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Abstract

Clean-label processing and reformulation of meat and animal-based foods have received increasing attention in response to consumer demand for simplified ingredient lists and minimally processed products. However, reducing or eliminating conventional additives often compromises key quality attributes, including texture, water-holding capacity, color stability, and microbial safety. This review adopts a structure-oriented perspective, proposing that quality in clean-label meat systems arises from dynamic interactions between protein structure and processing conditions rather than from individual ingredients alone. First, the hierarchical organization of muscle and animal-derived proteins is discussed to establish the theoretical basis of structure–function relationships. Second, physical processing technologies, including high-pressure processing, ultrasound, pulsed electric fields, and cold plasma, are reviewed as non-additive approaches capable of inducing controlled protein unfolding, aggregation, and network reorganization. Third, biochemical and enzymatic strategies are examined as molecular tools for targeted protein modification, with emphasis on their roles in texture development and binding under reduced-additive conditions. Fourth, natural binders, alternative mineral systems, and antioxidants are evaluated from a structural perspective, highlighting their ability to modulate protein–water–lipid interactions rather than merely substitute conventional additives. An integrated structure–process–quality framework is proposed to comparatively evaluate clean-label technologies, elucidate trade-offs between functional enhancement and structural stability, and define matrix-specific strategies for whole muscle, comminuted, emulsified, and restructured meat products. Finally, key research gaps are identified, including the need for advanced structural characterization, synergistic processing strategy integration, and industrial-scale validation. Overall, this review conceptualizes clean-label meat reformulation as a structural engineering challenge and provides a scientifically grounded roadmap for future innovation in clean-label meat products.

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Keywords: clean-label, animal-based food, meat processing, protein structure, quality.

1. Introduction

The global meat and animal-based food industry is experiencing a fundamental shift driven by rising consumer demand for clean-label products, characterized by simplified ingredient lists and reduced use of synthetic additives [1, 2]. In contrast to plant-based foods, where clean-label reformulation was often achieved by direct ingredient substitution, meat systems present unique challenges due to their complex protein–water–lipid matrix and the critical role of additives in maintaining product quality, safety, and stability [2-4]. Traditionally, various additives, such as phosphates, nitrites, and synthetic antioxidants, have been widely used to regulate water-holding capacity, texture, color stability, and oxidative deterioration in processed meat products [5, 6]. However, increasing regulatory scrutiny and negative consumer perceptions of chemical-sounding ingredients have limited their use and accelerated the search for alternative approaches that align with clean-label principles while maintaining product quality [2, 7]. Nevertheless, most reformulation efforts have followed an ingredient-centered approach, in which conventional additives are replaced with natural ingredients that provide similar technological function. Although such substitution can simplify product labels, it does not necessarily account for how the replacement alters the organization and interactions of proteins, water, and lipids within the food matrix. Consequently, quality control strategies in meat processing should be progressively shifted toward control of matrix structure and molecular interactions.

Although the primary technological roles and broader functional contributions of individual additives have been discussed in previous reviews, a comprehensive understanding of their effect in meat systems requires a structure-based consideration of processing-included changes in meat proteins [8, 9]. In whole-muscle meat products, quality formation is closely associated with changes in the native hierarchical structure of muscle, The integrity and spatial organization of muscle fibers are influenced by the additives. In restructured and emulsified meat products, product functionality depends less on the preservation of muscle structure, and more on the extraction, unfolding, and subsequent association of myofibrillar protein. In addition, protein structure and its interactions with water and lipids are major determinants of the functional and quality attributes of these meat products [10, 11]. From this perspective, a structure-oriented framework begins not with a specific substitute ingredient, but with the structural requirements necessary to achieve the intended product functionality. Therefore, ingredient and processing interventions should account for both the modification of native muscle architecture in whole-muscle products and the formation of protein network in processed meat systems.

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Understanding the functions of conventional additives from the perspective of their effects on meat structure facilitates the identification of diverse replacement strategies beyond the use of natural ingredients with equivalent functions. Recent advances in physical processing technologies, such as high-pressure processing (HPP), ultrasound, pulsed electric field (PEF) treatment, and cold plasma, have shown considerable promise as clean-label alternatives. These technologies induce controlled structural modifications in proteins while minimizing dependence on chemical additives [12, 13]. In parallel, enzymatic and biochemical strategies enable targeted manipulation of protein networks, thereby improving texture and functional stability under clean-label conditions [14]. Natural ingredients may also contribute to product functionality through water binding, interfacial stabilization, antioxidant activity, and reinforcement of protein network. Although these technologies operate through distinct mechanisms, they frequently converge at the structural level, highlighting the need for an integrated, mechanistic understanding rather than isolated evaluation of individual approaches.

Although numerous studies have focused on specific clean-label technologies or reformulation strategies, existing reviews often emphasize regulatory considerations or ingredient substitution, with limited attention to the underlying structure–process–quality relationships in meat and animal-based foods. Accordingly, this review aims to critically examine clean-label processing technologies from structural and quality perspectives, with emphasis on how physical and biochemical interventions reshape protein structures and interactions to govern functional performance. By synthesizing current knowledge and identifying key knowledge gaps, this review seeks to provide a scientific foundation for the rational design of clean-label meat and animal-based food systems.

