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| **Author** | Sang-Soon Kim[1], Yea-Ji Kim[1], Ji Yoon Cha[2], Tae-Kyung Kim[2], Min Kyung Park[2], Min-Cheol Kang[2], Yun-Sang Choi[1]* |
| **Affiliation** | [1] Food Engineering Major School on Animal & Food Science and Marketing, Konkuk University, Seoul 05029, Republic of Korea<br>[2]Food Processing Research Group, Korea Food Research Institute, Wanju, 55365, Republic of Korea |
| **Special remarks –** if authors have additional information to inform the editorial office | |
| **ORCID (All authors must have ORCID) https://orcid.org** | Sang-Soon Kim (https://orcid.org/0000-0002-7197-2814)<br>Yea-Ji Kim (https://orcid.org/0000-0003-0937-5100)<br>Ji Yoon Cha (https://orcid.org/0000-0002-1694-4343)<br>Tae-Kyung Kim (https://orcid.org/0000-0002-6349-4314)<br>Min Kyung Park (https://orcid.org/0000-0002-3619-9491)<br>Min-Cheol Kang (https://orcid.org/0000-0002-9658-9045)<br>Yun-Sang Choi (https://orcid.org/0000-0001-8060-6237) |
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## CORRESPONDING AUTHOR CONTACT INFORMATION

| **For the corresponding author (responsible for correspondence, proofreading, and reprints)** | **Fill in information in each box below** |
|---|---|
| First name, middle initial, last name | Yun-Sang Choi |
| Email address – this is where your proofs will be sent | kcys0517@konkuk.ac.kr |
| Secondary Email address | |
| Postal address | Food Engineering Major School on Animal & Food Science and Marketing, Konkuk University, Seoul 05029, Republic of Korea |
| Cell phone number | 82-10-4713-5623 |
| Office phone number | 82-2-450-3696 |
| Fax number | |

# Applying meat science principles to insect-containing foods: functionality, processing, and research priorities


## Abstract

Edible insect ingredients are being investigated as complementary protein resources for familiar food products, but their successful incorporation requires more than favorable nutrient composition or efficient biomass production. A major knowledge gap is the limited comparability of studies using whole-insect powders, defatted flours, protein concentrates, isolates, and hydrolysates under different extraction and processing conditions. This narrative review examines how meat science principles can guide the characterization, processing, and validation of insect-containing foods. The discussion focuses on ingredient variability, protein solubilization and heat-induced network formation, lipid oxidation and flavor development, hybrid formulations, and safety management. Particular attention is given to the mechanisms and trade-offs of fractionation, enzymatic hydrolysis, fermentation, extrusion, and emerging processing technologies. Comparisons are organized around equivalent ingredient classes and measurable product outcomes rather than biological origin alone. Available evidence supports selected laboratory-scale applications, including the incorporation of insect ingredients into emulsified products and extruded hybrid matrices; however, improved functionality is species-, formulation-, and process-dependent. Reduced allergen abundance or immunoreactivity does not establish clinical safety, and environmental advantages cannot be assumed without accounting for drying, fractionation, energy demand, and the functional unit used in assessment. Future work should prioritize matched-composition comparisons, application-specific process optimization, validated microbial controls, clinically relevant allergen assessment, and integrated techno-economic and life-cycle evaluation. Meat science therefore provides a framework for testing complementary integration, rather than evidence that insect ingredients universally outperform or can directly replace conventional animal proteins.



**Keywords**: Edible insects, Meat science, Protein functionality, Hybrid foods, Food processing, Food safety



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# 1. Introduction

Increasing demand for nutritionally adequate foods and interest in lower-impact production have encouraged diversification of protein resources [1,2]. Livestock meat remains an important source of protein and other nutrients [3]. Alternative ingredients must be evaluated together with processing, safety, and product requirements [4,5].

Edible insects are being investigated as complementary protein resources [4,6,7]. Their composition and processing response depend on species and production conditions [8]. Environmental comparisons require defined production systems and functional units; farm-level gas measurements should not be extrapolated to all finished ingredients [9]. Consumer acceptance, safety and manufacturing feasibility remain important constraints [2,5,10].

This narrative review evaluates the transferability of meat science principles to insect-containing foods, rather than presenting a general survey of alternative protein markets. Its central proposition is that ingredient identity, processing history, and intended product function must be specified before meaningful comparisons can be made. The review therefore considers livestock foods as sources of mechanistic knowledge and performance benchmarks, while examining where insect ingredients require distinct processing and safety validation. The discussion distinguishes experimentally demonstrated outcomes from proposed mechanisms and emerging applications, and identifies the experiments needed to support complementary integration into familiar food matrices.

The review is organized around ingredient characterization, comparative functional behavior, processing mechanisms, and validation priorities. Whole-insect powders, defatted flours, protein concentrates, isolates, and hydrolysates are considered separately because they differ in composition and processing response. Findings from plant–insect meat analogues are distinguished from those obtained in meat-containing formulations, and laboratory observations are not treated as evidence of industrial-scale performance.

# 2. Livestock foods as processing and quality benchmarks

Livestock foods provide established examples of how raw-material composition, protein chemistry, and process control determine product quality [1]. Meat, dairy, and egg systems nevertheless rely on different functional components and processing mechanisms. Their relevance to insect-containing foods is therefore best considered at the level of specific functions such as protein solubilization, interfacial stabilization, heat-induced network formation, flavor development, and microbial control rather than as a single model of uniformly predictable animal proteins [3,11]. Table 1 summarizes these food categories, their processing maturity, and the principles that may be transferred or require adaptation.

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### 2.1. Market shifts and consumer requirements

Market and consumer requirements help define the product targets for insect-containing foods. Acceptance varies with familiarity, cultural context and product presentation [2,10]. Nutritional and environmental messaging should therefore be accompanied by acceptable eating quality, transparent ingredient information and verifiable safety.

### 2.2. Raw-material variability and compositional control

Raw-material composition can be influenced by feeding and production management, although these interventions do not eliminate biological variation. Intramuscular fat deposition is subject to genetic and nutritional control [12]. A feeding study in finishing pigs illustrates how balanced branched-chain amino acids can modify meat-quality traits [13]. Such examples should not be interpreted as evidence for every breeding or feeding intervention.

### 2.3. Processing maturity and transferable quality benchmarks

Livestock ingredients provide useful nutritional and technological reference systems, but performance depends on the material and processing conditions [1,3]. Myofibrillar protein extraction and modification should be evaluated against defined functional endpoints rather than presumed uniform behavior [14].

Animal lipids contribute to the functional and sensory robustness of livestock food. Lipid composition varies among species, tissues, and production systems. Ruminant lipids contain saturated fatty acids (SFA) and conjugated linoleic acid (CLA), whereas lipid profiles in monogastric animals can respond to dietary composition [12]. Lipolysis and controlled lipid oxidation generate key aroma precursors that interact with the Maillard reaction products to produce characteristic meat flavors, providing a well-defined framework for flavor engineering [15]. These mechanistic insights are increasingly informing flavor design in nontraditional protein systems. Processing maturity should be described for individual operations and product categories. Conventional thermal processing, emulsification, fermentation, and packaging have extensive commercial applications, whereas the implementation of high-pressure processing (HPP) and pulsed electric fields (PEF) varies with product characteristics and process objectives. Their use in livestock foods does not by itself establish equivalent effectiveness in whole-insect ingredients.

