance in the system. High sodium chloride levels, for instance, can compete with psyllium for water molecules, reducing its swelling capacity. Likewise, the removal of phosphates alters the charge distribution on myofibrillar proteins, thereby altering how they interact with polysaccharides. To achieve optimal textural and stabilizing effects, psyllium can be combined with other hydrocolloids such as carrageenan, guar gum, or pectin. These mixtures often yield complementary effects, where psyllium enhances water retention and viscosity, while other gums improve elasticity and network strength. When used with plant oils such as linseed or chia, psyllium also helps stabilize oil-in-water systems, though oxidation control remains essential to prevent flavor deterioration.

Processing parameters have a marked influence on psyllium's behavior. Excessive shear during mixing can disrupt the polymeric chains, while insufficient agitation can lead to uneven hydration. Thermal treatment is equally critical: gradual heating between 40 and 75 °C favors the formation of uniform protein–polysaccharide gels, whereas rapid heating may cause premature gelation of psyllium before complete protein denaturation, leading to phase separation. Emerging technologies such as ultrasound-assisted processing have shown potential to enhance psyllium-protein interactions by promoting protein unfolding and crosslinking, thereby increasing gel strength and water-holding capacity. Such process-integrated approaches may provide the key to maximizing psyllium's efficiency in industrial-scale applications.

Storage stability represents another practical challenge. The high water activity associated with psyllium-rich systems may increase microbial susceptibility if not properly managed. Adjustments in packaging, such as vacuum sealing or modified-atmosphere systems, are recommended to control spoilage and maintain freshness. Although psyllium's inherent antioxidant capacity contributes to lipid stability during refrigerated storage, its long-term behavior in frozen or vacuum-packed products remains under investigation. Over time, partial retrogradation of polysaccharides or structural relaxation may affect texture and moisture distribution, emphasizing the need for shelf-life studies.

Finally, considerations related to cost, sourcing consistency, and scalability must be addressed for widespread industrial adoption. Variability in mucilage yield and viscosity across suppliers can lead to inconsistent performance, underscoring the importance of standardized quality parameters, such as the hydration index and purity. Economically, substituting phosphates or animal fat with psyllium can be cost-neutral or even advantageous when the nutritional and marketing benefits (clean label, reduced fat, and high fiber claims) are considered.

In summary, the successful use of psyllium in meat systems depends on the precise control of its hydration and dispersion, optimization of concentration and process conditions, and compatibility with other components. Combining psyllium with complementary ingredients, leveraging modern processing techniques, and establishing standardized quality metrics will be crucial to unlocking its full potential. Addressing these challenges through coordinated efforts in food chemistry, process engineering, and sensory science will enable psyllium to evolve from a promising additive to a cornerstone ingredient in healthier, more sustainable meat products.

8. Environmental and Sustainability Aspects

The growing emphasis on sustainability within the food industry has intensified the search for ingredients that not only improve nutritional and technological performance but also align with environmentally responsible production systems. Psyllium stands out as a renewable, low-impact raw material that supports this broader vision of sustainable meat processing. Its cultivation requires minimal water, fertilizers, and pesticides, and it thrives in semi-arid regions where few other crops are economically viable. Compared with the production of synthetic hydrocolloids or animal-derived stabilizers, psyllium cultivation and processing generate significantly lower greenhouse gas emissions and waste, positioning it as a resource-efficient alternative.

The processing of psyllium husk also aligns with circular-economy principles. The primary by-product of husk extraction—residual seed material—can be used as a source of insoluble fiber or incorporated into animal feed, thereby minimizing waste. Moreover, since the mucilage is extracted through mechanical and aqueous methods rather than chemical synthesis, the production process has a relatively small environmental footprint. This sustainability profile adds value to psyllium's application in the food sector, especially in reformulated meat products where clean-label positioning and environmental responsibility are key market drivers.

In the context of meat technology, the inclusion of psyllium indirectly improves environmental efficiency by enhancing water retention and product yield, thereby reducing cooking losses and food waste. Even small improvements in yield translate into lower energy and water consumption at an industrial scale, since less raw material is required to produce the same amount of finished product. These effects are particularly relevant for high-throughput operations, where incremental process efficiency has measurable environmental benefits.

Additionally, psyllium's ability to replace synthetic additives such as phosphates supports the transition toward formulations with reduced reliance on chemically processed inputs. Given that phosphate extraction and purification are energy-intensive processes, the use of psyllium as a functional substitute offers both environmental and regulatory advantages. Its plant origin, biodegradability, and lack of chemical modification make it well-suited for manufacturers seeking to comply with sustainability certifications and consumer expectations for natural ingredients.