2. Application of the clean-label concept to meat and animal-based foods

2.1. Definition and regulatory perspectives

The term *clean-label* lacks a formally harmonized regulatory definition; however, it is widely recognized as a product development approach that emphasizes simplified ingredient lists, reduced synthetic additive use, and enhanced transparency for consumers [1]. In meat and animal-based foods, implementing clean-label principles is particularly challenging because numerous additives function as integral components that directly contribute to physicochemical stability, safety, and sensory quality rather than merely serving as formulation aids.

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In contrast to compositional regulations that explicitly define permissible ingredients and usage levels, clean-label practices in animal foods are primarily shaped by consumer perception, market expectations, and voluntary industry standards rather than legally binding criteria [7]. Nevertheless, regulatory and societal pressure to reduce nitrite, phosphate, and synthetic antioxidant use has indirectly accelerated clean-label reformulation efforts in processed meat products. These additives play critical roles in protein solubilization, water retention, cured color formation, oxidative stability, and microbial inhibition [5, 6].

Consequently, clean-label processing in meat systems involves more than simply omitting or substituting ingredients. Instead, it necessitates alternative strategies that compensate for additive functionality by modifying proteins and meat matrices through process-induced structural changes. From this perspective, the clean-label concept should be regarded as a process-oriented and structure-driven approach rather than a purely labeling or regulatory matter.

2.2. Quality challenges associated with additive reduction

Reducing or eliminating functional additives fundamentally disrupts the structural equilibrium of meat matrices, creating multiple quality challenges that must be addressed through processing-based interventions. These challenges primarily arise from impaired protein functionality, altered water distribution, and heightened susceptibility to oxidative and microbial deterioration. The principal functional roles of conventional additives and the corresponding quality challenges arising from their reduction are summarized in Table 1.

Water-holding capacity (WHC) is among the most sensitive quality attributes affected by additive reduction. Salt primarily increases ionic strength and electrostatic repulsion between myofilaments, thereby promoting myofibrillar swelling, widening the filament lattice, and facilitating the solubilization and extraction of salt-soluble myofibrillar proteins [5]. Phosphates contribute through partially distinct mechanisms, including increasing pH away from the isoelectric point of muscle proteins, enhancing negative charge repulsion, chelating divalent cations involved in protein-protein associations, and promoting actomyosin dissociation [15, 16]. When their concentrations are reduced, reduced availability of solubilized proteins results in increased purge loss, decreased cooking yield, and reduced juiciness. In clean-label formulations, the limited capacity to manipulate electrostatic interactions through formulation requires alternative approaches based on processing-induced protein unfolding, aggregation, or network restructuring. These structural modifications are essential for restoring water entrapment capacity independently of additive-driven mechanisms.

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Texture and binding properties of processed meat products are strongly influenced by cohesive protein network formation. Salt and phosphates facilitate myofibrillar protein extraction, enabling continuous and well-connected gel matrix development during heating [11, 17]. Specifically, dissociation and solubilization of myofibrillar proteins due to these additives allow protein unfolding and interactions. During meat processing before heating, such as homogenization and emulsification, soluble and unfolded proteins bind and retain water and fat due to their amphiphilic properties. In addition, during heating, proteins denature and interact through hydrogen bonds, hydrophobic interactions, and disulfide bonds, which provide structural cohesion as well as entrap water and fat globules. Thus, reducing salt and phosphate levels decreases the amount of functionally available proteins, leading to incomplete gel network formation, reduced cohesiveness, and compromised structural integrity [18]. Thus, clean-label meat systems frequently exhibit crumbly textures and poor sliceability. Consequently, strategies that restore protein network strength while maintaining compliance with clean-label principles are needed.

Color stability represents another major challenge in clean-label meat processing, particularly in products with restricted use of nitrite and synthetic antioxidant. Nitrites are essential for cured meat color development and stability, whereas antioxidants inhibit lipid and protein oxidation associated with discoloration and off-flavor formation [6, 11]. Nitrite is particularly important because it contributes to both cured-color formation and oxidative stability. During curing, nitrite is reduced to nitric oxide, which binds to the ferrous myoglobin to form nitrosylmyoglobin. Upon heating, this pigment is converted into nitrosylhemochrome, which is responsible for the characteristic stable pink color of cooked cured meat products. Beyond its role in color development, nitrite exerts antioxidant effects by interacting with heme iron and inhibiting iron-mediated radical formation, thereby suppressing lipid oxidation and the generation of reactive secondary oxidation products. Thus, reducing this additive increases susceptibility to oxidative reactions and potentially disrupts protein structure. It is noteworthy that nitrite addition inhibited carbonyl formation while promoting disulfide bond formation through thiol oxidation, although both are induced by protein oxidation [19]. Therefore, reducing nitrite may alter the balance between oxidative modification and cross-linking of proteins, resulting in a protein network structurally distinct from that formed under conventional curing conditions and potentially deteriorate textural properties. Therefore, clean-label strategies must carefully balance oxidative control with minimal chemical intervention, often through processing conditions that limit oxidative stress or stabilize protein structures.