In addition to providing basic nutrition, livestock-based foods have become a platform for the development of functional ingredients. The enzymatic hydrolysis of meat and dairy proteins yields peptides with antihypertensive, antioxidant, and immunomodulatory activities, reflecting a broader shift toward health-oriented functionalization of conventional animal proteins [11,16]. The extensive

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analytical, processing, and regulatory experience accumulated in livestock-production systems provides a critical foundation for evaluating bioactive compounds derived from edible insects.

A lactose-free fermented-milk study combined refrigerated-storage quality measurements with cell-based evaluation of extracts, illustrating the importance of assessing product characteristics and biological responses separately [17].

Safety assessment of alternative protein sources requires attention to microbial and chemical hazards and the applicable regulatory framework [5]. Traceable material descriptions and process records should accompany product-specific validation.

# 3. Insect ingredients: identity, fractionation, and processing history

The suitability of an insect-derived ingredient depends on species, developmental stage and processing history [8]. Research use of an insect ingredient should not be equated with human-food authorization. Food and feed uses require separate regulatory evaluation [5,18].

### 3.1. Ingredient classes and compositional variability

Insect-derived materials include whole-insect powders, defatted flours, protein concentrates, isolates and hydrolysates [19,20,21,22]. Whole powders retain lipid, chitin-rich material and minerals; fractionation alters composition and subsequent processing response [19,20,22]. Findings for an extracted fraction should not be assumed to apply to its source whole powder.

Nutritional comparisons require a stated moisture basis and an explicit protein determination method. Crude protein calculated from total nitrogen may include contributions from non-protein nitrogen, and the nitrogen-to-protein conversion factor can influence the reported value. Amino acid composition, digestibility, and protein content should therefore be interpreted separately rather than combined into a general claim of nutritional equivalence [7,9]. Table 2 reports composition only for materials with traceable identities and analytical information.

Residual chitin-rich particles, lipid, and other non-protein components may influence extraction efficiency, water distribution, and measured functional properties. However, their individual contributions cannot be separated from processing-induced changes without controlled fractionation and reconstitution experiments. This variability highlights a central technological bottleneck: insect proteins require more tailored processing to achieve predictable functionality.

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### 3.2. Stabilization, fractionation, and functional consequences

Processing plays a decisive role in determining the safety, functionality, and sensory quality of insect-based ingredients. Drying effects depend on temperature, duration, oxygen exposure, and the initial state of the material. Freeze-drying and thermal drying should therefore be compared for defined ingredients and target functions, together with energy demand, throughput, and cost. [19]. Similar tradeoffs are well documented in high-value livestock protein processing, reinforcing the need for application-driven optimization rather than universal processing solutions. Fractionation should be evaluated as a balance between recovery yield and application-specific quality. Removing lipid or insoluble material may increase apparent protein concentration, but extraction pH, solvent exposure, drying, and precipitation can also alter aggregation and solubility. Protein yield alone is therefore insufficient for selecting a process intended for emulsified or gelled foods.

Alkaline solubilization and isoelectric precipitation can recover protein-rich fractions, but their effects depend on pH, precipitation and drying conditions [19,20]. Enzymatic hydrolysis changes molecular size and functional behavior in an application-dependent manner [16,21].

Lipid extraction changes the composition of the recovered oil and protein-rich fractions, with trade-offs associated with extraction method and yield [22,23]. Fermentation-related changes require starter- and matrix-specific evidence; altered immunoreactivity should not be interpreted as clinical safety.

### 3.3. Sensory and safety implications

Sensory properties and consumer acceptance depend on ingredient identity, processing and product format [8,10,24]. Volatile profiles from livestock-protein alternatives provide relevant analytical comparisons but do not by themselves establish consumer liking [24].

Food safety considerations further constrain the market expansion of insect-based foods. Microbial risks, contaminant accumulation, and allergenicity—particularly due to cross-reactive proteins such as tropomyosin and arginine kinase—necessitate rigorous processing control and transparent labeling [25]. Although regulatory frameworks are evolving, including the European Union’s framework for Novel Food approval, the absence of globally harmonized standards for farming, processing, and labeling insect-based products remains a major challenge [18]. Established livestock-related regulatory systems offer critical references for standardization and risk assessment in this respect. These ingredient-specific considerations

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provide the basis for the comparative framework in Section 4 and the processing strategies evaluated in Section 5.

## 4. Criteria for comparing livestock and insect ingredients

Meaningful comparison requires defined materials, matched assay conditions, and application-specific outcomes. This section compares nutritional evaluation, protein solubility and network formation, lipid oxidation and flavor, and environmental and economic performance. Differences associated with biological origin are distinguished from those caused by ingredient purity, residual components, and processing history. Although both sources deliver high nutritional value, they differ fundamentally in terms of their biochemical organization, techno-functional performance, and consumer perception. Recognizing these differences is essential for designing rational food technologies that facilitate the integration of insect-derived ingredients into established food matrices.

### 4.1. Equivalent material classes and protein quality

Comparisons between livestock and insect proteins should be made within equivalent material classes [3,7]. Native or extracted myofibrillar proteins should not be directly contrasted with whole-insect powder without accounting for differences in protein concentration, residual lipid, chitin, ash, particle size, and processing history. Relevant comparisons include whole-food ingredients on a common moisture basis, defatted flours at matched protein contents, and extracted protein fractions evaluated under the same pH, ionic strength, and thermal conditions [19,20].

Protein quality should be assessed from indispensable amino acid composition and digestibility using clearly identified methods. Crude protein concentration alone does not establish nutritional equivalence, and digestibility values obtained using different in vitro or in vivo procedures should not be presented as directly interchangeable.

### 4.2. Solubility, interfacial behavior, and gel formation

Native myofibrillar proteins are generally poorly soluble at low ionic strength. Salt-assisted extraction depends on ionic strength, pH, protein concentration, and processing history [14]. Accordingly, solubility comparisons with insect protein ingredients should use matched extraction and assay conditions; otherwise, observed differences may reflect preparation methods rather than biological origin [21].

Heat-induced gelation involves protein solubilization, unfolding, aggregation, and the development of a continuous network through hydrophobic interactions, hydrogen bonding, electrostatic interactions, and, where relevant, disulfide cross-linking [11]. The performance of insect-derived ingredients

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therefore depends on the composition and state of the extracted proteins, rather than simply on whether the source material possesses a muscle-like hierarchical structure.

Residual chitin-rich particles and lipids may alter water distribution, interfacial behavior, and network continuity, but their effects depend on particle size, concentration, and matrix composition. A general attribution of weak gelation to chitin–protein complexes remains a hypothesis unless supported by controlled fraction-removal and reconstitution experiments. Table 3 summarizes the material and assay conditions required for interpreting functional comparisons between myofibrillar and insect-derived proteins.

