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From live handling to food safety: an integrative review of mud crabs and spiny lobsters

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ABSTRACT

Mud crabs (Scylla spp.) and spiny lobsters (Panulirus spp.) are premium seafood, but evidence on live handling, freshness indicators, processing, food safety, and shell utilization is rarely integrated across the postharvest chain. This critical integrative review analyzes 30 commodity-focused sources originally published between 1997 and 2026, complemented by 16 recent methodology and cross-commodity references. The underlying literature search covered PubMed, Google Scholar, publisher databases, the JPHPI portal, and reference chaining; heterogeneous outcomes were compared narratively without statistical pooling. In Scylla serrata, initial decomposition occurred after six days at 10 °C compared with three days at 25 °C. In Panulirus argus, a reflex-based mortality model reached an area under the curve of 0.897, while a separate sous-vide study reported refrigerated crab-meat shelf life beyond 60 days under defined experimental conditions. These results are study-specific, not interchangeable treatment effects or universal safety thresholds. Evidence converges on the need to link initial animal condition, transport stress, tissue-specific freshness indices, pathogen controls, process validation, and packaging. Major gaps concern the relationship between live stress and subsequent edible quality, cross-species transferability, and validation in Indonesian commercial supply chains. An integrated decision-linked framework is proposed as a testable research model, not an already validated industrial standard. Original screening-flow and inter-rater records were unavailable and are not retrospectively invented.

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Introduction

Mud crabs (Scylla spp.) and spiny lobsters (Panulirus spp.) command high value in live and processed seafood markets, but biological value does not automatically translate into shelf-stable, traceable food. Pre-harvest nutritional status, species, and molt stage affect starting quality; subsequent handling, temperature exposure, hygienic conversion, and packaging influence whether that potential is maintained. The unresolved challenge is not to replace aquaculture management with food processing, but to connect variables measured on either side of harvest. Evidence on crab nutrient composition (Gao et al., 2023), temperature sensitivity (Tsai et al., 2019), and live-lobster mortality (Ross et al., 2024) already demonstrates why this interface warrants explicit assessment.

Recent studies have examined different fragments of the chain. Zhang et al. (2021) and Lin et al. (2022) evaluated storage-linked metabolites, ATP breakdown, and bacterial succession in Scylla paramamosain; Day et al. (2022) related postharvest water quality to physiological condition in Jasus edwardsii; Pozhoth and Jeffs (2022) assessed handling-related interventions for tropical Panulirus; and Ross et al. (2024) tested

reflex impairment as a predictor of P. argus mortality. These findings are valuable but use different animals, conditions, matrices, and endpoints. Their juxtaposition does not demonstrate an agreed temperature threshold, transferable shelf-life limit, or integrated safety outcome for commercial Indonesian supply chains.

The specific gap is a lack of decision-linked synthesis connecting (i) source and receiving quality, (ii) live-transport exposure, (iii) postmortem sensory–chemical–microbial verification, (iv) validated preservation and packaging, and (v) food-safe use of processing residues. The literature also contains a plausible competing explanation: aquaculture inputs and postharvest interventions interact, rather than one category of factors replacing the other. A convincing framework must therefore identify interfaces and constraints, distinguish direct Scylla/Panulirus data from analogues, and avoid treating an association from one species as a general causal law.

Existing management-oriented texts describe efficient harvest, careful handling, live storage, traceability, and diversification (Sucipto, 2026), whereas processing-focused investigations quantify deterioration or intervention responses (Chiou & Huang, 2004; Olatunde & Benjakul, 2021). Broader advances in seafood microbial risk (Sheng & Wang, 2021), temperature-dependent freshness modelling (García et al., 2022), and smart seafood packaging (Abedi-Firoozjah et al., 2023) offer relevant analytical comparators. None should be presented as direct validation of Indonesian Scylla or Panulirus where species-level tests were not performed.

The review asks: Which measured postharvest variables and outcomes recur across Scylla and Panulirus studies; which evidence is commodity-specific versus transferable only as a mechanism; and where do disconnected measurements prevent an integrated quality-to-safety claim? Accordingly, the objectives are to map evidence by commodity, treatment and endpoint; critically compare reported quantitative results where available; assess interpretation limits and counterarguments; and construct a transparent operational framework for future validation. Outcomes of interest include reflex/mortality performance, physical condition, K value and ATP catabolites, sensory quality, volatile bases, microbial growth, process lethality, packaging integrity, and shelf life. This is a literature synthesis, not a primary experiment, so no laboratory hypothesis test or respondent sampling frame is asserted.

