

Review

Valorization of Seafood Processing Byproducts for Sustainable Fertilization: Opportunities and Food Safety Considerations in Agriculture 4.0

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Abstract

The transition toward sustainable and circular bioeconomies in Agriculture 4.0 demands fertilization strategies that reduce environmental impacts while maintaining agronomic productivity. This article presents a structured narrative review of peer-reviewed literature integrating evidence across waste management, soil science, food safety, and regulatory frameworks to evaluate the potential of seafood processing byproducts including fish offal, shellfish residues, and aquaculture effluents as nutrient-rich fertilizers. These materials provide nitrogen, phosphorus, calcium, and essential micronutrients and may contribute to nutrient recycling within precision and resource-efficient agricultural systems. Evidence from diverse cropping contexts indicates that seafood waste-derived fertilizers can improve crop yield, nutrient use efficiency, and soil biological activity under site-specific conditions. Biological processing methods, including composting, enzymatic hydrolysis, and fermentation, are examined for their roles in enhancing nutrient bioavailability and reducing undesirable constituents. Particular emphasis is placed on food safety considerations, including heavy metals, persistent organic pollutants, antimicrobial resistance, pathogens, and microplastics, with discussion of speciation-based risk assessment and mitigation strategies such as thermal treatment, microbial screening, and compliance with international standards. Regulatory fragmentation, economic feasibility, and lifecycle environmental implications are also critically assessed. Emerging digital tools, including Internet of Things (IoT)-enabled nutrient monitoring and artificial intelligence (AI)-assisted compost optimization, are discussed as enabling technologies for integrating seafood-derived biofertilizers into smart farming systems. Overall, this interdisciplinary synthesis highlights the potential contribution of seafood waste valorization to circular nutrient management, environmental stewardship, and sustainable food production.

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1. Introduction

The global agricultural system faces the dual challenge of meeting the food demands of a projected 9.7 billion people by 2050 while reducing its environmental footprint [1,2]. Conventional agricultural practices remain heavily dependent on synthetic, energy-intensive fertilizers, which have been identified as major contributors to aquatic eutrophication, soil degradation, and greenhouse gas emissions. In particular, nitrogen fertilizer

production via the Haber–Bosch process is estimated to account for approximately 1–2% of global energy consumption and associated CO₂ emissions [3]. This linear “take–make–dispose” model is increasingly regarded as environmentally and economically unsustainable, accelerating the transition toward circular bioeconomy frameworks that emphasize resource efficiency, waste reduction, and nutrient loop closure [4,5].

In parallel, agricultural systems are undergoing a digital transformation characterized as Agriculture 4.0, driven by the integration of Internet of Things (IoT) technologies, artificial intelligence (AI), big data analytics, and distributed ledger systems into farm management. Agriculture 4.0 and Industry 4.0 describe the integration of digital technologies such as IoT, artificial intelligence, automation, and data-driven decision support into agricultural and industrial systems to enhance efficiency, traceability, and sustainability, as summarized in recent reviews on digital and AI-enabled agriculture [6–10]. These technologies enable precision agriculture approaches in which spatially and temporally resolved data support optimized input management, thereby improving productivity while reducing environmental externalities. The convergence of circular bioeconomy principles with Agriculture 4.0 tools provides a compelling framework for the development of next-generation sustainable fertilization strategies. Within the Agriculture 4.0 paradigm, data-driven nutrient management and real-time monitoring frameworks enhance the feasibility of integrating seafood-derived fertilizers into precision systems.

For clarity, this review uses the term “seafood processing byproducts” to refer to organic materials generated during the processing of finfish, shellfish, and other aquatic organisms for human consumption, including heads, frames, viscera, skins, shells, and processing sludges. The term “seafood waste” is used more broadly when discussing disposal pathways, environmental burdens, or regulatory contexts, whereas “fish waste” is reserved for finfish-derived residues when species-specific distinctions are relevant. This terminology is adopted to distinguish between materials considered recoverable resources within circular bioeconomy frameworks and those traditionally regarded as waste.