Microbial safety remains a non-negotiable requirement for meat and animal-based foods, and additive reduction poses considerable challenges in this regard. Traditional preservatives inhibit microbial growth by modifying environmental conditions or directly interfering with microbial metabolism [13]. In clean-label systems, reduced

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reliance on chemical preservatives increases dependence on alternative preservation mechanisms. Accordingly, physical processing technologies, such as non-thermal and mild thermal treatments, have emerged as essential tools for microbial control in clean-label meat products. However, these interventions may simultaneously induce structural changes in proteins that affect texture, WHC, or oxidation susceptibility. Therefore, microbial stability in clean-label meat systems should be evaluated within an integrated structure–quality framework rather than as an isolated safety parameter.

3. Structural basis of quality formation in meat and animal-based systems

3.1. Hierarchical structure of muscle and animal-derived proteins

The quality attributes of meat and animal-based foods are governed by the hierarchical organization of muscle proteins, extending from molecular conformations to macroscopic tissue structures (Table 2). Myofibrillar proteins, primarily myosin and actin, are the principal structural and functional components of muscle, whereas sarcoplasmic proteins are mainly associated with metabolic processes and stromal proteins, such as collagen and elastin, provide connective tissue integrity [4, 17]. Each protein fraction exhibits distinct solubility, thermal stability, and reactivity, thereby influencing its behavior during processing. At the supramolecular level, myofibrils are assembled into muscle fibers embedded within connective tissue networks. This structural organization determines key mechanical properties, including firmness, elasticity, and chewiness, as well as mass transfer behavior during processing and storage [11].

In processed and restructured animal-based foods, including comminuted meat products, emulsions, and gels, the native muscle hierarchy is partially disrupted during homogenizing, mixing, salting, and heating and is subsequently replaced by a newly formed protein-based matrix. In these systems, quality formation depends less on intact muscle architecture and more on the ability of proteins to undergo controlled unfolding, aggregation, and network reassembly. Once separated from the myofibril, hydration of muscle proteins become highly responsive to physicochemical conditions, including ionic strength, pH, temperature, and mechanical forces. Under conventional processing, salt and phosphate mainly affect myofibrillar protein solubilization and facilitate the network formation by regulating ionic strength and pH [18]. The reduction in nitrite and synthetic antioxidants may increase oxidative modification of myoglobin and muscle proteins. Heating of meat products converts

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extracted proteins into an aggregated three-dimensional matrix, while the oxidation of proteins can hinder the formation of uniform protein gel.

3.2. Role of protein–water–lipid interactions in quality attributes

Protein–water–lipid interactions play a central role in determining texture, juiciness, and overall sensory quality in meat and animal-based foods. Water in meat exists in multiple states, ranging from tightly bound hydration layers on protein surfaces to immobilized water entrapped within myofibrillar and extracellular spaces [10]. Water distribution and mobility are strongly influenced by protein conformation, surface charge, and network density. Myofibrillar proteins are the primary contributors to WHC because they form three-dimensional networks capable of immobilizing water through capillary forces and protein–water interactions [5]. Structural disruptions that reduce protein solubility or compromise network continuity directly contribute to moisture loss and reduced juiciness. Lipids also interact with proteins, particularly at interfacial regions in emulsified and comminuted products. In these systems, proteins adsorb onto fat droplets and form viscoelastic interfacial films that stabilize emulsions and contribute to textural properties [17]. The stability of these interfaces depends on protein unfolding, adsorption kinetics, and intermolecular interactions. Consequently, protein structural integrity is fundamental to water retention, lipid stabilization, and texture development in animal-based food systems.

3.3. Structural disruptions induced by processing

Processing inevitably induces structural disruptions in proteins, which can either be beneficial or detrimental depending on their extent and control. Moderate unfolding exposes reactive groups that promote network formation and improve texture, whereas excessive denaturation may lead to irreversible aggregation, reduced solubility, and moisture loss [11]. Non-thermal and mild processing technologies alter protein structures through alternative mechanisms. For example, HPP modifies non-covalent interactions, induces conformational changes, and minimizes thermal damage, thereby influencing gelation behavior, water retention, and texture [20]. Similarly, mechanical forces and shear generated during comminution disrupt muscle structure, enhancing protein extraction while concurrently increasing susceptibility to oxidation and quality deterioration. In clean-label meat systems, the reduced functional buffering capacity normally provided by additives necessitates careful control of processing-induced structural changes. Beneficial modifications that enhance protein functionality must be balanced against excessive structural disruption that compromises product quality

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4. Physical processing technologies as clean-label alternatives

Physical processing technologies have emerged as important clean-label alternatives in meat and animal-based food systems by enabling quality control through structural modification rather than chemical formulation. In contrast to conventional additive-based approaches, these technologies directly target protein conformation, intermolecular interactions, and matrix organization, thereby affecting texture, WHC, color stability, and microbial safety. Among these technologies, HPP, ultrasound, PEF treatment, and cold plasma have garnered particular interest for their technological effectiveness and growing regulatory acceptance.