Method

A critical integrative review with structured narrative synthesis was selected because the evidence spans live-transport physiology, postmortem chemistry, food safety, processing technologies, and material valorization, with no common intervention, comparator, or outcome suitable for meta-analysis. The search already described in the source manuscript was updated in August 2026 and used PubMed, Google Scholar, scientific publisher databases, the JPHPI portal, and reference lists. The reported term families comprised ("Scylla" OR "mud crab") OR ("Panulirus" OR "spiny lobster"), combined conceptually with ("postharvest" OR "transport" OR "storage" OR "freshness" OR "processing" OR "food safety" OR "packaging" OR "chitosan"), with Indonesian equivalents in local sources. The reportable coverage is 1997–2026 and international evidence with relevance to Indonesian commodities. Exact historical search strings, search dates per database, initial hit counts, duplicate-removal records, and an archived protocol were not supplied in the source files; these cannot be reconstructed reliably and are not represented as having been prospectively recorded (Page et al., 2021).

The original manuscript lists 30 core sources (25 empirical studies, three reviews, one book, and one food-safety code); this is a documented retained-source count, not the denominator of an auditable PRISMA screening flow. Sixteen independently identified supporting references are now cited for review methodology, risk interpretation, seafood technology, smart packaging, and by-product pathways; they are contextual support rather than retrospectively claimed outputs of the original screening. The resulting 46-item bibliography must not be confused with a 46-study systematic review. Sources were discussed within seven a priori topical domains: receiving/raw material, live handling, postmortem indicators, preservation, safety/traceability, packaging, and product/by-product development. Comparisons preferentially use direct Scylla/Panulirus experiments, then explicitly flagged cross-crustacean evidence, and finally general seafood or method reviews. No dual-screening exercise, Cohen's kappa, independent dual extraction, or numerical quality scores are claimed because the original audit trail and full-text assessment forms were unavailable. Instead, evidentiary weaknesses are documented and a prospective quality-assessment rubric is specified below.

Eligibility and extraction were operationalized for critical interpretation as shown in Table 1. This makes review judgements inspectable while acknowledging that the original search log cannot support a valid PRISMA flowchart. In future updates, reviewers should preserve deduplicated record exports, document reasons for full-text exclusion, pilot the extraction form, and independently screen a pre-specified fraction of records to compute agreement; the present review does not fabricate these missing quantities.

Table 1. Explicit eligibility, evidence-weighting, and extraction rules

Item	Operational rule	Required recorded fields
Population / food matrix	Direct: Scylla spp. or Panulirus spp. in postharvest/food settings; indirect: other crab/lobster/seafood when used only to explain a transfer mechanism	Scientific name; tissue or product; country/setting
Intervention / exposure	Harvest or postharvest handling, transport, storage, quality measurement, cooking, packaging, sanitation or by-product recovery	Exposure, comparison, storage conditions, sample size when available
Outcome	Relevant, directly measured vitality/mortality, sensory, biochemical, chemical, microbial, safety, shelf life, packaging, recovery or materials outcome	Analytical method, endpoint, units, time point, uncertainty if reported
Exclusions	Feed/growth-only studies without measured postharvest link; unsupported opinion; non-retrievable bibliographic identity; studies lacking method and outcome descriptions	Reason for exclusion, DOI or stable identifier when available
Evidence weighting	Tier A: directly studied Scylla/Panulirus; Tier B: related crustaceans; Tier C: broader seafood/method review; never transfer cutoffs without validation	Species transfer flag; design limitations; confounding; conclusion scope
Critical appraisal fields	Assess comparator, replication, outcome validity, storage/time reporting, contamination control, statistical uncertainty, and transferability; do not impute absent details	Yes / no / not reported for each field; limitations quoted from article

Table 2. Review-selection information recoverable from the provided manuscript

Review-reporting item	Available evidence / limitation
Search update and date window	Update stated: August 2026; publication years: 1997–2026.
Search resources	PubMed, Google Scholar, publisher databases, JPHPI portal, and backward reference checking; platform-specific hit logs not retained.
Records identified / duplicates removed	Not reported; not possible to provide a valid numeric PRISMA flow without original exports.
Titles/abstracts screened / full texts excluded	Not reported; exclusion counts and inter-rater agreement must not be inferred.
Core sources retained	30 stated in the original manuscript (25 primary studies, 3 reviews, 1 book, 1 code).
Additional interpretive sources	16 newly added method/seafood/packaging/valorization sources, kept analytically separate from the original core.
Statistical synthesis	Narrative and structured side-by-side comparison only; no pooled effect size or confidence interval is claimed.

Table 2 is a disclosure of missing audit items, not a PRISMA flow diagram. The minimum information necessary for a future fully reproducible update is the query-by-database log, export date, duplicate decisions, full-text exclusion ledger, prespecified appraisal instrument, and independent screening/extraction records. The 30-source count is reported because it is verifiable in the submitted bibliography; neither statistical power nor thematic saturation is an appropriate post hoc justification for its selection.

Results and Discussion

Why biological and postharvest indicators must be linked

The 30-source core supports a conditional pathway rather than the proposition that processing alone determines final product quality. Aquaculture stage and nutrition establish a biological starting point; subsequent emersion, handling, holding-water quality, time–temperature exposure, slaughter, and hygienic processing alter or preserve that condition. For example, Gao et al. (2023) related sex and molt stage to edible composition, whereas Chiou and Huang (2004) isolated a storage-temperature difference in postharvest biochemical deterioration. These are complementary, not competing, explanatory levels; feed conversion ratio and biomass gain remain useful before harvest, while meat quality and food-safety endpoints become decisive afterward.