### 4.3. Lipid oxidation, flavor, and consumer evaluation

Livestock- and insect-derived foods further differ in their lipid composition. The degree of lipid unsaturation varies among insect species and production conditions; oxidation susceptibility should therefore be evaluated for the specific lipid fraction and finished formulation [9,22]. In contrast, livestock lipid systems, despite their higher saturated fat content, have undergone decades of optimization in terms of antioxidant application, formulation, and packaging strategy derived from meat science research [12].

Flavor development further highlights the divergence between the two protein sources. In cooked meats, the characteristic savory and roasted notes arise from well-characterized interactions among Maillard reaction substrates, phospholipids, and sulfur-containing amino acids, yielding heterocyclic compounds such as pyrazines and thiols [15]. Differences in precursor composition, lipid oxidation, and processing history can produce volatile profiles that differ from those of conventional meat products. [10]. In insect-based food production, many flavor-masking and modulation strategies, including fermentation, controlled Maillard reactions, and lipid fractionation, have been directly adapted from meat flavor science, reflecting effective knowledge transfer.

Shelf-life stability presents distinct but convergent challenges. Insect-derived ingredients are particularly vulnerable to lipid oxidation and residual enzymatic activity, whereas livestock meats face persistent risks related to microbial growth, oxidative discoloration, and lipid degradation [22,26]. Advanced preservation approaches, including high-pressure processing, antioxidant incorporation, and intelligent packaging, have been extensively validated in livestock systems and are increasingly being applied to insect-based products [27].

Consumer acceptance is the most pronounced differentiator. Livestock foods benefit from long-established cultural familiarity and sensory expectations, whereas insect-based foods often evoke neophobia, particularly in Western markets [2]. Familiar product formats and

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flavor or texture modification may improve acceptance in specific consumer groups, but this should be demonstrated using defined formulations and appropriate sensory study designs. [28].

Consumer evaluation should distinguish willingness to try a product from liking after consumption and repeated-purchase intention. Results can depend on labeling, information provided before testing, familiarity with insect foods, and the comparator product. Technological improvement alone should therefore not be assumed to remove culturally or contextually mediated barriers.

### 4.4. Environmental and economic comparability

Environmental comparisons should distinguish farm-level biomass production from the manufacture of dried powders, defatted ingredients, and protein isolates. Results expressed per kilogram of harvested biomass are not directly interchangeable with those expressed per kilogram of edible ingredient, protein, or nutritionally equivalent product. Relevant system boundaries include feed production, rearing energy, harvesting, stabilization, drying, fractionation, solvent recovery, wastewater treatment, and distribution.

Potential advantages can be reduced by energy-intensive drying or low ingredient recovery. Environmental performance should therefore be evaluated alongside manufacturing cost, throughput, coproduct allocation, and marketable product yield. Neither lower farm-level emissions nor successful laboratory processing is sufficient to establish the commercial sustainability of an insect-containing food.

## 5. Processing strategies: mechanisms, evidence, and trade-offs

Processing strategies should be selected according to ingredient composition and the function required in the final product. The transfer of meat science principles is useful when it provides a mechanistic basis for controlling protein extraction, network formation, fat stabilization, flavor, and safety. However, each intervention can introduce trade-offs, and improvements in one analytical property may not translate into better product performance. Meat science provides a useful mechanistic framework for developing insect-containing foods, particularly through control of protein extraction, thermal denaturation, aggregation, and gel-network formation. These principles can guide the selection of processing conditions for defined insect ingredients, but their effectiveness depends on protein concentration, extraction history, residual lipid and chitin-rich material, and the composition of the final formulation. Processing should therefore be evaluated as a means of optimizing application-specific performance, rather than correcting presumed intrinsic deficiencies of all insect proteins. The following subsections examine these interventions in terms of their mechanisms, demonstrated outcomes, and trade-offs. Table 4 provides an overview of the processing mechanisms, potential applications, and trade-offs discussed in this section.

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### 5.1. Fractionation and controlled protein modification

Enzymatic hydrolysis can increase the abundance of soluble peptides, but the optimum degree of hydrolysis is application-specific. Extensive cleavage may reduce the molecular size required for continuous gel networks or stable interfacial films, while the exposure or release of hydrophobic peptides can contribute to bitterness. Improved solubility should therefore not be interpreted as simultaneous improvement in gelation, emulsification, and sensory quality.

Enzymatic hydrolysis of egg-white ovalbumin modified antioxidant and cell-based activities; these endpoints should be distinguished from gelation, emulsification and finished-food performance [29].

Processing studies should report enzyme identity, enzyme-to-substrate ratio, pH, temperature, treatment time, and the method used to determine the degree of hydrolysis. The resulting ingredient should then be evaluated in the intended food matrix, because a hydrolysate with antioxidant activity in a chemical assay may still have limited value as a structural protein.

### 5.2. Hybrid formulations and extrusion

Hybrid formulations can be used to investigate whether insect-derived ingredients contribute complementary nutritional or functional properties [11,28]. However, positive performance in a plant–insect matrix should not be treated as evidence of equivalent performance in meat emulsions. Inclusion levels must state whether they refer to the total formulation, dry ingredients, or replacement of a specific component.

High-moisture extrusion combines thermal and mechanical stresses with water-mediated plasticization. These conditions can promote unfolding, aggregation, phase alignment, and anisotropic structure formation in suitable blends. Nevertheless, increasing insect inclusion may also change melt viscosity, lubrication, color, and cooling-die behavior [30]. Extrusion performance must be interpreted together with formulation, moisture content, residence time, and thermal history; a fibrous appearance alone does not establish sensory equivalence or industrial feasibility [31].

Table 5 summarizes selected primary studies on meat–insect emulsion models, plant–insect hybrid structuring, and ingredient-level modification, with attention to ingredient identity, reported processing conditions, measured outcomes, and study limitations.

### 5.3. Fermentation, flavor development, and stabilization

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Fermentation outcomes depend on the microorganism, substrate and process conditions. Product characteristics and biological endpoints should be evaluated separately [17]. Altered allergen abundance or immunoreactivity does not establish clinical safety [18,25].

Studies of food-associated microorganisms illustrate distinct evidence levels. Antioxidant and epithelial-protective responses have been evaluated in cell models [32,33], while a heat-killed microbial preparation was evaluated in a mouse model [34]. These methodological examples do not establish equivalent effects, allergen safety or clinical efficacy in insect-containing foods.

Flavor design represents another domain of strong convergence. The chemistry of meat flavor formation, which is driven by Maillard reactions involving amino acids, reducing sugars, and lipid-derived intermediates, offers a conceptual blueprint for developing roasted and savory attributes in insect-based matrices [15]. Although insect proteins differ in their precursor composition, controlled thermal processing and the targeted modulation of reaction substrates enable partial alignment with familiar meat-like flavor profiles. This underscores the fact that successful flavor development in insect foods depends less on ingredient novelty than on informed manipulation of reaction pathways.

Lipid stabilization strategies further illustrate this transfer of knowledge. Insect lipids, characterized by a high degree of unsaturation, are particularly vulnerable to oxidative degradation. Antioxidant incorporation, lipid encapsulation, and structured fat systems—originally developed to stabilize livestock-derived fats are therefore essential for improving shelf-life and sensory consistency in insect-based products [23,26]. Collectively, these examples position livestock food science as a technological accelerator rather than a legacy constraint.