Within this context, the global seafood processing industry represents a largely underutilized reservoir of nutrients. Processing of finfish and shellfish for human consumption generates substantial quantities of organic byproducts, including viscera, heads, frames, skins, scales, fins, and crustacean exoskeletons. Depending on species and product type, approximately 30–70% of the original biomass is discarded during processing [11,12]. Recent FAO estimates indicate that global fisheries and aquaculture generate tens of millions of tonnes of byproducts annually, with finfish processing contributing the largest share and crustacean shell waste representing a concentrated but compositionally distinct fraction [13,14]. Historically, these residues have been disposed of through land-filling, ocean dumping, or incineration, practices associated with nutrient loss, methane emissions, and localized eutrophication in coastal environments [15,16].

The conversion of seafood processing byproducts into organic fertilizers offers a synergistic solution to challenges in both waste management and sustainable agriculture. These materials represent complex matrices of bioactive components rather than inert waste. Fish offal is particularly rich in nitrogen-containing proteins, amino acids, phosphorus, and trace elements essential for plant nutrition [17,18]. Crustacean shells are characterized by high contents of chitin and chitosan (approximately 15–40%), along with calcium carbonate (20–50%), conferring both nutritional and soil-conditioning properties [19,20]. When appropriately processed, these constituents can function as slow-release nutrient sources, enhance soil aggregation, stimulate beneficial microbial communities, and induce plant defense responses against pathogens [21,22].

The application of Agriculture 4.0 principles can substantially improve the efficiency, safety, and scalability of these valorization pathways. Digital technologies enable

optimization across the entire value chain, from processing to field application. Real-time monitoring of temperature, pH, moisture, and oxygen during composting or fermentation can be achieved using IoT sensors, while AI-based control algorithms can dynamically adjust process conditions to enhance nutrient recovery and ensure hygienic stabilization [23,24]. At the farm level, sensor-based soil and crop monitoring supports variable-rate application of organic fertilizers, reducing nutrient losses and aligning inputs with crop demand [7,25]. Blockchain-enabled traceability systems can document material flows from waste origin through processing and land application, facilitating regulatory compliance and strengthening transparency across agri-food supply chains [26,27]. European initiatives under Horizon 2020 and Horizon Europe have demonstrated the technical feasibility of converting aquaculture sludge and fish processing residues into standardized biofertilizers within controlled, traceable systems [28,29].

Despite these opportunities, food safety remains the most critical barrier to widespread adoption. Marine ecosystems act as sinks for anthropogenic contaminants, and seafood byproducts may therefore carry hazardous substances into agricultural systems if inadequately treated. Of particular concern are heavy metals such as cadmium, lead, mercury, and arsenic, which can accumulate in fish tissues and shellfish and pose risks of soil contamination and trophic transfer [30]. Persistent organic pollutants, including dioxins and polychlorinated biphenyls (PCBs), are lipophilic compounds known to concentrate in fish lipids [31]. Residues of veterinary drugs and antimicrobials used in aquaculture raise additional concerns regarding the dissemination of antimicrobial resistance genes in soil microbiomes [32,33]. Raw seafood waste may also harbor pathogenic bacteria such as *Listeria monocytogenes*, *Vibrio* spp., and *Salmonella* spp, necessitating effective hygienization [34,35]. Furthermore, microplastics have emerged as contaminants of growing concern, with evidence indicating their persistence in soils and potential impacts on soil structure and microbial function [36,37].

Accordingly, the safe agricultural application of seafood-derived fertilizers (SDFs) requires robust, science-based risk assessment frameworks and multi-hurdle mitigation strategies encompassing source control, processing interventions, and post-application monitoring.

Against this backdrop, the present work critically examines the role of seafood processing byproducts as fertilizers within sustainable and digitally enabled agricultural systems. The analysis (i) characterizes the scale and composition of global seafood waste streams, (ii) compares biological and thermochemical valorization technologies and their integration with digital tools, (iii) evaluates food safety risks and mitigation strategies, (iv) assesses regulatory, economic, and life-cycle environmental dimensions, and (v) discusses pathways for integrating seafood-derived biofertilizers into smart, precision farming systems. Collectively, this synthesis aims to provide a structured roadmap for transforming seafood processing byproducts from an environmental burden into a strategic resource within circular, resilient, and technologically advanced agricultural systems. This review focuses on system-level integration, safety governance, and digital enablement rather than crop-specific agronomic performance (Figure 1).