Interpretation is stronger when study designs are compared rather than only topics listed. In S. serrata muscle, initial decomposition occurred after 6 days at 10 °C and 3 days at 25 °C (Chiou & Huang, 2004): a within-study doubling of time to initial decomposition, not a universal twofold shelf-life effect. In live P. argus, reflex impairment alone predicted mortality with AUC 0.897 and approximately 88% correct classification, whereas a model adding haemolymph protein and collection month reached AUC 0.938 and 90% classification (Ross et al., 2024). For crab lump meat, Olatunde and Benjakul (2021) reported refrigerated shelf life beyond 60 days after the tested sous-vide treatments; differences in species, unit processing, and endpoints preclude pooling these results. Tables 3 and 4 position such observations alongside their boundaries.

Table 3. Representative direct and transferable postharvest evidence (original core studies)

Study	Commodity	Operation or exposure	Processing relevance
Chiou & Huang (2004)	*Scylla serrata*	Storage at 10 and 25 degrees C	At 10 °C initial decomposition was seen after 6 d versus 3 d at 25 °C; species-specific quality response.
Ninlanon & Tangkrock-Olan (2008)	*S. serrata*	Precooling and chela tying during emersion	Handling affected stress-related glycogen and lactate; careful handling supported quality.
Tsai et al. (2019)	Mud crab	Thermal response during handling	Cardiac performance supported species-specific temperature control.
Zhang et al. (2021)	*S. paramamosain*	Room, ice, and frozen storage	Storage changed TMA, organic acids, ATP catabolites, and freshness.
Lin et al. (2022)	*S. paramamosain*	Postmortem ATP and bacterial succession	Muscle K value was proposed as an integrated freshness indicator.
Gao et al. (2023)	*S. paramamosain*	Harvest by sex and molt stage	Harvest stage affected minerals, amino acids, fatty acids, and carotenoids.
Sun et al. (2026)	*S. paramamosain*	Four live-preservation methods	Ice chilling delayed shell hardening and better retained desirable flavor.
Goncalves et al. (2015)	*Panulirus argus*	Whole lobster stored in ice for 18 days	A QIM scheme linked sensory deterioration with chemical and microbial change.
Ross et al. (2024)	*P. argus*	Simulated live-export handling	Reflex-only mortality model AUC 0.897 (~88% correct); combined model AUC 0.938 (~90% correct).
Pozhoth & Jeffs (2022)	Tropical *Panulirus*	Food-safe anesthetic during live transport	Treatment modified transport stress and survival outcomes.
Lorentzen et al. (2014)	Cooked red king crab	Chilled cluster storage	Different anatomical portions deteriorated at different rates, constraining shelf-life assignment.
Olatunde & Benjakul (2021)	Crab lump meat	Vacuum sous-vide processing	Study-specific sous-vide treatments yielded refrigerated shelf life >60 d; cannot generalize to all crab products.
Olatunde et al. (2021)	Blue swimming crab meat	In-package high-voltage cold plasma	Tested 10–15 min plasma treatments suppressed detectable bacteria, but oxidation and nutritional changes constrain adoption.
Luthfiyana et al. (2022)	*Scylla* shell	Chitosan demineralization	Process conditions influenced ash removal and chitosan quality.

Source: Comparison of the cited experiments; numerical values are study-specific and are not pooled.

Across the original evidence matrix, at least 14 named experiments or technology studies are compared directly in Table 3. The additional benchmarks in Table 4 make the comparative discussion exceed 15 studies

or reviews while explicitly distinguishing evidence from other crustaceans and non-crustacean seafood. Such triangulation maps plausible processes but does not establish transportability of microbial limits or treatment parameters. Differences in tissue, species, initial contamination, temperature, and detection protocol are major sources of between-study heterogeneity.

Table 4. Quantitative endpoints, contextual findings, and generalizability limits