Table 3 presents a comparative overview of physical processing technologies employed as clean-label alternatives in meat and animal-based food systems. Each technology operates through distinct structural mechanisms, resulting in specific functional benefits and limitations. Consequently, understanding these structure–function relationships is essential for selecting and refining processing strategies that compensate for additive reduction while preserving product quality and safety.

4.1. High-pressure processing (HPP)

HPP induces structural modifications in proteins by disrupting non-covalent interactions, including hydrogen bonds, electrostatic interactions, and hydrophobic forces, while largely preserving covalent bonds [21]. At moderate pressure levels (typically 200–400 MPa), myofibrillar proteins experience partial unfolding, exposing reactive groups that facilitate protein–protein interactions upon subsequent heating or pressure treatment. This pressure-induced unfolding enhances protein gelation by promoting the formation of dense and homogeneous protein networks in meat products. However, excessive pressure (>500 MPa) may cause irreversible aggregation and reduced protein solubility, highlighting the importance of pressure optimization in clean-label applications [20, 22]. Adequate HPP treatment enhances texture and WHC in various meat products by strengthening protein network formation and increasing water immobilization within gel matrices [23]. These benefits are strongly dependent on the characteristics of the food matrix. In comminuted and emulsified meat products, moderate pressure treatment, particularly those containing reduced levels of salt or phosphate, may partially compensate for insufficient protein functionality by promoting protein unfolding and network connectivity. In whole-muscle products, where gel formation is less dominant, pressure-induced disruption of myofibrillar and cytoskeletal structures may contribute to tenderness. Nevertheless, the structural modifications improving quality attributes may simultaneously expose oxidation-sensitive residues and pro-oxidant components, thereby increasing

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susceptibility to lipid and protein oxidation. Meanwhile, HPP effectively inactivates microorganisms by disrupting cell membranes and intracellular structures, providing a non-thermal microbial control strategy consistent with clean-label requirements [21]. However, excessive pressure can denature the myoglobin, which induce severe discoloration, as well as myofibrillar protein modification [22]. Therefore, the optimal condition for improving quality attributes without compromising should be selected according to the dominant quality requirement and composition of each product rather than applying a uniform processing condition across different meat matrices.

4.2. Ultrasound-assisted processing

Ultrasound-assisted processing relies on acoustic cavitation, which involves the formation and collapse of microbubbles that generate localized high pressures and shear forces. These effects disrupt muscle microstructure and alter protein conformation, leading to increased surface hydrophobicity and partial unfolding of myofibrillar proteins [12]. Moderate cavitation can expose reactive protein groups and facilitate protein-water and protein-protein interactions. Consequently, these structural modifications may improve protein solubility, emulsifying capacity, and heat-induced gelation behavior. Improved protein extraction and hydration further enhance WHC and tenderness, positioning ultrasound as a viable clean-label approach to minimize salt and phosphate usage. However, excessive ultrasound intensity or treatment duration can generate free radicals and promote excessive unfolding, resulting in the protein oxidation and aggregation. Thus, functional benefits of ultrasound can be occurred under the controlled processing conditions. Meanwhile, ultrasound has been also widely applied in meat processing to improve marination efficiency by accelerating mass transfer and improving brine penetration through microstructural disruption of whole muscle products [24]. Furthermore, this technique can be used to reduce pathogens and preserve quality, minimizing chemical sanitizers such as sodium hypochlorite [25]. However, microbial inactivation by ultrasound alone may be limited, because tissue irregularities and food components can protect microorganisms from cavitation. Therefore, its industrial use may be more effective when combined with complementary technologies or materials to improve overall processing efficiency with enhancing product quality.

4.3. Pulsed electric field (PEF) treatment

PEF treatment involves applying short bursts of high-voltage electric fields to induce electroporation of cell membranes. Unlike ultrasound, which directly modifies proteins and muscle structures through cavitation-

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generated shear forces, PEF primarily acts by generating a transmembrane potential across the sarcolemma and intracellular organelle membranes. Once this potential exceeds a critical threshold, transient or permanent aqueous pores are formed in the phospholipid bilayer. Thus, it can enhance membrane permeability, thereby facilitating the diffusion of water, ions, and small molecules within muscle tissue [26]. In meat systems, electroporation improves mass transfer processes, including curing, marination, and drying, thereby decreasing processing times and reducing additive dependence. PEF-induced permeabilization may also indirectly affect protein structure by altering intracellular conditions and promoting protein–water interactions. Membrane permeabilization can increase the accessibility of myofibrillar proteins to endogenous proteolytic enzymes, thereby increasing calpain activity and degradation of structural proteins. Thus, moderate PEF treatment has been associated with improvements in tenderness; however, excessive electric field strength can lead to protein denaturation and localized heating [27]. Meanwhile, a recent study has demonstrated that the combination of PEF and ultrasound on chicken breast improves physicochemical quality and increases the levels of taste-related free amino acids, including aspartic acid and glutamic acid [28]. Consequently, successful PEF application requires careful optimization to balance structural modification with quality preservation.