### 5.4. Emerging structuring and data-driven tools

Digitalization has emerged as a key enabler of convergence. Artificial intelligence and machine learning facilitate the predictive modeling of protein unfolding, aggregation, emulsification, and gelation, enabling rapid optimization of processing conditions and ingredient interactions [11]. For insect proteins, which exhibit high compositional variability, such tools offer particular value by reducing empirical trial-and-error and enabling consistency across species and production batches. In flavor engineering, AI-driven integration of chemical, sensory, and kinetic data further supports the rational design of volatile profiles, signaling a shift toward computationally guided food formulation [35].

Three-dimensional printing primarily controls spatial deposition and product geometry. It does not by itself resolve inadequate protein functionality, microbial safety, or allergenicity. Its feasibility depends on printable rheology, shape retention, post-printing stabilization, production speed, and sanitation.

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Artificial intelligence-assisted formulation may support the analysis of composition–process–property relationships, but the quality of predictions depends on the relevance and consistency of the training data. For insect-containing foods, models should be validated using independent ingredient batches and manufacturing conditions. Predictive performance in a limited laboratory dataset does not establish robustness across species, extraction methods, or production scales. Table 4 summarizes the mechanisms and trade-offs of these technologies, whereas Table 5 illustrates experimentally reported outcomes and their limitations.

# 6. Progress achieved and priorities for validation

Research has progressed from identifying insects as potential nutrient sources to developing fractionated ingredients and testing them in specific food formulations. The next stage requires stronger links between ingredient characterization, processing mechanisms, safety, product quality, and manufacturing feasibility. The priorities below distinguish progress already demonstrated from the validation needed before broader implementation.

### 6.1. From ingredient recovery to batch standardization

Protein recovery, defatting, and ingredient fractionation have enabled more targeted investigation of insect-derived materials. However, increased protein concentration does not guarantee consistent performance across species or batches. Standardization should include species and developmental stage, rearing substrate, moisture, protein determination method, residual lipid and chitin-rich material, particle size, and processing history [5,7].

The next priority is to establish acceptance criteria linked to the intended application. For emulsified products, these may include extraction behavior, emulsion stability, cooking yield, and expressible moisture; for structured products, relevant criteria include rheology, anisotropy, texture, and water retention. Multi-omics characterization may help explain batch differences, but its practical value must be demonstrated against these measurable quality outcomes.

### 6.2. From analytical allergen reduction to clinical validation

Processing effects on allergenicity should be interpreted at three distinct levels: degradation or alteration of allergenic proteins, changes in immunoreactivity such as IgE binding, and demonstrated clinical outcomes [25]. A reduction in detectable allergen abundance or IgE binding does not establish that an ingredient is safe for allergic consumers. Residual cross-reactivity, processing-dependent epitope changes, and possible carryover of feed allergens require consideration. Table 6 summarizes allergen-related considerations

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together with microbial and chemical hazards and the corresponding validation requirements for insect-containing foods.

The next phase should combine validated analytical methods with clinically relevant evaluation, using appropriately characterized ingredients and study populations [5]. Claims of hypoallergenicity require evidence beyond conventional compositional analysis or fermentation-associated changes. Until such evidence is available, processing benefits should be described using the endpoint actually measured.

### 6.3. From hazard identification to validated microbial control

Whole-insect ingredients differ from muscle meat because the gastrointestinal tract and associated microbiota may remain within the harvested material. Blanching can reduce vegetative microorganisms, but it should not be assumed to eliminate bacterial spores. Drying can restrict microbial growth through water-activity reduction without necessarily providing a validated lethal treatment.

Transfer of livestock hazard-management principles therefore requires insect-specific validation of raw-material acceptance, time–temperature treatments, water activity, post-process contamination control, and storage conditions. Studies should distinguish reductions in indicator counts from validated control of relevant pathogens and should consider the possibility of survival or growth after rehydration and incorporation into a finished food. The microbial validation requirements summarized in Table 6 should be applied to the specific ingredient, process, and finished-food matrix.

### 6.4. From prototypes to consumer and industrial validation

Prototype studies have shown that insect ingredients can be incorporated into selected familiar food matrices, but technical feasibility should be separated from consumer and commercial validation. Sensory studies should assess the finished formulation against an appropriate comparator and distinguish willingness to try, liking after consumption, and repeated-use intention [10].

Scale-up should evaluate continuous operation, ingredient variability, throughput, cleaning requirements, process yield, and energy demand. Pilot-scale results should be linked to techno-economic and life-cycle analyses using explicit product specifications and system boundaries. This approach can identify whether a functional improvement remains meaningful after manufacturing cost and resource use are considered.

### 6.5. Product-specific regulatory compliance

Regulatory evaluation should distinguish human food from feed and should identify the jurisdiction, ingredient form, intended use, and applicable conditions [18]. European Union

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novel food authorizations concern specified products and conditions rather than unrestricted approval of an insect species. In the United States, USDA-FSIS responsibilities for meat, poultry, and egg products within its jurisdiction should be distinguished from FDA oversight. Table 7 summarizes the scope-specific regulatory considerations discussed here for the European Union and the United States. This summary is not a complete inventory of authorized insect ingredients or permitted uses.

Product development should therefore begin with verification that the specific ingredient and proposed use are permitted in the target market. Regulatory status should be checked using official sources and should not be inferred from traditional consumption, publication of a processing study, or authorization for feed use.

Figure 1 links ingredient characteristics, processing interventions, measurable product outcomes, and validation requirements. The feedback loop emphasizes application-specific optimization and verification rather than replacement of livestock foods by insect ingredients.

## 7. Conclusions

Meat science provides useful principles for ingredient characterization, protein network formation, flavor development, oxidation control, and process validation in insect-containing foods. The evidence supports selected formulation-specific applications rather than universal substitution of livestock proteins. Hybrid emulsified products and extruded matrices are practical test platforms, but their performance depends on insect species, ingredient form, inclusion level, and processing conditions.

The highest-priority experiments are matched-protein and matched-moisture comparisons, controlled evaluation of residual lipid and chitin fractions, validation of cooking yield and emulsion stability, shelf-life and sensory testing, and insect-specific microbial and allergen assessment. Industrial feasibility additionally requires pilot-scale processing, techno-economic analysis, and life-cycle assessment using explicit functional units and boundaries.

Complementary integration is therefore a testable development strategy, not an established guarantee of improved functionality, acceptance, or sustainability. The contribution of meat science is to provide mechanisms, performance criteria, and validation practices with which such integration can be critically assessed.

## Competing interests

No potential conflict of interest relevant to this article was reported.

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## Availability of data and material

Upon reasonable request, the datasets of this study can be available from the corresponding author.

## Ethics approval and consent to participate

This article does not require IRB/IACUC approval because there are no human and animal participants.

## Declaration of generative AI

No AI tools were used in this article.