Evidence / matrix	Reported comparison or measured focus	Quantitative or directional observation	Interpretive limit
Chiou & Huang (2004), S. serrata	10 °C vs 25 °C storage	Initial decomposition: day 6 vs day 3	Single species and study-defined decomposition
Ross et al. (2024), P. argus	Reflex-only vs combined mortality prediction	AUC 0.897 vs 0.938; 88% vs 90% correct classification	Requires local external validation
Olatunde & Benjakul (2021), crab meat	Sous-vide time × temperature	Refrigerated shelf life reported >60 d	Only under specific process and package conditions
Olatunde et al. (2021), Portunus meat	In-package plasma: 0, 5, 10, 15 min	No detected bacteria after tested 10–15 min treatments; oxidation concern	Not evidence for pathogen lethality in Scylla
Gao et al. (2023), S. paramamosain	Sex × molt-stage comparisons	Significant compositional differences in selected nutrients	Composition ≠ subsequent pathogen safety
Lin et al. (2022), S. paramamosain	ATP metabolites and microbial succession	Muscle K value showed indicator promise	Tissue and storage-specific thresholds
Goncalves et al. (2015), P. argus	Iced whole lobsters; QIM development	Sensory scheme related to chemical/microbial change	QIM scores require product validation
Wang et al. (2022), shrimp film	Antimicrobial film with freshness response	Packaging proof of concept for shrimp	Different species/material and safety profile
Roobab et al. (2022), seafood review	High-pressure processing	Mechanistic support for safety and meat recovery	Review of heterogeneous fish/shellfish
Sheng & Wang (2021), seafood review	Microbial hazards and prevention	Safety risk is not synonymous with sensory spoilage	Cross-commodity risk synthesis

Source: Primary results from the cited articles and clearly labeled contextual reviews. Numerical entries are reported study-specific results, not pooled effects.

Raw-material quality and harvest decisions

Raw-material quality begins before the animal enters the processing facility, but it must be expressed in postharvest terms. Species, size, sex, molt stage, shell hardness, injury, missing appendages, vitality, gut condition, and contamination history determine which product route is technically defensible. Harvest timing is therefore both a biological and a processing decision. Gao et al. (2023) showed that sex and molt stage influenced minerals, amino acids, fatty acids, and carotenoids in soft-shell mud crab. Such differences affect nutritional labeling, flavor, texture, color, and the timing of preservation.

A practical receiving specification should classify animals into live-premium, soft-shell, chilled or frozen meat, immediate processing, or rejection streams. Vital animals with intact appendages and appropriate market size can be routed to live distribution. Precisely staged soft-shell crabs require rapid harvest and preservation before shell hardening. Animals that die during distribution cannot automatically be converted into food; routing must consider the verified time of death, temperature history, sensory condition, physical damage, and microbiological risk.

Sucipto (2026) emphasizes harvest efficiency and product standardization. For fishery-product processing, this recommendation should be operationalized as measurable acceptance criteria, sampling plans, lot codes, and documented product-routing decisions. Without these controls, variability generated at harvest is merely transferred to later processing stages.

Live handling and transport as postharvest process control

Live crabs and lobsters remain raw food materials under physiological stress. Emersion, crowding, handling, vibration, temperature fluctuation, low oxygen, and ammonia accumulation disturb respiration, acid-base balance, energy metabolism, and immunity. Morris and Oliver (1999) demonstrated linked circulatory, respiratory, and metabolic responses to emersion and low temperature in southern rock lobster. Jussila et al. (1997, 2001) showed that haemocyte profiles and haemolymph clotting time respond to postharvest stress in

western rock lobster. These measurements are valuable for research, although routine processors need faster operational indicators.

Reflex assessment is a feasible non-destructive triage measurement rather than a universal laboratory substitute. Ross et al. (2024) reported AUC 0.897 for a reflex-only mortality model in P. argus and AUC 0.938 after adding blood protein and season; apparent improvement was modest and applies to the sampled trade context, not automatically to P. homarus or P. ornatus. Paterson et al. (2005) independently associated haemolymph parameters with simulated-handling survival in western rock lobster. Together with Jussila et al. (1997, 2001) and Day et al. (2022), these studies support an integrated physiological model while indicating that outcome definition, temperature, and species should be prespecified in local validation trials.

Water quality is a processing variable during wet holding. Day et al. (2022) linked suboptimal water quality to haemolymph biochemistry, immune status, and condition in postharvest *Jasus edwardsii*. During dry transport, humidity, ventilation, packing density, immobilization, and temperature replace water-quality management as the main controls. Food-safe anesthetics may reduce activity, but efficacy, recovery, residues, and consumer safety must be validated for the target species (Pozhoth & Jeffs, 2022).

The objective is not simply to keep animals alive. A technically adequate system should deliver animals that are alive, responsive, physically intact, and capable of yielding acceptable meat quality after slaughter. Mortality, reflex loss, damaged appendages, recovery time, haemolymph indicators, and later meat quality should therefore be measured together in transport trials.

Table 5. Critical control points from harvest to packaged product

Stage	Main hazard or quality risk	Evidence-based control
Harvest	Wrong molt stage, injury, contamination	Define species, size, molt stage, integrity, and harvest-time specifications.
Live holding	Hypoxia, ammonia, crowding, temperature stress	Control water quality, density, time, and recovery; monitor vitality and mortality.
Dry transport	Desiccation, overheating, vibration, reflex loss	Validate humidity, ventilation, packing, immobilization, and time-temperature profile.
Reception	Unknown time of death or broken cold chain	Verify lot identity, vitality, temperature, sensory status, and routing decision.
Primary processing	Cross-contamination and physical hazards	Apply hygienic design, potable water and ice, sanitation, and shell-fragment control.
Thermal/nonthermal process	Under-processing or quality loss	Validate lethality and product quality for the actual species, size, and package.
Packaging	Seal failure, gas imbalance, migration, recontamination	Verify material suitability, seal integrity, headspace, barrier function, and labeling.
Storage/distribution	Temperature abuse and excessive shelf-life	Record time-temperature history; validate limits using sensory, chemical, and microbial data.