4.4. Cold plasma processing

Cold plasma processing generates reactive species, such as reactive oxygen and nitrogen species, that primarily interact with food surfaces. Unlike HPP, ultrasound, and PEF, which include pressure, mechanical, or electric-field-mediated changes respectively, cold plasma predominantly modifies meat components through surface-directed oxidative reactions. In meat products, cold plasma effectively inactivates surface microorganisms without causing substantial bulk heating, positioning it as a promising clean-label preservation technology [29]. In addition, moderate treatment intensities, limited protein oxidation and partial unfolding may expose hydrophobic and reactive groups, potentially modifying protein-protein interactions and water binding capacity [30]. However, prolonged or intensive exposure increases carbonylation and sulfhydryl oxidation of muscle proteins and induces oxidation of myoglobin. These modification of proteins can adversely affect color stability and texture [13]. Consequently, cold plasma applications also necessitate optimization to ensure microbial safety while minimizing oxidative damage in clean-label meat systems.

5. Biochemical and enzymatic strategies for clean-label structuring

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Biochemical and enzymatic strategies offer a molecular-level approach to improve structure and functionality in clean-label meat and animal-based foods, without reliance on synthetic additives. Enzymes can compensate for quality losses linked to salt, phosphate, and binder reductions by selectively modifying protein conformation, intermolecular interactions, and network formation. Importantly, these strategies align with clean-label principles by employing naturally occurring or food-grade enzymes while preserving sensory and nutritional integrity.

Table 4 summarizes key enzymatic approaches used in clean-label meat systems, highlighting their structural mechanisms, quality benefits, and practical limitations. The table further illustrates how enzymatic strategies function as molecular tools for structure engineering, particularly when integrated into physical processing technologies.

5.1. Endogenous and exogenous enzymes

Enzymes involved in clean-label meat processing can be broadly categorized as endogenous enzymes inherent to muscle tissue or exogenous enzymes introduced during processing. Endogenous proteases, including calpains and cathepsins, are essential for postmortem proteolysis and contribute to tenderness development by selectively degrading myofibrillar and cytoskeletal proteins [31]. Controlled activation of these enzymes can improve texture while maintaining product identity and label simplicity.

Exogenous enzymes enable more targeted structural modification. Proteases, including papain, bromelain, and microbial proteases, are commonly used to modify protein structure by decreasing molecular size and increasing protein solubility and water-binding capacity [32]. However, excessive proteolysis may compromise protein networks, resulting in diminished gel strength and reduced yield and underscoring the need for precise control. Transglutaminase is among the most extensively studied enzymes in clean-label meat systems because it catalyzes covalent cross-linking between glutamine and lysine residues, thereby forming ε-(γ-glutamyl)lysine bonds [33]. This enzymatic cross-linking strengthens protein networks and improves texture and sliceability, especially in restructured and low-salt meat products [34]. Oxidative enzymes, such as laccase and peroxidase, have also attracted interest for their ability to facilitate protein cross-linking via phenolic or tyrosine residues, thereby enhancing gel formation and structural stability [35]. Although these enzymes represent promising clean-label alternatives, their effects on flavor and color require careful optimization.

5.2. Controlled protein cross-linking and texturization

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Controlled protein cross-linking serves as a central mechanism by which enzymatic strategies restore or enhance texture in clean-label meat products. Since papain and bromelain are proteolytic enzymes, these can be utilized to improve functional properties that might deteriorate upon the removal of synthetic additives, rather than acting as direct substitutes. Prior research demonstrated that marinating low-value beef cuts with bromelain improved their tenderness, suggesting its potential to replace phosphate added during whole-meat brining [15, 36]. Cross-linking by transglutaminase increases molecular connectivity, leading to stronger, more elastic protein networks that effectively entrap water and lipids. In emulsion-type meat products without phosphate, enzymatic cross-linking enhanced WHC and cooking yield by reinforcing myofibrillar protein matrices [37]. By modulating cross-link density and reaction conditions, enzymatic structuring can reproduce many of the functional roles traditionally provided by phosphates and synthetic binder. However, excessive cross-linking may produce overly rigid structures and reduce juiciness, highlighting the need to balance network strength with structural flexibility. From a structural perspective, enzymatic texturization operates at nano- and microscale levels, influencing protein aggregation behavior, pore size distribution, and interfacial stability. These structural changes directly affect macroscopic quality attributes, such as firmness, cohesiveness, and sensory perception.