Although extensive research has examined seafood byproduct utilization [38–41], organic waste-derived fertilizers, and circular bioeconomy frameworks independently, the literature remains conceptually and methodologically fragmented across technological, agronomic, and food safety domains [42]. In particular, there is a lack of integrative reviews that simultaneously evaluate processing pathways, associated food safety risks, and the role of digital and AI-enabled management within Agriculture 4.0 systems. This review addresses this gap by providing a critical synthesis of seafood byproduct valorization technologies for fertilization, explicitly linking sustainability outcomes with safety considerations and emerging data-driven tools.

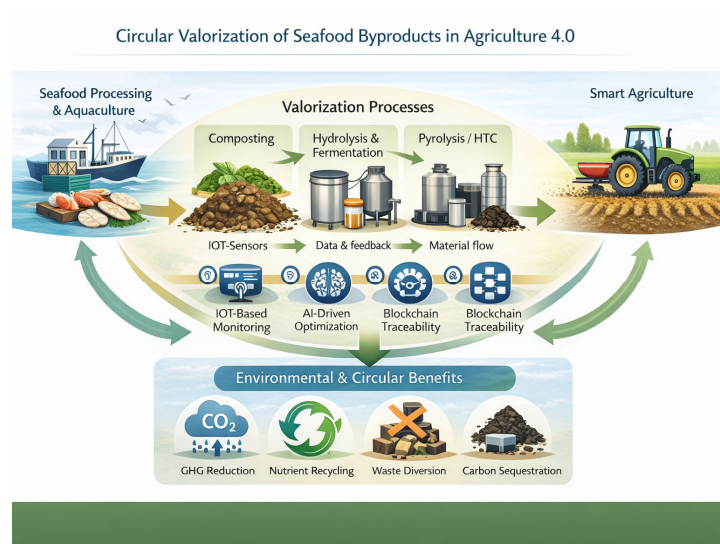


Figure 1. Conceptual framework for the circular valorization of seafood processing byproducts within Agriculture 4.0 systems. Seafood byproducts are converted into organic fertilizers through alternative valorization pathways (composting, hydrolysis/fermentation, and pyrolysis/HTC), supported by digital technologies including IoT-based monitoring, AI-driven process optimization, and blockchain-enabled traceability. Solid arrows represent material flows, while curved arrows indicate data exchange and feedback loops. Environmental benefits include nutrient recycling, waste diversion, greenhouse gas reduction, and carbon sequestration.

Literature was identified through searches in Web of Science, Scopus, and Google Scholar using keyword combinations related to “seafood byproducts”, “SDFs”, “heavy metals”, “PFAS”, “microplastics”, and “circular bioeconomy”, prioritizing contemporary peer-reviewed research while also incorporating seminal earlier studies where directly relevant.

2. Global Seafood Waste: Volumes, Composition, and Current Disposal Practices

The sustainable management of seafood processing residues requires a clear understanding of their global magnitude, material composition, and prevailing disposal pathways. Seafood waste streams represent one of the largest underutilized biomass resources within the global food system, and their current management practices pose both environmental risks and missed opportunities for nutrient recovery. This section synthesizes recent data on the scale of seafood waste generation, its biochemical characteristics, and the environmental consequences of dominant disposal practices.

2.1. Quantification of Global Seafood Waste Streams

Global fisheries and aquaculture production have continued to increase over the past decade, driven primarily by the rapid expansion of aquaculture. According to the Food and Agriculture Organization, total global production reached approximately 214 million tonnes in 2020, of which 178 million tonnes were used for human consumption [43]. Aquaculture now accounts for more than half of all aquatic food produced worldwide, fundamentally reshaping the volume and characteristics of seafood processing waste.

Across capture fisheries and aquaculture, a substantial fraction of harvested biomass is converted into byproducts during processing. Depending on species, processing method, and final product, 30–70% of the original wet weight may be discarded as waste [41,44]. Filleting operations for finfish commonly yield only 30–40% edible product, with the remainder consisting of heads, viscera, frames, skin, and trimmings. In crustacean

processing, shells and cephalothoraxes typically represent 40–50% of total body weight, while mollusk processing generates even higher proportions of inert shell material, often exceeding 75% of total mass [20,45,46].