Beyond traditional meat applications, psyllium is also relevant to the development of hybrid and plant-based meat alternatives. When combined with plant proteins, its strong water-binding and gelling capacities help compensate for the lack of myofibrillar proteins, thereby improving texture and juiciness—two of the main challenges in alternative protein formulations. By enabling partial substitution of animal ingredients without compromising sensory quality, psyllium can help reduce the environmental burden of livestock production, supporting global goals for responsible consumption and climate mitigation.

Ultimately, incorporating psyllium into meat reformulation strategies exemplifies how technological innovation can converge with sustainability. Its use not only supports cleaner and healthier food design but also aligns with several United Nations Sustainable Development Goals, particularly SDG 12 (Responsible Consumption and Production) and SDG 13 (Climate Action). In this sense, psyllium represents more than a functional hydrocolloid: it embodies a model of ingredient innovation rooted in environmental stewardship and resource efficiency, advancing the shift toward a more sustainable and resilient meat industry.

9. Future Trends, Challenges, and Perspectives

Although the technological and nutritional benefits of psyllium in meat reformulation are increasingly evident, several knowledge gaps remain that limit its optimized and standardized application at the industrial level. Future research must move beyond empirical formulation adjustments to a deeper understanding of the molecular, structural, and sensory mechanisms that define psyllium's multifunctional behavior within complex food matrices.

At the molecular level, the interaction between psyllium arabinoxylans and myofibrillar proteins remains poorly understood. While current studies suggest the formation of hydrogen bonds, ionic interactions, and entanglement networks, the kinetics and spatial organization of these associations remain poorly characterized. Applying advanced analytical tools such as molecular docking, small-angle X-ray scattering, or atomic force microscopy could provide mechanistic insights into how psyllium affects protein unfolding, aggregation, and crosslinking during heating. Such information would allow the prediction and control of gelation dynamics, supporting the rational design of formulations with targeted textural properties.

Another promising direction involves the synergistic combination of psyllium with other natural biopolymers. Blending psyllium with inulin, pectin, β-glucans, or plant proteins could enhance both gel strength and water-holding capacity, while tailoring texture to specific product types. These interactions may be particularly advantageous in low-fat or low-salt formulations, where the functional performance of myofibrillar proteins is reduced. Optimizing the ratios and hydration profiles of these composite systems could open new possibilities for cleaner and more efficient formulations.

Emerging processing technologies represent a parallel frontier for exploration. Techniques such as ultrasound-assisted emulsification, high-pressure processing, or enzymatic crosslinking have shown potential to improve the dispersion and interaction of psyllium with muscle proteins. Integrating these methods may lead to more uniform gels, enhanced oxidative stability, and improved microstructural homogeneity, particularly in phosphate-free emulsions. Future studies should also examine the effect of combined treatments, such as ultrasound coupled with enzymatic modification, on the molecular flexibility and hydration behavior of psyllium networks.

While most research has focused on technological and compositional aspects, the nutritional and physiological implications of consuming psyllium-enriched meat products remain largely unexplored. The health benefits of psyllium are well documented in supplement or bakery contexts, but few studies have evaluated its bioactivity when incorporated into meat matrices. It is important to verify whether the cholesterol-lowering, glycemic-modulating, and prebiotic effects observed in isolated systems persist in the presence of proteins, fats, and curing agents. Controlled human or in vivo studies could validate these outcomes and provide evidence for future functional or health claims related to psyllium-fortified meats.

Consumer perception research also deserves greater attention. Acceptance of psyllium-enriched meat products will depend not only on sensory performance but also on the perceived health value and naturalness of the ingredient. Cross-cultural studies comparing markets with different dietary traditions could help identify marketing strategies and communication approaches that best highlight psyllium's dual benefits—its technological and functional attributes. Understanding consumer willingness to pay for products labeled as "fiber-enriched," "phosphate-free," or "clean-label" will be essential for successful commercialization.

Finally, sustainability-oriented innovation will continue to shape psyllium's future role in meat processing. With growing demand for ingredients that contribute to environmental efficiency, psyllium's plant origin and biodegradability position it as a model hydrocolloid for circular food design. Exploring its application in hybrid and plant-based meat systems could further reduce environmental impact while expanding its technological relevance. The convergence of molecular science, processing innovation, and sustainable product design is likely to define the next decade of psyllium research and its impact on the meat industry.

In essence, the exploration of psyllium in meat technology is still evolving. Progress will depend on interdisciplinary studies that bridge food chemistry, rheology, sensory science, and human nutrition to move from empirical application to predictive formulation. As these scientific and technological gaps are addressed, psyllium is expected to consolidate its position as a benchmark hydrocolloid in the design of next-generation meat products that combine functionality, nutritional enhancement, and environmental responsibility.

Author Contributions

L.P.C. and P.C.B.C.: conceptualization, methodology, data curation, writing—original draft preparation; J.M.L.: writing—reviewing and editing. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

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Use of AI and AI-Assisted Technologies

No AI tools were utilized for this paper.