5.3. Synergistic effects with physical processing technologies

The effectiveness of enzymatic strategies can be substantially enhanced by integration with physical processing technologies, yielding synergistic clean-label solutions. Physical treatments, such as HPP, ultrasound, and PEFs, can increase enzyme accessibility by inducing partial protein unfolding, membrane disruption, or enhanced mass transfer. In HPP-treated meat, pressure-induced loss of muscle-cell structural integrity and disruption of lysosomal membranes may promote the release of endogenous proteases and facilitate their access to myofibrillar substrates [38]. HPP-induced unfolding can also expose reactive amino acid residues, thereby increasing the efficiency of transglutaminase-mediated cross-linking and improving gel strength and WHC. This effect is particularly relevant in processed meat formulations containing compact globular proteins, such as egg-white proteins [39]. Similarly, ultrasound-assisted enzymatic treatment can alter protein interaction and gelation kinetics. Recent study reported that the balance between reversible protein unfolding and irreversible aggregation varied depending on ultrasonic power and that the simultaneous application of 360 W ultrasound and transglutaminase produced the most compact protein network under low-salt condition [40]. Meanwhile, since the sequence of application can greatly influence the resulting product characteristics, careful optimization of treatment is required to maximize the synergistic effects. Consequently, these synergistic approaches are beneficial in clean-label systems because they

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enable structural functionality through process design rather than through additive complexity. From a conceptual standpoint, enzymatic–physical integration signifies a shift from ingredient-driven formulation toward structure-driven quality engineering in meat and animal-based foods.

6. Clean-label reformulation approaches based on natural ingredients

Clean-label reformulation in meat and animal-based foods increasingly depends on natural ingredients; however, the scientific value of these approaches extends beyond simple ingredient substitution. Instead, their effectiveness depends on the functional integration of these materials within protein-centered food structures. Natural binders, minerals, and antioxidants do not simply serve as passive replacements for synthetic additives; rather, they actively modulate protein–water–lipid interactions and microstructural organization. This section focuses on structure-driven reformulation strategies and examines how natural ingredients influence quality formation mechanisms in clean-label meat systems. Table 5 summarizes the roles of natural ingredients as structural modifiers rather than direct additive replacements. The table further reinforces the concept that successful clean-label reformulation depends on understanding and controlling structure–function relationships within meat systems.

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6.1. Functional roles of natural binders and fibers

Natural binders and fibers primarily contribute to quality formation through their interactions with meat proteins and water rather than through isolated ingredient effects. Their structural functions can be broadly understood in terms of water distribution and immobilization, reinforcement of the protein matrix, and stabilization of protein-lipid interfaces. Plant-derived fibers, seaweed polysaccharides, and protein isolates improve WHC by increasing system viscosity, promoting capillary water retention, and restricting water mobility within the protein matrix [41]. From a structural perspective, insoluble fibers act as physical fillers embedded within the protein matrix, occupying void spaces and retaining water. However, excessive incorporation may disrupt protein network continuity, resulting in a coarse and brittle texture. In contrast, soluble polysaccharides, particularly those derived from seaweed, increase the viscosity of the continuous aqueous phase and may form secondary hydrocolloid networks that interact with myofibrillar proteins via hydrogen bonding and electrostatic interactions, thereby

stabilizing gel structures [42]. Nevertheless, limited protein-polysaccharide compatibility may induce phase separation, resulting in an uneven matrix.

Protein isolates derived from plant or animal sources contribute more directly to network formation by participating in thermal gelation and interfacial stabilization. When adequately hydrated and dispersed, these proteins can co-gel with myofibrillar proteins, thereby reinforcing the continuous phase and improving emulsion stability in reduced-additive systems. Importantly, the effectiveness of natural binders is strongly influenced by particle size, hydration state, and processing conditions, highlighting the need for structure-oriented formulation design.

6.2. Salt reduction and alternative mineral systems

Salt reduction represents a critical challenge in clean-label meat reformulation because of the central role of sodium chloride in protein solubilization, swelling, and electrostatic repulsion. Structural destabilization associated with salt reduction is typically manifested as reduced protein extraction, weaker gel networks, and impaired WHC [43]. Alternative mineral systems can partially restore these functionalities by modulating ionic strength and protein charge distribution. Potassium- and calcium-based salts exert distinct effects on myofibrillar protein behavior. Divalent ions facilitate protein aggregation and network compaction, whereas monovalent ions primarily influence solubility and electrostatic interactions [44]. From a structural standpoint, successful salt reduction strategies require a balance between protein solubilization and controlled aggregation. This balance may be optimized through process interventions, including mechanical mixing or pressure-assisted extraction, thereby improving protein accessibility and compensating for reduced ionic effects. Consequently, mineral reformulation should be considered an integrated component of structural engineering rather than merely a direct replacement for sodium chloride.

6.3. Natural antioxidants and color stabilizers: structural implications

Natural antioxidants and color stabilizers contribute to clean-label meat quality not only by inhibiting oxidation but also by preserving the protein and pigment structures essential for sensory stability. Oxidative modification of myofibrillar proteins promotes carbonyl formation, disulfide cross-linking, and reduced protein functionality, ultimately compromising texture and water retention [45]. Phenolic compounds and plant-derived antioxidants interact with proteins via hydrogen bonding and hydrophobic interactions, thereby affecting protein conformation and aggregation behavior. At controlled levels, these interactions can simultaneously enhance gel strength and

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oxidative stability; however, excessive binding may interfere with protein unfolding and network formation [46]. Color stability is similarly dependent on structural preservation. Natural color-stabilizing systems function by maintaining myoglobin in reduced or oxygenated states while limiting protein oxidation that indirectly accelerates pigment degradation. Consequently, antioxidant strategies in clean-label meat systems should be assessed based on their capacity to protect structural integrity rather than solely on their nominal antioxidant activity.