Recent global estimates suggest that seafood processing generates more than 20 million tonnes of solid byproducts annually, excluding liquid effluents and aquaculture sludge [23,41,47]. Finfish processing alone is estimated to produce 4.7–5.5 million tonnes of byproducts each year, while crustacean waste contributes approximately 0.5–1.0 million tonnes, depending on species composition and reporting methodology [23,41]. In parallel, aquaculture operations generate increasing quantities of nutrient-rich sludge composed of uneaten feed, feces, and microbial biomass, which represents a distinct but closely related waste stream with high fertilization potential [25,48].

Geographically, seafood waste generation is concentrated in major processing regions, including East and Southeast Asia, Northern Europe, and North and South America, reflecting the spatial distribution of both aquaculture production and industrial processing infrastructure [49,50]. This regional clustering creates both logistical challenges and opportunities for localized valorization strategies integrated with regional agricultural systems. Table 1 distinguishes nutrient contributions, functional components, and potential contaminants to clarify differences among major seafood byproduct streams.

Table 1. Major seafood processing waste streams, quantities, and key components.

Waste Stream	Typical Share of Biomass (%)	Main Components	Key Nutrients	Functional/Bioactive Components	Potential Contaminants or Concerns	Primary Valorization Potential
Finfish heads & frames	30–40	Bone, muscle residues	Ca, P	Collagen, protein-N	Heavy metals (species-dependent)	Compost, hydrolysate, biochar
Finfish viscera	10–20	Organs, lipids	N, P	Protein-N, lipids, micronutrients	Pathogens, residues of veterinary drugs	Fermentation, hydrolysis (controlled)
Skin & scales	2–7	Collagen, minerals	N, Ca	Gelatin, collagen peptides	Low (processing-dependent)	Compost, gelatin/hydrolysate
Crustacean shells	40–50	Chitin, CaCO ₃	Ca	Chitin/chitosan	Trace metals (e.g., Cd), salinity	Soil amendment, biostimulant
Mollusk shells	75–85	CaCO ₃	Ca	—	Low (inert mineral matrix)	Liming material, mineral amendment
Aquaculture sludge	Variable	Feces, uneaten feed	N, P	Organic matter	Antibiotic residues, pathogens	Compost, AD digestate

Beyond absolute quantities, several structural trends emerge from global seafood byproduct data. First, the continued expansion of aquaculture relative to capture fisheries is shifting the composition of byproducts toward more homogeneous but geographically dispersed waste streams, particularly in coastal and inland farming regions [49,50]. Second, processing intensity is increasing, with larger proportions of biomass removed at centralized facilities, amplifying the need for efficient collection and stabilization strategies [38,41,44].

At the same time, available estimates are subject to substantial uncertainty. FAO statistics rely on national reporting frameworks that vary widely in resolution, frequently aggregate byproducts with other waste categories [51], and often underrepresent informal, small-scale, or seasonal processing activities. In addition, byproduct generation rates are typically inferred from processing yields rather than directly measured, introducing variability related to species, product form, and regional practices [44]. These limitations highlight the need for region-specific assessments and flexible valorization systems

capable of accommodating heterogeneous and uncertain waste streams, rather than relying solely on global averages [23,41,52].

2.2. Biochemical Composition and Resource Potential

Seafood processing residues are frequently described as “waste,” yet their chemical composition reveals a nutrient-dense and functionally valuable matrix. These materials contain macronutrients, micronutrients, and bioactive compounds that are directly relevant to soil fertility and plant health.

Protein-rich fractions derived from fish muscle, viscera, and frames typically contain 10–30% protein on a wet weight basis, providing a substantial source of organically bound nitrogen [12,51,53]. During biological processing or soil mineralization, these proteins are converted into ammonium and nitrate, enabling gradual nutrient release that contrasts with the rapid solubility of synthetic nitrogen fertilizers [11,41]. This slow-release behavior is particularly relevant for reducing nitrogen losses through leaching and volatilization.

Mineral components constitute another critical fraction. Fish bones and scales are rich in calcium and phosphorus, largely present as hydroxyapatite, while crustacean shells contain high levels of calcium carbonate along with phosphorus and trace minerals such as magnesium, zinc, and selenium [19,54]. Although these minerals are not immediately soluble, biological processing and soil acidification can enhance their plant availability over time, supporting long-term soil nutrient balance.

Lipid-rich fractions, particularly from fatty fish species, may contain 10–30% lipids, including omega-3 polyunsaturated fatty acids such as EPA and DHA [53,55,56]. While lipids can complicate composting processes if unmanaged, they contribute to organic matter content and microbial energy supply in soil systems.