Source: Author synthesis based on Codex Alimentarius Commission (2019), Neil (2012), Sucipto (2026), and the primary studies reviewed.

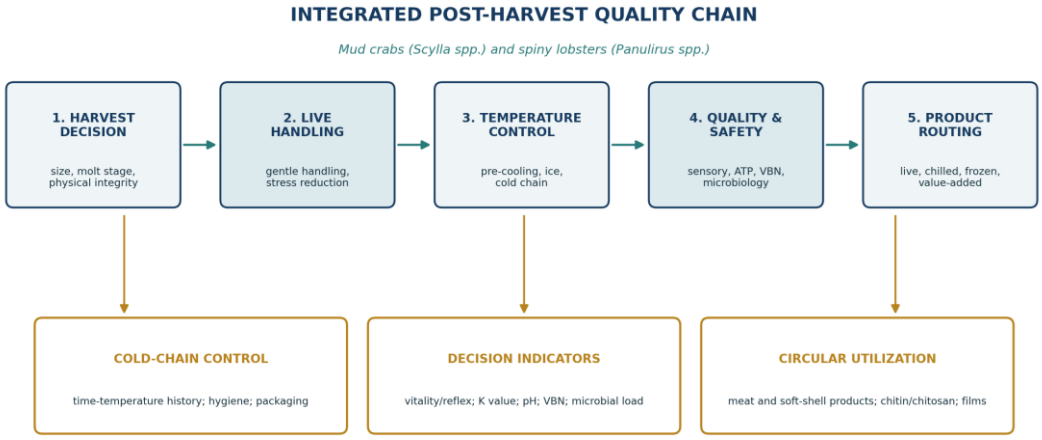


Figure 1. Decision-linked postharvest quality and safety chain
Source: Author synthesis.

Postmortem biochemistry and freshness verification

Biochemical freshness is not a single interchangeable index. In S. serrata, Chiou and Huang (2004) observed initial muscle decomposition on day 6 at 10 °C versus day 3 at 25 °C, showing why product-specific time–temperature history must be measured. Zhang et al. (2021) further associated storage condition with changes in organic acids, trimethylamine, and ATP-derived metabolites, and Lin et al. (2022) related ATP catabolism to bacterial succession in S. paramamosain. However, their experiments differ in body region, storage regimen, and measurement timing. A single pooled K-value slope or universal spoilage threshold would therefore misrepresent the published evidence.

K value summarizes selected ATP-related compounds and can provide an early freshness signal. Lin et al. (2022) linked ATP catabolism with bacterial succession in postmortem *Scylla paramamosain* and proposed muscle K value as an integrated indicator. However, no single universal limit should be assumed. Tissue, species, molt stage, pre-mortem stress, temperature, and analytical protocol can change the baseline and rate of increase.

Convergent evidence from independent measurements strengthens claims. Goncalves et al. (2015) developed a species-specific Quality Index Method (QIM) for iced P. argus and examined sensory, chemical, and microbiological change; Lorentzen et al. (2014) identified differing chilled deterioration across parts of cooked red king crab. More broadly, García et al. (2022) show that freshness prediction depends on models calibrated to storage stresses and validated against observable endpoints. Such findings favour multimodal verification with clear tissue-, time-, and product-specific decision rules, not reliance on one chemical indicator to determine microbiological safety.

Hepatopancreas and muscle should be analyzed separately when their enzymatic and microbial behavior differs. For soft-shell mud crab, free amino acids, nucleotides, shell hardening, and texture are particularly relevant because preservation may retain freshness while changing flavor development (Sun et al., 2026). A credible quality specification must therefore state the tissue, method, sampling position, storage condition, and decision purpose.

Table 6. Complementary indicators for quality and safety verification

Indicator group	Examples	Primary use	Limitation
Vitality	Reflexes, movement, survival, recovery	Triage of live products	Species and temperature dependent
Physical	Damage, limb loss, shell stage, yield	Grading and product routing	Requires trained assessors
Sensory	Appearance, odor, texture, QIM	Acceptance and remaining-life estimate	Needs species-specific validation
Biochemical	ATP compounds, K value, glycogen, lactate	Stress and early freshness change	Tissue and method affect results
Chemical	pH, VBN/TVB-N, TMA-N, oxidation markers	Spoilage and process verification	No single universal threshold
Microbiological	Aerobic count, psychrotrophs, pathogens	Safety support and shelf-life validation	Sampling and methods must be standardized
Process history	Core temperature, time, package gas, seal status	Cold-chain and package verification	Needs calibrated instruments and records

Source: Synthesized from Chiou and Huang (2004), Goncalves et al. (2015), Zhang et al. (2021), Lin et al. (2022), and Ross et al. (2024).