References

1. Stadnik, J. Nutritional Value of Meat and Meat Products and Their Role in Human Health. *Nutrients* **2024**, *16*, 1446. https://doi.org/10.3390/nu16101446.
2. Rios-Mera, J.D.; Saldaña, E.; Patinho, I.; et al. Advances and Gaps in Studies on Healthy Meat Products and Their Relationship with Regulations: The Brazilian Scenario. *Trends Food Sci. Technol.* **2021**, *110*, 833–840. https://doi.org/10.1016/j.tifs.2021.01.092.
3. Singh, A.; Benjakul, S.; Prodpran, T.; et al. Effect of Psyllium (*Plantago ovata* Forks) Husk on Characteristics, Rheological and Textural Properties of Threadfin Bream Surimi Gel. *Foods* **2021**, *10*, 1181. https://doi.org/10.3390/foods10061181.
4. Waleed, M.; Saeed, F.; Afzaal, M.; et al. Structural and Nutritional Properties of Psyllium Husk Arabinoxylans with Special Reference to Their Antioxidant Potential. *Int. J. Food Prop.* **2022**, *25*, 2505–2513. https://doi.org/10.1080/10942912.2022.2143522.
5. Gibb, R.D.; Sloan, K.J.; McRorie, J.W. Psyllium Is a Natural Nonfermented Gel-Forming Fiber That Is Effective for Weight Loss: A Comprehensive Review and Meta-Analysis. *J. Am. Assoc. Nurse Pract.* **2023**, *35*, 468–476. https://doi.org/10.1097/JXX.0000000000000882.
6. McRorie, J.W.; Gibb, R.D.; Sloan, K.J.; et al. Psyllium: The Gel-Forming Nonfermented Isolated Fiber That Delivers Multiple Fiber-Related Health Benefits. *Nutr. Today* **2021**, *56*, 169–182. https://doi.org/10.1097/NT.0000000000000489.
7. Aleshkov, A.; Ivashkin, M.; Zhebo, A.; et al. Technology and Characteristics of Boiled Sausages Enriched with Dietary Fibers of Plantago Psyllium l. *Biointerface Res. Appl. Chem.* **2020**, *10*, 5715–5723. https://doi.org/10.33263/BRIAC104.715723.
8. Susilo, A.; Evanuarini, H.; Wahyuningsih, S.; et al. Influence of Psyllium Husk Flour Incorporation on the Physicochemical and Nutritional Properties of Chicken Sausages. *CYTA—J. Food* **2025**, *23*, 2563597. https://doi.org/10.1080/19476337.2025.2563597.
9. Zhao, Z.; Sun, N.; Li, C.; et al. Application of Psyllium Husk Powder Addition on the Textural Properties, Oxidative Stability and Sensory Attributes of Non-Phosphates Luncheon Meat. *Meat Sci.* **2025**, *222*, 109760. https://doi.org/10.1016/j.meatsci.2025.109760.
10. Jovanovichs, M.R.C.; Basso Pinton, M.B.; et al. Replacing Animal Fat with Gels of Psyllium Fiber and Combined Linseed Oil–Psyllium Fiber in Salamis: Impacts on Technological, Nutritional, Oxidative, and Sensory Properties. *Foods* **2023**, *12*, 2439. https://doi.org/10.3390/foods12132439.
11. Kausar, T.; Kausar, M.A.; Azaz Ahmad Azad, Z.R. Improving the Quality and Shelf Life of Goat Meat Patties with Herb and Husk Incorporation. *Biochem. Cell. Arch.* **2018**, *18*, 1569–1576.
12. Kausar, T.; Kausar, M.A.; Khan, S.A.; et al. Optimum Additive Composition to Minimize Fat in Functional Goat Meat Nuggets: A Healthy Red Meat Functional Food. *Processes* **2021**, *9*, 475. https://doi.org/10.3390/pr9030475.
13. Kausar, T.; Bashir, K.; Jan, S.; et al. Optimizing Psyllium Husk and Fenugreek Leaves in Meat Patties: Enhanced Nutrition, Reduced Cholesterol and Improved Texture and Color. *J. Food Meas. Charact.* **2024**, *18*, 3287–3299. https://doi.org/10.1007/s11694-024-02403-2.