## References

1. Loveday SM. Food proteins: technological, nutritional, and sustainability attributes of traditional and emerging proteins. Annu Rev Food Sci Technol. 2019;10:311-339. https://doi.org/10.1146/annurev-food-032818-121128
2. Dobermann D, Swift JA, Field LM. Opportunities and hurdles of edible insects for food and feed. Nutr Bull. 2017;42:293-308. https://doi.org/10.1111/nbu.12291
3. Pereira PMDCC, Vicente AFDRB. Meat nutritional composition and nutritive role in the human diet. Meat Sci. 2013;93:586-592. https://doi.org/10.1016/j.meatsci.2012.09.018
4. Kim TK, Cha JY, Yong HI, Jang HW, Jung S, Choi YS. Application of edible insects as novel protein sources and strategies for improving their processing. Food Sci Anim Resour. 2022;42:372-388. https://doi.org/10.5851/kosfa.2022.e10
5. van der Spiegel M, Noordam MY, van der Fels-Klerx HJ. Safety of novel protein sources (insects, microalgae, seaweed, duckweed, and rapeseed) and legislative aspects for their application in food and feed production. Compr Rev Food Sci Food Saf. 2013;12:662-678. https://doi.org/10.1111/1541-4337.12032
6. van Huis A. Potential of insects as food and feed in assuring food security. Annu Rev Entomol. 2013;58:563-583. https://doi.org/10.1146/annurev-ento-120811-153704
7. Rumpold BA, Schlüter OK. Nutritional composition and safety aspects of edible insects. Mol Nutr Food Res. 2013;57:802-823. https://doi.org/10.1002/mnfr.201200735
8. Meyer-Rochow VB, Gahukar RT, Ghosh S, Jung C. Chemical composition, nutrient quality and acceptability of edible insects are affected by species, developmental stage, gender, diet, and processing method. Foods. 2021;10:1036. https://doi.org/10.3390/foods10051036

ACCEPTED

9. Oonincx DGAB, van Itterbeeck J, Heetkamp MJW, van den Brand H, van Loon JJA, van Huis A. An exploration on greenhouse gas and ammonia production by insect species suitable for animal or human consumption. PLoS One. 2010;5:e14445. https://doi.org/10.1371/journal.pone.0014445
10. Syartiwidya, Iwansyah AC, Fikri AM, Harianti R, Yunita R, Saghita EP. A global perspective and acceptability of edible insects as novel food in Western and Asian Countries: a systematic literature review. Food Prod Process Nutr. 2025;7:38. https://doi.org/10.1186/s43014-024-00301-0
11. Galanakis CM. Functionality of food components and emerging technologies. Foods. 2021;10:128. https://doi.org/10.3390/foods10010128
12. Hocquette JF, Gondret F, Baéza E, Médale F, Jurie C, Pethick DW. Intramuscular fat content in meat-producing animals: development, genetic and nutritional control, and identification of putative markers. Animal. 2010;4:303-319. https://doi.org/10.1017/S1751731109991091
13. Zhang L, Li F, Guo Q, Duan Y, Wang W, Yang Y, et al. Balanced branched-chain amino acids modulate meat quality by adjusting muscle fiber type conversion and intramuscular fat deposition in finishing pigs. J Sci Food Agric. 2022;102:3796-3807. https://doi.org/10.1002/jsfa.11728
14. Gong H, Liu J, Wang L, You L, Yang K, Ma J, et al. Strategies to optimize the structural and functional properties of myofibrillar proteins: physical and biochemical perspectives. Crit Rev Food Sci Nutr. 2024;64:4202-4218. https://doi.org/10.1080/10408398.2022.2139660
15. Park MK, Choi YS. Effective strategies for understanding meat flavor: a review. Food Sci Anim Resour. 2025;45:165-184. https://doi.org/10.5851/kosfa.2024.e124
16. Toldrá F, Reig M, Aristoy MC, Mora L. Generation of bioactive peptides during food processing. Food Chem. 2018;267:395-404. https://doi.org/10.1016/j.foodchem.2017.06.119
17. Kim SB, Baek JY, Lee ES, Lee NK, Paik HD. Lactose-free fermented milk production using Lactococcus lactis NK24 and NK34 with immune-enhancing effects on RAW 264.7 cells. J Microbiol Biotechnol. 2026;36:e2601014. https://doi.org/10.4014/jmb.2601.01014
18. EFSA Panel on Nutrition, Novel Foods and Food Allergens (NDA), Turck D, Bohn T, Castenmiller J, De Henauw S, Hirsch-Ernst KI, et al. Safety of frozen and dried formulations from whole yellow mealworm (Tenebrio molitor larva) as a novel food pursuant to Regulation (EU) 2015/2283. EFSA J. 2021;19:e06778. https://doi.org/10.2903/j.efsa.2021.6778
19. Bußler S, Rumpold BA, Jander E, Rawel HM, Schlüter OK. Recovery and techno-functionality of flours and proteins from two edible insect species: meal worm (Tenebrio molitor) and black soldier fly (Hermetia illucens) larvae. Heliyon. 2016;2:e00218. https://doi.org/10.1016/j.heliyon.2016.e00218
20. Yi L, Lakemond CMM, Sagis LMC, Eisner-Schadler V, van Huis A, van Boekel MAJS. Extraction and characterisation of protein fractions from five insect species. Food Chem. 2013;141:3341-3348. https://doi.org/10.1016/j.foodchem.2013.05.115

ACCEPTED

21. Hall FG, Jones OG, O'Haire ME, Liceaga AM. Functional properties of tropical banded cricket (Gryllodes sigillatus) protein hydrolysates. Food Chem. 2017;224:414-422. https://doi.org/10.1016/j.foodchem.2016.11.138
22. Laroche M, Perreault V, Marciniak A, Gravel A, Chamberland J, Doyen A. Comparison of conventional and sustainable lipid extraction methods for the production of oil and protein isolate from edible insect meal. Foods. 2019;8:E572. https://doi.org/10.3390/foods8110572
23. Rose A, Jaczynski J, Matak K. Extraction of lipids from insect powders using a one-step organic solvent extraction process. Future Foods. 2021;4:100073. https://doi.org/10.1016/j.fufo.2021.100073
24. Park MK, Shin DM, Choi YS. Comparison of volatile compound profiles derived from various livestock protein alternatives including edible-insect, and plant-based proteins. Food Chem X. 2024;23:101570. https://doi.org/10.1016/j.fochx.2024.101570
25. Broekman HCHP, Knulst AC, den Hartog Jager CF, van Bilsen JHM, Raymakers FM, Kruizinga AG, et al. Primary respiratory and food allergy to mealworm. J Allergy Clin Immunol. 2017;140:600-603.e7. https://doi.org/10.1016/j.jaci.2017.01.035
26. Bolumar T, LaPeña D, Skibsted LH, Orlien V. Rosemary and oxygen scavenger in active packaging for prevention of high-pressure induced lipid oxidation in pork patties. Food Packag Shelf Life. 2016;7:26-33. https://doi.org/10.1016/j.fpsl.2016.01.002
27. Balasubramaniam VM, Martinez-Monteagudo SI, Gupta R. Principles and application of high pressure-based technologies in the food industry. Annu Rev Food Sci Technol. 2015;6:435-462. https://doi.org/10.1146/annurev-food-022814-015539
28. Smetana S, Larki NA, Pernutz C, Franke K, Bindrich U, Toepfl S, et al. Structure design of insect-based meat analogs with high-moisture extrusion. J Food Eng. 2018;229:83-85. https://doi.org/10.1016/j.jfoodeng.2017.06.035
29. Cho HY, Lee JE, Lee JH, Ahn DU, Kim KT, Paik HD. Improved antioxidant and anti-melanogenic effects of ovalbumin derived from egg white after enzymatic hydrolysis. Food Sci Anim Resour. 2026;46:15. https://doi.org/10.1007/s44463-025-00024-x
30. Dekkers BL, Boom RM, van der Goot AJ. Structuring processes for meat analogues. Trends Food Sci Technol. 2018;81:25-36. https://doi.org/10.1016/j.tifs.2018.08.011
31. Liu Z, Zhang M, Bhandari B, Wang Y. 3D printing: printing precision and application in food sector. Trends Food Sci Technol. 2017;69:83-94. https://doi.org/10.1016/j.tifs.2017.08.018
32. Park KM, Lee YR, Lee NK, Paik HD. Lactiplantibacillus plantarum WB3801 and Lactiplantibacillus plantarum WB3808 showed antioxidant effect and anti-apoptosis through activation of the Keap1/Nrf2/HO-1 pathway in H2O2-induced HT-29 cells. J Microbiol Biotechnol. 2025;35:e2508014. https://doi.org/10.4014/jmb.2508.08014