Preservation and process technology

Temperature is a recurring quality determinant but cannot be represented as a single universal optimum. The S. serrata comparison at 10 and 25 °C (Chiou & Huang, 2004) demonstrates differential postharvest quality trajectories, whereas cardiac performance studies in live mud crab require avoiding injurious cooling at species-specific lower limits (Tsai et al., 2019). For chilled seafood in general, predictive models emphasize process history and the joint effects of temperature, pH, and other stress variables (García et al., 2022). Therefore, live holding, ice chilling of killed animals, frozen storage, and heat processing must be separately validated for their respective physiological and food-quality objectives.

For postmortem products, rapid chilling slows enzymatic reactions and microbial growth, whereas freezing provides longer stabilization but may affect drip loss, texture, protein structure, and oxidation.

Product form matters: whole animals, clusters, picked meat, hepatopancreas, and soft-shell crab have different heat-transfer paths and contamination risks. Consequently, process validation must identify the slowest-cooling or slowest-heating location and must use the actual package, loading pattern, and commercial portion size.

Value-adding processes show measurable benefits and trade-offs. In crab lump meat, Olatunde and Benjakul (2021) reported more than 60 days of refrigerated shelf life under their validated sous-vide conditions, but lipid oxidation increased with more severe heating. Olatunde et al. (2021) reported strong microbial suppression after 10–15 min high-voltage cold-plasma treatment of Portunus meat while also observing quality changes. Roobab et al. (2022) reviewed high-pressure processing of fish and shellfish and identified potential benefits for microbial control and meat recovery. These technologies cannot be ranked by efficacy without matching treatment intensity, initial bioburden, contamination targets, product form, and uncertainty estimates.

For Indonesian mud crab and spiny lobster products, comparative trials should include conventional ice, slurry ice, superchilling, rapid freezing, sous-vide or other validated thermal processes, and selected nonthermal technologies. Outcomes should include sensory scores, cooking yield, drip loss, texture, protein oxidation, lipid oxidation, ATP-related compounds, microbial behavior, package performance, and consumer acceptance.

Food quality, safety, and traceability

Freshness and safety are distinct endpoints. A sensory-acceptable product can still carry relevant hazards, while some deteriorated products fail quality expectations before a pathogen threshold is reached. The Codex Alimentarius Commission (2019) anchors hazard analysis, hygiene, time–temperature management, and traceability in fishery processing. Sheng and Wang (2021) review the contribution of microbial contamination routes to fish-product safety. Neither color, K value, nor modified atmosphere alone is a pathogen-control validation; any claim of inactivation requires a defined target organism, sampling and recovery method, and validated treatment under intended commercial conditions.

Biological hazards include pathogenic and spoilage microorganisms introduced from the harvest environment, water, ice, equipment, workers, and post-cooking contact. Chemical hazards may include environmental contaminants, residues of processing aids or anesthetics, cleaning chemicals, allergens, and packaging migrants. Physical hazards include shell fragments, metal, and damaged packaging. Control begins with approved suppliers, hygienic facility and equipment design, potable water and ice, cleaning and sanitation, personal hygiene, separation of raw and cooked zones, and validated cooking and cooling where applicable.

A hazard analysis should identify critical or operational control points at receiving, live holding, slaughter, washing, cooking, cooling, meat picking, packaging, and storage. For extended-shelf-life refrigerated foods, reduced oxygen or vacuum conditions must never be treated as a substitute for temperature control and validated lethality. Shelf life should be established under realistic and reasonably foreseeable temperature conditions using sensory, chemical, and microbiological evidence.

Traceability connects product condition to origin, harvest time, transport history, mortality, receiving temperature, grading, process parameters, packaging batch, storage, and destination. Sucipto (2026) emphasizes recording origin and production history; the processing system should extend this record to include time-temperature data, inspection results, lot codes, corrective actions, and distribution. These records enable targeted recall and root-cause analysis instead of broad product disposal.

Packaging technology

Packaging performs four distinct functions: containment, protection, information, and process support. For live products, the package must manage humidity, ventilation, temperature, compression, and physical movement. For chilled or frozen meat, it must limit contamination, dehydration, oxidation, drip leakage, and mechanical damage. The package is therefore part of the preservation system rather than a final cosmetic layer.

Vacuum and modified-atmosphere packaging can reduce exposure or influence spoilage profiles but also create safety obligations for chilled, reduced-oxygen foods. Appropriate process lethality, rapid cooling, integrity testing, and strict storage-temperature control remain essential. Seafood smart-packaging reviews identify time–temperature labels and indicator systems as promising monitoring aids (Abedi-Firoozjah et al., 2023; Nami et al., 2024); a sensor warning cannot replace validated food-safety controls. For Indonesian

Scylla and Panulirus, barrier films, gas mixes, migration safety, and microbiological endpoints must be compared experimentally rather than adopted from unrelated seafood matrices.