14. Qaisrani, T.B.; Qaisrani, M.M.; Qaisrani, T.M. Arabinoxylans from Psyllium Husk: A Review. *J. Environ. Agric. Sci.* **2016**, *6*, 33–39.
15. Assi, A.G.; Kalkan, E.; Maskan, M. Effect of Extraction Conditions on the Extraction Yield, Swelling Capacity, Emulsion Capacity and Emulsion Stability of Psyllium Husk Seed Mucilage Extracted from Plantago Ovate. 2023. Available online: https://doi.org/10.21203/rs.3.rs-3610684/v1 (accessed on 1 November 2025).
16. Geremew Kassa, M.; Alemu Teferi, D.; Asemu, A.M.; et al. Review on Psyllium Husk: Nutritional, Functional, Health Benefits, Food Industry Applications, Waste Treatment, and Potential Negative Effects. *CyTA—J. Food* **2024**, *22*, 2409174. https://doi.org/10.1080/19476337.2024.2409174.
17. Farahnaky, A.; Askari, H.; Majzoobi, M.; et al. The Impact of Concentration, Temperature and PH on Dynamic Rheology of Psyllium Gels. *J. Food Eng.* **2010**, *100*, 294–301. https://doi.org/10.1016/j.jfoodeng.2010.04.012.
18. Hashem, M.A.; Abd-Allah, N.A.; Mahmoud, E.A.; et al. A Preliminary Study on the Effect of Psyllium Husk Ethanolic Extract on Hyperlipidemia, Hyperglycemia, and Oxidative Stress Induced by Triton X-100 Injection in Rats. *Biology* **2021**, *10*, 335. https://doi.org/10.3390/biology10040335.
19. Chen, C.; Shang, C.; Xin, L.; et al. Beneficial Effects of Psyllium on the Prevention and Treatment of Cardiometabolic Diseases. *Food Funct.* **2022**, *13*, 7473–7486. https://doi.org/10.1039/D2FO00560C.
20. Zhou, Y.; Dai, H.; Ma, L.; et al. Effect and Mechanism of Psyllium Husk (*Plantago ovata*) on Myofibrillar Protein Gelation. *LWT* **2021**, *138*, 110651. https://doi.org/10.1016/j.lwt.2020.110651.
21. Bi, J.; Sun, Y.; Pan, D.; et al. Effect of Ultrasound Combined with Psyllium Husk Powder on the Structure and Gel Properties of Goose Myofibrillar Protein. *Process. Biochem.* **2024**, *136*, 202–211. https://doi.org/10.1016/j.procbio.2023.12.003.
22. Juanquan, C.; Xinyue, L.; Jing, X.; et al. Effects of Psyllium Husk Powder on Gel Properties and Protein Structure of Chicken Myofibrillar Protein. *Sci. Technol. Food Ind.* **2023**, *44*, 100–107. https://doi.org/10.13386/j.issn1002-0306.2022110120.
23. Maritsha, D.P.; Susilo, A.; Evanuarini, H. Application of Chicken Sausage Using Psyllium Husk Flour as a Natural Antioxidant. *Proc. BIO Web Conf.* **2025**, *165*, 05005
24. Osheba, A.S.; Hussien, S.A.; El-Dashlouty, A.A. Evaluation of Some Vegetal Colloids on the Quality Attributes of Beef Sausage. *Adv. J. Food Sci. Technol.* **2013**, *5*, 743–751. https://doi.org/10.19026/ajfst.5.3158.
25. Gao, X.; Sharma, M.; Bains, A.; et al. Application of Seed Mucilage as Functional Biopolymer in Meat Product Processing and Preservation. *Carbohydr. Polym.* **2024**, *339*, 122228. https://doi.org/10.1016/j.carbpol.2024.122228.
26. Franco, E.A.N.; Silva, A.S.; Dos Ribeiro-Santos, R.; et al. De Psyllium (*Plantago ovata* Forsk): From Evidence of Health Benefits to Its Food Application. *Trends Food Sci. Technol.* **2020**, *96*, 166–175. https://doi.org/10.1016/j.tifs.2019.12.006.
27. Mendis, M.; Leclerc, E.; Simsek, S. Arabinoxylans, Gut Microbiota and Immunity. *Carbohydr. Polym.* **2016**, *139*, 159–166. https://doi.org/10.1016/j.carbpol.2015.11.068.
28. Yang, C.; Liu, S.; Li, H.; et al. The Effects of Psyllium Husk on Gut Microbiota Composition and Function in Chronically Constipated Women of Reproductive Age Using 16S RRNA Gene Sequencing Analysis. *Aging* **2021**, *13*, 15366–15383. https://doi.org/10.18632/aging.203095.
29. Reyaz Shah, A.; Sharma, P.; Gour, V.S.; et al. Antioxidant, Nutritional, Structural, Thermal and Physico-Chemical Properties of Psyllium (*Plantago ovata*) Seeds. *Curr. Res. Nutr. Food Sci. J.* **2020**, *8*, 727–743. https://doi.org/10.12944/CRNFSJ.8.3.06.
30. Zhou, Y.; Ma, L.; Dai, H.; et al. Effect of Psyllium Husk Powder Addition on Quality of Meat Patties. *J. Food Sci. Technol.* **2019**, *37*, 42–49. https://doi.org/10.3969/j.issn.2095-6002.2019.05.006.