ACCEPTED

33. Cha YJ, Jang HJ, Lee GW, Lee NK, Paik HD. Intestinal epithelial-protective effects of Leuconostoc mesenteroides H40 in LPS-stimulated HT-29 cells. J Microbiol Biotechnol. 2026;36:e2607028. https://doi.org/10.4014/jmb.2607.07028
34. Lee NK, Lee Y, Hwang J, Park E, Paik HD. Heat-killed Leuconostoc mesenteroides H40 alleviates cognitive impairment by anti-inflammation and antioxidant effects in a scopolamine-induced mouse model. J Microbiol Biotechnol. 2025;35:e2411013. https://doi.org/10.4014/jmb.2411.11013
35. Cui Z, Qi C, Zhou T, Yu Y, Wang Y, Zhang Z, et al. Artificial intelligence and food flavor: how AI models are shaping the future and revolutionary technologies for flavor food development. Compr Rev Food Sci Food Saf. 2025;24:e70068. https://doi.org/10.1111/1541-4337.70068
36. Raikos V. Effect of heat treatment on milk protein functionality at emulsion interfaces. A review. Food Hydrocolloids. 2010;24:259-265. https://doi.org/10.1016/j.foodhyd.2009.10.014
37. Corredig M, Nair PK, Li Y, Eshpari H, Zhao Z. Invited review: Understanding the behavior of caseins in milk concentrates. J Dairy Sci. 2019;102:4772-4782. https://doi.org/10.3168/jds.2018-15943
38. Tian Y, Lv X, Oh DH, Kassem JM, Salama M, Fu X. Emulsifying properties of egg proteins: Influencing factors, modification techniques, and applications. Compr Rev Food Sci Food Saf. 2024;23:e70004. https://doi.org/10.1111/1541-4337.70004
39. Montowska M, Kowalczewski PŁ, Rybicka I, Fornal E. Nutritional value, protein and peptide composition of edible cricket powders. Food Chem. 2019;289:130-138. https://doi.org/10.1016/j.foodchem.2019.03.062
40. Stone AK, Tanaka T, Nickerson MT. Protein quality and physicochemical properties of commercial cricket and mealworm powders. J Food Sci Technol. 2019;56:3355-3363. https://doi.org/10.1007/s13197-019-03818-2
41. Lee JH, Kim YJ, Kim TK, Song KM, Choi YS. Effect of ethanol treatment on the structural, techno-functional, and antioxidant properties of edible insect protein obtained from Tenebrio molitor larvae. Food Chem. 2024;437:137852. https://doi.org/10.1016/j.foodchem.2023.137852
42. Kim TK, Lee MH, Yu MH, Yong HI, Jang HW, Jung S, et al. Thermal stability and rheological properties of heat-induced gels prepared using edible insect proteins in a model system. LWT. 2020;134:110270. https://doi.org/10.1016/j.lwt.2020.110270
43. Lee JH, Kim TK, Park SY, Kang MC, Cha JY, Lim MC, et al. Effects of blanching methods on nutritional properties and physicochemical characteristics of hot-air dried edible insect larvae. Food Sci Anim Resour. 2023;43:428-440. https://doi.org/10.5851/kosfa.2023.e4
44. Lee JH, Kim TK, Jeong CH, Yong HI, Cha JY, Kim BK, et al. Biological activity and processing technologies of edible insects: a review. Food Sci Biotechnol. 2021;30:1003-1023. https://doi.org/10.1007/s10068-021-00942-8
ACCEPTED

45. Kim TK, Lee MH, Yong HI, Jung S, Paik HD, Jang HW, et al. Effect of interaction between mealworm protein and myofibrillar protein on the rheological properties and thermal stability of the prepared emulsion systems. Foods. 2020;9:1443. https://doi.org/10.3390/foods9101443
46. Kim YJ, Cha JY, Kim JH, Keum DH, Jang HW, Choi YS. Ultrasound-assisted ionic extraction modulates the structural, interfacial, and digestive properties of Protaetia brevitarsis larval proteins. Food Chem X. 2026;36:104051. https://doi.org/10.1016/j.fochx.2026.104051
47. Kim YJ, Cha JY, Kim JH, Keum DH, Gu BJ, Choi YS. Fibrous structuring and physicochemical properties of high-moisture meat analogues formulated with defatted edible insect proteins: Effects of species and inclusion level. Food Chem X. 2026;39:104345. https://doi.org/10.1016/j.fochx.2026.104345
48. Belluco S, Halloran A, Ricci A. New protein sources and food legislation: the case of edible insects and EU law. Food Secur. 2017;9:803-814. https://doi.org/10.1007/s12571-017-0704-0
49. Siddiqui SA, Osei-Owusu J, Yunusa BM, Rahayu T, Fernando I, Shah MA, et al. Prospects of edible insects as sustainable protein for food and feed–a review. J Insects Food Feed. 2023;10:191-217. https://doi.org/10.1163/23524588-20230042
50. European Commission. Approval of insects as novel food [Internet]. Brussels: European Commission; [cited 2026 Oct 5]. Available from: https://food.ec.europa.eu/food-safety/novel-food/authorisations/approval-insect-novel-food_en
51. United States Department of Agriculture, Food Safety and Inspection Service. About FSIS [Internet]. Washington, DC: USDA-FSIS; [cited 2026 Oct 5]. Available from: https://www.fsis.usda.gov/about-fsis

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## Figure Legend

Figure 1. **An application-specific framework for developing and validating insect-containing foods using meat science principles**