Circular packaging offers a plausible, but incompletely proven, connection between shell waste and primary-product protection. Casariego et al. (2009) described reinforcement of chitosan films; Haghighi et al. (2020), Qu and Luo (2021), Flórez et al. (2022), and Oladzadabbasabadi et al. (2022) identify significant effects of plasticization, nanofillers, modification, and moisture sensitivity on material performance. Crab- and lobster-derived polymers may provide added value (Muthu et al., 2021; Lalarukh et al., 2024), but film functionality in vitro is not proof of microbial safety on a specific food. Food-contact migration, standardized molecular properties, regulatory suitability, consumer acceptance, and shelf-life testing remain necessary.

Future package trials should compare conventional polymer, vacuum, modified atmosphere, absorbent systems, and active chitosan-based materials under the same product and temperature conditions. Package evaluation must be integrated with food results: headspace gas, seal strength, water-vapor and oxygen transmission, drip control, oxidation, microbial growth, sensory quality, and end-of-shelf-life criteria.

Species-specific packaging outcomes are not captured by cross-commodity proof of concept. A shrimp study demonstrated a dual-functional freshness-indicating film (Wang et al., 2022), whereas Zhang et al. (2023) reported effects of electrolytic water and chitosan on fish quality during refrigeration. Both strengthen the mechanistic rationale for pairing antimicrobial action with monitoring, but neither supplies a crab- or lobster-specific shelf-life limit; the material, matrix, microbial target, and use conditions must be validated together.

Product development and circular utilization

Product development should begin with raw-material fitness. High-vitality animals suit live-premium markets; precisely staged soft-shell crabs suit chilled, frozen, or ready-to-cook products; fresh hygienic meat can be processed as chilled or frozen portions, sous-vide products, pastes, broths, or flavor-rich ingredients. Each concept requires a defined consumer, formulation, process flow, packaging system, safety target, sensory profile, and shelf-life protocol. A list of possible products is not evidence of successful development.

Shells, heads, and residual tissues are secondary raw materials rather than undifferentiated waste. Luthfiyana et al. (2022) demonstrated that demineralization conditions influence chitosan extraction from *Scylla* shells. Mohan et al. (2021) compared alpha-chitin structures from marine crustacean shell waste, while Chakravarty et al. (2018) demonstrated microbial-culture-based chitin extraction from lobster shells. Biological extraction may reduce dependence on harsh chemicals, but yield, ash, degree of deacetylation, molecular properties, water use, effluent load, time, and cost must be reported.

Crustacean shells and process residues may be sources of chitin, chitosan, proteins, pigments, flavor fractions, and other bioactives (Nguyen et al., 2017; Santos et al., 2020; Gautam et al., 2026). For Scylla serrata, mechanochemical conversion of shell-derived chitin has been investigated (Asrahwi et al., 2023), providing a technology comparator to acid/alkali extraction; neither route can be deemed environmentally superior without yield, reagent, and life-cycle comparisons. Protein-rich residues are perishable and must be stabilized and screened for allergen, oxidation, microbial, and chemical hazards before food or packaging use.

Circularity is strongest when the primary and secondary product systems are designed together. Clean segregation of shells at the processing line improves chitin quality; rapid chilling protects protein and pigment fractions; process water and chemicals can be quantified through mass balance; and a standardized chitosan stream can be evaluated as a film or coating for the primary seafood product. This creates a measurable link between waste reduction, packaging innovation, and product value.

Table 7. Processing, packaging, and product-development pathways

Product route	Raw-material requirement	Core process	Packaging concept	Required validation
Live premium product	High vitality; intact appendages	Stress-controlled holding and transport	Ventilated, humid, insulated live pack	Survival, reflexes, damage, mortality
Soft-shell product	Verified molt stage	Rapid harvest; chilling or freezing	Moisture-protective chilled/frozen pack	Shell hardness, flavor, texture, microbes

Product route	Raw-material requirement	Core process	Packaging concept	Required validation
Chilled/frozen meat	Fresh, hygienic raw material	Picking; chilling or rapid freezing	Barrier pack; vacuum where validated	QIM, K value, pH, TVB-N, oxidation, microbes
Sous-vide/ready-to-eat	Standardized meat portion	Validated vacuum heat process and rapid cooling	Heat-stable, high-integrity vacuum pouch	Lethality, seal, oxidation, sensory, shelf life
Active packaged product	Validated food and chitosan fraction	Film/coating formation and application	Active or biodegradable material	Migration, barrier, antimicrobial action, safety
Chitin and chitosan	Clean, segregated, stabilized shells	Demineralization, deproteinization, deacetylation	Moisture-resistant bulk pack	Yield, ash, molecular properties, contaminants
Protein/flavor/pigment ingredients	Cold-stabilized residual tissues	Recovery, hydrolysis, separation, concentration	Oxygen/light barrier as required	Composition, oxidation, allergens, sensory function

Source: Author synthesis based on Olatunde and Benjakul (2021), Olatunde et al. (2021), Gao et al. (2023), Nguyen et al. (2017), Luthfiyana et al. (2022), and Sun et al. (2026).