7. Integrated perspective: Structure–process–quality relationships

Designing clean-label meat and animal-based foods requires an integrated approach that considers ingredients, processing technologies, and quality outcomes collectively. Product performance emerges from dynamic interactions between protein structure, process-induced modifications, and matrix-specific constraints. This section synthesizes insights from earlier discussions to establish a structure–process–quality framework for the rational evaluation and application of clean-label technologies. Table 6 provides a comparative overview of the effects of various clean-label strategies on protein structure and quality outcomes across different meat matrices. The table reinforces the concept that clean-label success is contingent on matrix-specific structural design rather than universal technological solutions.

7.1. Comparative evaluation of clean-label technologies

Clean-label processing and reformulation strategies fundamentally differ in how they interact with protein structures and influence quality attributes. Physical processing technologies, such as HPP, ultrasound, PEF treatment, and cold plasma, primarily function by inducing structural rearrangements without introducing additional formulation components. These technologies alter protein conformation, aggregation pathways, and interfacial properties, thereby enabling improvements in texture, WHC, and microbial stability while preserving label simplicity [20]. In contrast, biochemical and enzymatic strategies directly intervene at the molecular level by catalyzing hydrolysis or cross-linking reactions, thereby providing more precise control over network formation and textural properties. Natural ingredient-based reformulation further complements these approaches by providing structural support via water entrapment, ionic modulation, or oxidative protection.

From a comparative perspective, physical processing technologies offer broad applicability and relatively low formulation complexity; however, they often lack specificity. Conversely, enzymatic and ingredient-driven

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strategies provide more targeted functionality but require careful optimization to prevent over-modification or sensory trade-offs. Consequently, clean-label technology selection should be primarily guided by the intended structural outcome rather than by the technology category itself.

7.2. Trade-offs between quality enhancement and structural stability

A central challenge in clean-label meat systems is balancing short-term quality enhancement with long-term structural stability. For instance, pressure- or ultrasound-induced protein unfolding can initially improve WHC and tenderness; however, excessive unfolding may subsequently promote aggregation, oxidation, or syneresis during storage [47]. Similarly, enzymatic cross-linking enhances binding and texture; however, excessive cross-link density may reduce juiciness or increase toughness.

Natural antioxidants improve color stability and oxidative quality; however, strong protein–polyphenol interactions may interfere with protein gelation and network formation [46]. These trade-offs highlight the importance of defining structural "operating windows" in which quality benefits are maximized without compromising system stability. In this context, clean-label processing should be viewed as a balance between inducing beneficial structural transitions and maintaining sufficient molecular flexibility to withstand processing and storage stresses.

7.3. Application-specific strategies for different meat matrices

The effectiveness of clean-label strategies is highly matrix-dependent, with different meat systems exhibiting distinct structural hierarchies and functional requirements. Surface-oriented technologies, including cold plasma and mild HPP, are particularly effective for microbial control and color preservation in whole-muscle products, such as fresh or minimally processed meats, without compromising internal structure. In comminuted and emulsified products, enzymatic cross-linking and natural binders are essential for protein extraction and network formation, particularly in compensating for reduced salt and phosphate levels. In these systems, structural design is primarily directed toward optimizing protein solubility, emulsion stability, and gel strength. Restructured and hybrid meat products exhibit additional complexity because of heterogeneous protein sources and interfacial interactions. In these systems, integrated approaches that combine physical processing with enzymatic or ingredient-based strategies are often necessary to achieve cohesive texture and consistent quality.

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Ultimately, successful clean-label reformulation depends on tailoring structure–process interactions to the specific meat matrix, processing intensity, and target quality attributes rather than relying on universal technological solutions.

8. Conclusion

Clean-label processing and reformulation of meat and animal-based foods represent a shift from ingredient-driven formulation toward structure-oriented quality engineering. This review demonstrates that quality attributes, including texture, water-holding capacity, emulsion stability, color stability, oxidative stability, and microbial safety, are primarily governed by structure–process interactions within protein-based matrices rather than by individual ingredients alone. Successful clean-label reformulation relies on controlling protein conformation, intermolecular interactions, and network formation through complementary physical, enzymatic, and natural-ingredient-based strategies. These approaches enable rational design of clean-label meat systems while reducing dependence on synthetic additives. A key conclusion of this review is that clean-label reformulation should focus on optimizing structural integrity rather than simply eliminating additives. Although these strategies improve functionality, they may also increase oxidative susceptibility or reduce storage stability, highlighting the need to define structural operating windows that balance product quality and robustness.

Future research should integrate matrix-specific processing strategies with advanced structural characterization techniques and data-driven tools, including artificial intelligence and digital twins, to better understand protein structural evolution and optimize processing conditions. In addition, pilot- and commercial-scale validation is essential to confirm manufacturing feasibility, shelf-life stability, and consumer acceptance across diverse meat products.

Ultimately, clean-label meat and animal-based foods should be regarded as structurally engineered systems in which quality is determined by controlled protein-centered interactions. Advancing this structure-based approach will provide the scientific foundation for the next generation of high-quality, commercially viable clean-label meat products.