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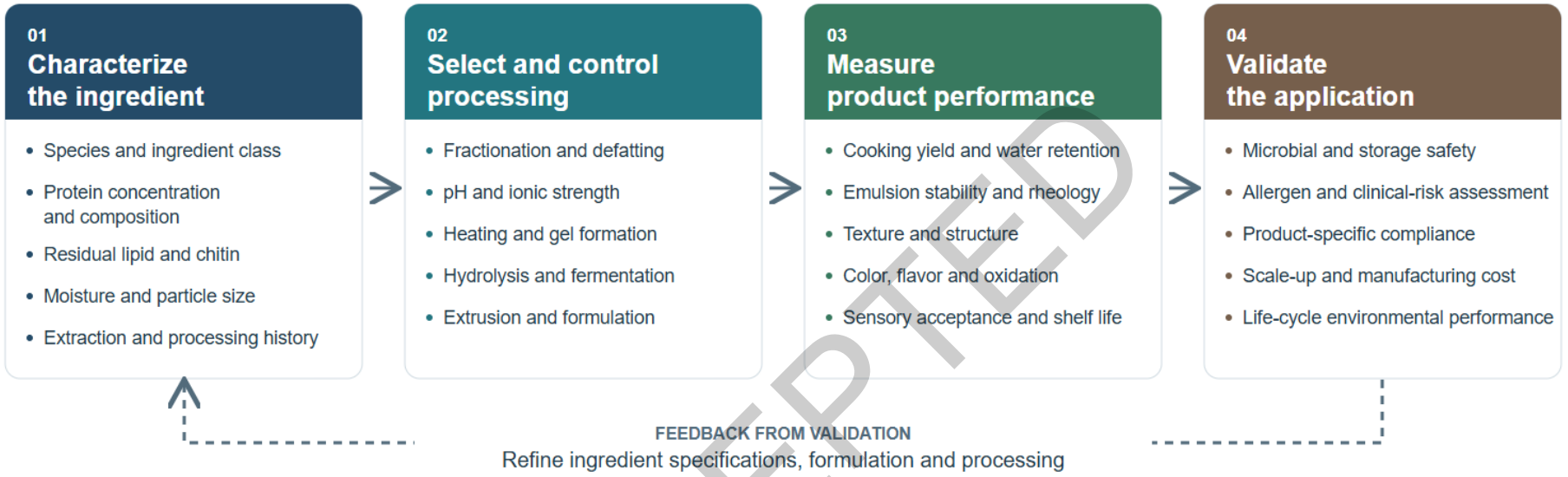



Figure 1.

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**Table 1. Livestock food categories as processing and quality benchmarks for insect-containing foods**

| Food category | Functional components and mechanisms | Processing maturity | Transferable principles and limitations | Reference |
|---|---|---|---|---|
| Meat and meat products | Myofibrillar extraction, interfacial adsorption, heat-induced aggregation and gel networks; fat and water retention. | Comminution, curing and thermal processing are established; performance remains formulation-dependent. | Match protein concentration, pH and ionic strength; do not assume uniform quality across muscles or postmortem conditions. | [3,14,15] |
| Milk and dairy products | Casein-based colloidal behavior; whey-protein unfolding and aggregation; fermentation-associated acidification. | Pasteurization, fermentation and concentration are established for defined dairy products. | Control pH, mineral balance and heat history; casein behavior cannot be assumed for insect proteins. | [36,37] |
| Eggs and egg-derived ingredients | Protein adsorption at air–water and oil–water interfaces; heat-induced coagulation and gelation. | Foaming, emulsification and thermal setting are established in specified applications. | Use interface-specific and thermal benchmarks; purity and residual components affect comparability. | [29,38] |
| Specialized preservation operations | Pressure, electric-field treatment and packaging act through different physical mechanisms. | Commercial maturity varies by product, operation and process objective. | Validate lethality and product quality in the actual insect matrix; adoption elsewhere does not prove transferability. | [11,26,27] |

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**Table 2. Material identity and reporting requirements for compositional comparisons of livestock and insect ingredients**

| Material class | Minimum sample description | Required compositional information | Interpretation and exclusion criteria | References |
|---|---|---|---|---|
| Whole-insect powder | Species, developmental stage, whole-body material, feed withdrawal and drying history. | Moisture, protein method and nitrogen conversion factor, lipid, ash, fiber/chitin definition and carbohydrate calculation. | Do not compare dried whole-body powder directly with fresh lean meat on an unstated basis. | [7,8,39,40] |
| Defatted insect flour | Species, starting powder, defatting method and residual lipid. | Composition after defatting; moisture and analytical basis; extraction recovery if reported. | Higher protein percentage after fat removal does not demonstrate improved protein quality or functionality. | [19,22,23,41] |
| Protein concentrate or isolate | Species, extraction solvent, pH, precipitation and drying. | Protein purity, residual lipid/ash, moisture and protein assay; amino-acid data when available. | Do not treat the fraction as compositionally equivalent to its source insect. | [19,20,21] |
| Protein hydrolysate | Starting fraction, enzyme, treatment conditions and degree-of-hydrolysis method. | Protein/peptide content, moisture, residual salts and analytical basis. | Peptide abundance or assay activity is not a measure of structural performance in a food. | [16,21] |
| Lean livestock meat | Species, muscle/tissue, raw or cooked state, trimming and storage history. | Moisture, protein, lipid and ash on the same reporting basis as the comparator. | Distinguish fresh tissue from isolated myofibrillar protein; cooking alters composition. | [3,12,14] |
| Extracted livestock protein | Tissue source, extraction and purification history. | Protein concentration/purity, residual components and assay conditions. | Suitable functional comparator only after concentration and assay conditions are matched. | [14] |

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633 **Table 3. Conditions for interpreting functional comparisons between myofibrillar and insect-derived proteins**

| Property | Myofibrillar reference | Insect-ingredient considerations | Matched comparison and outcome | References |
|---|---|---|---|---|
| Solubility | Generally poor at low ionic strength; salt extraction depends on pH and history. | Fraction purity, extraction, aggregation and residual components affect measured solubility. | Match pH, ionic strength, concentration, temperature and assay. | [14,19,20] |
| Emulsification | Adsorption and film formation depend on extraction and formulation. | Emulsifying capacity and emulsion stability can respond differently to processing. | Report oil fraction, homogenization, droplet size, separation and thermal stability separately. | [14,19,21] |
| Gelation | Heat-induced unfolding, aggregation and network formation. | Do not infer weak gelation solely from absence of muscle-like structure or presence of chitin. | Match protein concentration, heating/cooling and salt; measure rheology, texture and released water. | [11,14,21,42] |
| Foaming | Not a single source-specific constant; interfacial conditions matter. | Residual lipid and protein modification may alter capacity and stability. | Match air incorporation, concentration and observation time; distinguish capacity from stability. | [19,41] |
| Water retention | Affected by pH, extraction, network formation and postmortem state. | Whole powder and isolated protein differ in particle and residual-component effects. | Report cooking yield, expressible moisture and centrifugation protocols separately. | [14,19,22] |
| Thermal behavior | Transitions depend on protein fraction and analytical preparation. | Species, extraction and drying can change denaturation/aggregation profiles. | Use matched sample hydration, concentration and scan protocol; do not generalize lower stability. | [19,42] |
| Digestibility / protein quality | Requires a defined material and test method. | Nitrogen conversion, chitin-rich material and processing complicate comparisons. | Separate amino-acid score, in vitro digestibility and clinical outcomes; no unsupported fixed percentage ranges. | [3,7,21] |