Research priorities for Indonesian aquatic-product technology

The principal gap emerging from this review is a missing experimentally verified link between live animal stress, subsequent edible-tissue quality, validated microbial hazard control, and commercial packaging performance in Indonesian Scylla and Panulirus. Published studies are largely modular: transport studies predict mortality, storage studies estimate freshness, and processing studies test separate products. This is a gap in integrated research designs rather than evidence that existing Indonesian operators systematically fail to comply with standards. The review has not observed or audited industry facilities and makes no such prevalence claim.

For *Scylla*, priorities include validation of precooling, humidity, tying, transport density, and temperature; species-specific QIM development; K-value, TVB-N, and microbial baselines; preservation of soft-shell quality; hygienic meat-picking systems; and comparative packaging trials. For *Panulirus homarus*, *P. ornatus*, and other Indonesian lobsters, priorities include reflex-based mortality models, water-quality limits, recovery protocols, residues from transport aids, humane slaughter, and the effect of live stress on later meat quality.

A testable next step would randomize lots of identified Scylla and Panulirus species across pre-slaughter handling duration and permitted holding-temperature bands, record baseline vigor and dissolved oxygen/ammonia (where applicable), and assign processing/packaging treatments under a factorial design. Prespecified primary outcomes should include day-to-end-of-life, species-calibrated QIM score, ATP-derived K value, log CFU/g, process lethality against a justified target, oxidation, and blinded sensory acceptability. Models should include source lot and molt stage as covariates and report effect sizes with 95% confidence intervals. A separate export-transport cohort should validate reflex-model discrimination and calibration before using predictions operationally.

Digital traceability can connect harvest data, receiving inspection, time-temperature history, process records, package codes, shelf-life decisions, and distribution. Such a system would allow quality deviations to be analyzed across the complete chain and would generate the evidence needed for product standards, certification, and export-market confidence.

This review does not show that feed-based or grow-out variables can be replaced by postharvest metrics. Harvest inputs may act as effect modifiers: animals with different molt stages or nutritional status may respond differently to identical handling and cooling exposures. The conditional model is therefore upstream biological condition × handling and transport × product processing × packaging and distribution, with measured safety endpoints. Direct experimental evidence in Scylla and Panulirus is weighted more heavily than evidence transferred from Portunus, Jasus, red king crab, shrimp, or finfish; no cross-species temperature cutoffs, K-value limits, or lethality targets are recommended without testing.

The original review supplied 30 bibliographic sources but no source-search exports, independent screeners, exclusion ledger, prospectively registered protocol, quality-scoring sheets, or quantitative dataset. Its 16 supplementary citations broaden contextual interpretation but were not part of a prospectively re-

screened corpus. Publication and selection bias cannot be quantified, and the reviewed interventions have non-comparable storage conditions and outcomes. Thus, no PRISMA compliance, inter-rater coefficient, pooled mean difference, or meta-analytic inference is claimed. The present analytical contribution is a falsifiable map of missing interconnections, not the validation of a new commercial processing system.

Prospective appraisal can be strengthened by a two-reviewer protocol, reproducible electronic search strings, versioned database exports, piloted extraction forms, formal risk-of-bias and transferability fields, and transparent inclusion/exclusion counts. Where numerical outcomes are available, standardized endpoints can be extracted with uncertainty and tested for between-study comparability before any meta-analysis. Retrospective invention of these quantities would undermine rather than improve the scientific record (Page et al., 2021).

Conclusions

This critical integrative review addressed how postharvest exposure, freshness measures, validated processing, food safety, and circular product development connect across Scylla and Panulirus supply chains. The core synthesis covered 30 originally reported sources and was contextually interpreted with 16 additional references; it did not generate new animal-level observations. Three quantitative results illustrate both the potential and boundaries of this evidence: initial decomposition in stored S. serrata was reported at six days at 10 °C versus three days at 25 °C (Chiou & Huang, 2004); the P. argus reflex-only mortality model achieved AUC 0.897 (Ross et al., 2024); and tested sous-vide processing of crab lump meat yielded refrigerated shelf life beyond 60 days (Olatunde & Benjakul, 2021). These outcomes are not exchangeable effect sizes and should not be transferred to untested Indonesian products. The unique synthesis is a decision-linked, conditional framework spanning baseline animal condition, handling, tissue-specific freshness measurement, hazard control, processing, packaging, and by-product recovery. It also makes clear that aquaculture and postharvest factors complement one another. The major constraint is missing integrated species-specific validation, compounded by incomplete original search-audit records. A multisite factorial study should jointly measure live stress, subsequent quality, calibrated freshness indices, log microbial counts, validated process lethality, package integrity, and consumer acceptance, while reporting uncertainties and source-lot effects. Until such trials are conducted, the framework is a research and control-point map rather than a validated safety or shelf-life standard.

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