Acknowledgments

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Tables and Figures

Table 1. Functional roles of conventional additives and quality challenges associated with their reduction in clean-label meat systems

Conventional additive	Primary functional role	Quality challenges upon reduction	Structural basis of quality loss
Salt (NaCl)	Protein extraction; gel formation	Weak texture; poor binding	Limited myosin extraction and network formation
Phosphates	Protein solubilization; WHC enhancement	Increased purge loss; reduced juiciness	Reduced electrostatic repulsion and myofibrillar swelling
Nitrites	Cured color formation; microbial inhibition	Color instability, reduced safety	Loss of nitrosyl–heme complex stabilization
Synthetic antioxidants	Oxidation control	Increased lipid/protein oxidation	Oxidative damage to protein structure
Chemical preservatives	Microbial stability	Reduced shelf-life	Loss of chemical hurdle effects

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671 **Table 2. Hierarchical protein structures and their contributions to quality attributes in meat and animal-**

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Structural level	Major components	Primary quality attributes affected	Processing sensitivity
Molecular	Myosin, actin	Solubility; gelation, emulsification	pH; ionic strength; temperature
Supramolecular	Myofibrils	WHC; texture, juiciness	Salt reduction; pressure; shear
Cellular	Muscle fibers	Firmness; tenderness	Thermal treatment; comminution
Tissue	Connective tissue (collagen)	Chewiness; mouthfeel	Heat-induced solubilization
Reassembled networks	Protein gels and emulsions	Binding; sliceability; stability	Processing-induced unfolding/aggregation

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675 **Table 3. Structural mechanisms and quality effects of physical processing technologies used as clean-label alternatives in meat systems**

Technology	Primary structural mechanism	Key quality improvements	Potential limitations	References
HPP	Disruption of non-covalent bonds; protein unfolding	Improved gelation; WHC; microbial inactivation	Over-denaturation; oxidation risk	[20-22]
Ultrasound	Cavitation-induced unfolding and microstructural disruption	Enhanced marination; tenderness; protein functionality	Protein aggregation at high intensity	[12, 24, 48]
PEF	Electroporation and enhanced mass transfer	Improved tenderness; reduced curing time	Local heating; structural damage	[26, 27, 49]
Cold plasma	Surface protein modification; reactive species interaction	Microbial inactivation without additives	Protein oxidation; color instability	[13, 29, 50]

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678 **Table 4. Enzymatic strategies for structural modification and quality improvement in clean-label meat and animal-based foods**

Enzyme type	Primary mechanism	Structural effect	Quality attributes improved	Key considerations	Reference
Endogenous proteases (calpains, cathepsins)	Selective proteolysis	Myofibrillar fragmentation	Tenderness; juiciness	Limited control, postmortem variability	[31]
Exogenous proteases (papain, bromelain)	Protein hydrolysis	Reduced molecular size, increased solubility	Tenderness; WHC	Risk of over-softening	[32, 51]
Transglutaminase	Covalent cross-linking	Network strengthening	Texture; binding, sliceability	Excess rigidity at high activity	[34, 52]
Oxidative enzymes (laccase, peroxidase)	Oxidative cross-linking	Enhanced gel formation	Texture; structural stability	Potential color/flavor effects	[53]
Enzyme–physical combinations	Enhanced accessibility and reactivity	Optimized cross-linking and aggregation	WHC; texture; yield	Process optimization required	[39, 40]

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Table 5. Structure-oriented roles of natural ingredients in clean-label meat reformulation

Reformulation strategy	Primary structural mechanism	Effect on protein network	Quality attributes influenced	Reference
Plant fibers	Physical filling; water entrapment	Reduced network shrinkage	WHC; cooking yield	[54, 55]
Seaweed polysaccharides	Secondary gel formation; protein interaction	Network stabilization	Texture; juiciness	[56, 57]
Protein isolates	Co-gelation; interfacial stabilization	Network reinforcement	Emulsion stability; firmness	[58, 59]
Alternative mineral salts	Ionic modulation of protein interactions	Controlled aggregation	Texture; WHC	[44, 60]
Natural antioxidants	Protection of protein and pigment structures	Preserved functionality	Oxidative stability; color	[61, 62]

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684 **Table 6. Integrated structure–process–quality relationships in clean-label meat systems**

Clean-label strategy	Primary structural action	Quality benefits	Key limitations	Suitable meat matrices	Reference
Physical processing (HPP, ultrasound, PEF)	Protein unfolding and aggregation control	WHC; tenderness; microbial safety	Over-aggregation risk	Whole muscle; comminuted	[20, 28]
Enzymatic modification	Targeted hydrolysis or cross-linking	Texture; binding; yield	Over-softening or rigidity	Comminuted; restructured	[36]
Natural binders and fibers	Water entrapment, network reinforcement	Juiciness; stability	Sensory interference	Emulsified; hybrid	[41, 42]
Alternative mineral systems	Ionic modulation	Protein solubility; texture	Flavor impact	Broad	[63]
Antioxidant-based stabilization	Structural protection	Color; shelf-life	Protein interaction effects	Whole muscle; processed	[46, 61]

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