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636 **Table 4. Processing mechanisms, potential benefits and trade-offs in insect-containing food development**
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| Operation | Mechanism and target | Potential application | Trade-offs and validation | References |
|---|---|---|---|---|
| Fractionation and defatting | Changes protein concentration and removes selected lipid or insoluble fractions. | Select ingredient classes for emulsification, gelation or structured matrices. | Recovery, residual solvent, aggregation, energy and waste must be considered; concentration is not performance. | [19,20,22,23] |
| Controlled heating | Unfolding, aggregation and network formation; microbial reduction under validated conditions. | Thermal setting and stabilization. | Excess treatment may reduce dispersibility or increase oxidation; lethality and texture require separate endpoints. | [42,43,44] |
| Enzymatic hydrolysis | Peptide-bond cleavage changes molecular size and interfacial behavior. | Soluble peptide ingredients and application-specific modification. | Excess hydrolysis may impair network formation or cause bitterness; report enzyme, time and degree of hydrolysis. | [16,21] |
| Fermentation | Microbial metabolism changes pH, substrates, proteins and volatile precursors. | Flavor modification and controlled bioprocessing. | Starter- and matrix-dependent; lower IgE binding does not establish clinical safety. | [17] |
| High-moisture extrusion | Thermomechanical treatment and alignment during flow/cooling. | Plant–insect hybrid structuring. | Species, moisture, inclusion basis and melt behavior affect structure; scale-up and sensory equivalence remain separate questions. | [28,30] |
| Ultrasound-assisted extraction | Changes extraction and dispersion under defined solvent and acoustic conditions. | Recovery and interfacial-property adjustment. | Benefits differ by solvent and endpoint; increased emulsion stability need not mean higher emulsifying capacity. | [20,44] |
| High-pressure processing | Pressure-dependent structural and microbial effects. | Potential stabilization where matrix-specific validation exists. | Do not infer spore control or insect-food effectiveness from livestock applications. | [26,27] |
| Packaging | Modifies oxygen exposure, moisture transfer or storage atmosphere. | Oxidation and shelf-life management. | Residual enzymes, contamination and storage temperature remain relevant. | [26] |
| 3D printing / AI-assisted formulation | Spatial deposition / data-based composition–process modeling. | Geometry control / hypothesis generation and optimization. | Neither provides automatic safety or functionality; validate printability, hygiene and independent-batch predictions. | [31,35] |

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638 **Table 5. Selected primary evidence on meat–insect emulsions, hybrid structuring and ingredient modification**
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| Study / matrix | Ingredient and inclusion basis | Reported processing conditions | Comparator and measured outcomes | Limitations and relevance |
|---|---|---|---|---|
| Pork-protein/insect emulsion model [45] | *Tenebrio molitor* extract and pork myofibrillar extract, each adjusted to 30 mg/mL. Protein ratios 100:0, 80:20, 60:40, 40:60, 20:80 and 0:100. | Mixed protein solution:fat = 4:1 (v/w); homogenization at 14,500 rpm for 60 s; temperature maintained below 5 °C. | Pork-protein-only control. Increasing insect fraction decreased apparent viscosity, several texture parameters and thermal-stability measures; color and pH changed. | Model extracted-protein system, not whole-powder sausage. Authors proposed up to 40% replacement under their conditions; not a universal threshold. Extraction included sodium azide, so the analytical preparation is not a ready-to-adopt food process. |
| Ingredient-level extraction comparison [46] | *Protaetia brevitarsis* larval proteins; water or salt extraction, each with/without ultrasound. No food inclusion rate. | Extraction using distilled water or 0.6 M NaCl, each with or without ultrasound. Detailed acoustic parameters are not reproduced in this summary. | Water + ultrasound gave the highest yield and solubility at pH ≥6. Salt + ultrasound showed higher emulsion stability and in vitro digestibility but lower emulsifying capacity than other preparations. | Demonstrates endpoint-specific trade-offs; not evidence of cooking yield, consumer acceptance or clinical digestibility in finished foods. |
| Soy–gluten high-moisture meat analogues [47] | Defatted *Tenebrio molitor*, *Protaetia brevitarsis* or *Gryllus bimaculatus* proteins; reported inclusion levels 4% and 8%. | High-moisture extrusion; inclusion levels are reported as 4% and 8% in the study. Detailed operating settings are not reproduced in this summary. | Species/inclusion comparisons. Higher inclusion reduced lightness and increased redness; T. molitor at 4% showed favorable fibrous/meat-like texture in the study; interaction and microstructure changes were reported. | Plant–insect matrix, not meat emulsion. Does not establish industrial-scale manufacture, universal superiority or environmental benefit. |

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641 **Table 6. Safety hazards and validation requirements for insect-containing foods**
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| Hazard / issue | Livestock-system context | Insect-specific consideration | Validation requirement | References |
|---|---|---|---|---|
| Vegetative microorganisms | Established raw-material and post-process controls. | Whole-body material may include gastrointestinal microbiota. | Validate the actual time–temperature or alternative process in the relevant matrix. | [5,43,44] |
| Bacterial spores | Heat resistance varies by organism and process. | Blanching/drying must not be presumed to eliminate spores. | Assess survival and possible outgrowth during storage or rehydration. | [5,7,44] |
| Water activity and storage | Temperature and moisture determine growth opportunities. | Drying inhibits growth without necessarily providing lethality. | Specify water activity, packaging, storage and finished-food behavior. | [19,26,43] |
| Post-process contamination | Separation of raw and treated materials is important. | Milling, handling and incorporation may reintroduce contamination. | Validate hygienic zoning, sanitation and finished-product controls. | [5,19] |
| Allergenicity / cross-reactivity | Milk, egg and other animal foods have distinct allergen profiles. | Cross-reactivity with crustaceans and mites may be relevant. | Distinguish allergen abundance, IgE binding and clinical safety; apply product-specific labeling. | [18,25,48] |
| Feed-allergen carryover | Ingredient and feed histories support risk assessment. | Allergens in rearing substrates may remain in the harvested material. | Assess substrate history, carryover and appropriate analytical endpoints. | [5,18] |
| Chemical contaminants | Residues and contaminants depend on production and controls. | Substrate, species and accumulation may affect contaminant profiles. | Use compliant substrates and validated sampling/testing; do not infer safety from species identity. | [5,7] |
| Traceability | Batch records enable investigation and recall. | Track species, developmental stage, substrate and processing batch. | Link raw material and final product; digital systems are tools, not safety evidence. | [5,18,49] |

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645 **Table 7. Scope-specific regulatory considerations for insect-containing human foods**
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| Jurisdiction | Conventional animal-food oversight | Insect human-food interpretation | Development implication | Official source |
|---|---|---|---|---|
| European Union | Conventional products and establishments are subject to applicable food-safety requirements; this column is not a complete legal summary. | Novel food authorizations concern specified products, forms, conditions of use and labeling, not unrestricted species approval. | Check the exact authorization and intended food category. Keep human-food and feed permissions separate. | European Commission [50] |
| United States | USDA-FSIS oversees meat, poultry and egg products within its jurisdiction; FDA oversight must be distinguished. | The cited FSIS overview does not establish a species-specific edible-insect approval, GRAS determination or blanket permission. | Determine the authority and legal route for the exact ingredient and finished product; obtain a product-specific official basis before asserting authorization. | USDA-FSIS [51] |

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