A distinctive feature of crustacean waste is its high chitin content, typically 15–40% of dry shell weight. Chitin and its deacetylated derivative chitosan exhibit properties that extend beyond nutrient provision. These polymers can improve soil aggregation, stimulate beneficial microbial communities, and act as elicitors of plant defense responses, reducing disease pressure and enhancing crop resilience [21,22,57]. The presence of such functional compounds distinguishes SDFs from conventional organic amendments.

2.3. Current Disposal Practices and Environmental Implications

Despite their demonstrated resource value, seafood processing byproducts are still predominantly managed through linear disposal pathways. These practices generate environmental externalities while failing to recover embedded nutrients and organic matter.

Landfilling remains common in many regions, particularly where processing facilities are distant from agricultural land. Due to their high moisture and organic content, seafood wastes decompose rapidly under anaerobic landfill conditions, generating leachate and methane. Methane emissions from organic waste disposal impose a considerable climate burden because of methane’s elevated global warming potential [16,58].

In some coastal areas, sea disposal or nearshore dumping persists despite increasing regulatory restrictions. The introduction of concentrated organic matter into marine environments can lead to localized hypoxia, alteration of benthic communities, and nutrient enrichment of already stressed coastal ecosystems [47,58,59].

Incineration offers volume reduction and potential energy recovery, but results in the irreversible loss of nitrogen and organic carbon, while phosphorus recovery remains limited to ash residues that are often landfilled [41,60,61]. Furthermore, incineration can generate air pollutants if combustion conditions are not tightly controlled.

A proportion of high-quality byproducts is diverted to fishmeal and fish oil production, primarily for animal feed. While this represents a form of recycling, it remains

constrained by market volatility, quality requirements, and centralized processing infrastructure, and does not directly contribute to closing nutrient loops in terrestrial agriculture [11,41].

Collectively, these disposal pathways highlight the inefficiency of current management systems. Nutrient-rich materials are treated as liabilities rather than resources, imposing disposal costs on processors and environmental costs on society. Transitioning toward circular models that return these nutrients to agricultural soils through safe, controlled valorization pathways represents a critical opportunity to improve sustainability across both food and agricultural systems.

It is important to situate fertilizer valorization of seafood byproducts in relation to their established use in fishmeal and fish oil production for animal feed. From a resource-efficiency perspective, conversion of high-quality, fresh byproducts into feed generally represents a preferred valorization route, as it retains nutrients within the food production system. However, this pathway is constrained by stringent quality requirements, centralized processing infrastructure, and economic scale. A substantial fraction of seafood byproducts—particularly those generated by small and medium processors, seasonally dispersed operations, or geographically remote facilities—do not meet feed-grade specifications due to spoilage risk, heterogeneity, or logistical limitations.

For these streams, fertilizer production does not displace feed use but instead represents a secondary, context-dependent valorization option that prevents landfilling or marine disposal while returning nutrients to agricultural soils. In this sense, SDFs should be understood as a complementary pathway within a circular bioeconomy, targeting residual streams that are structurally excluded from feed markets rather than competing with them.

3. Valorization Technologies: From Waste to Resource

Transforming seafood byproducts into fertilizers is not a single technology choice but a design problem that balances nutrient recovery, hygienic safety, emissions control, product stability, and logistics. Raw fish offal, shell residues, and aquaculture sludges are highly biodegradable and can contain pathogens, high salinity, and variable lipid fractions; these properties make direct land application risky and often impractical. Processing therefore serves three simultaneous purposes: (i) stabilizing the material (odor control, shelf-life, transportability), (ii) converting nutrients into agronomically useful forms (slow-release solids or readily available liquids), and (iii) reducing food safety hazards through sanitization and contaminant management. Recent reviews emphasize that technology selection depends strongly on the waste stream (solid byproducts vs. sludge/effluents), the targeted fertilizer function (nutrient source vs. biostimulant), and local infrastructure for heat, electricity, and distribution [16,38,39,61].

3.1. Biological Processing Methods

Biological routes rely on microbial or enzymatic conversions at mild temperatures and typically preserve organic matter that benefits soil structure and microbial ecology. Their limitations are usually process time, variability of feedstock, and the need for robust hygiene control.

3.1.1. Composting

Aerobic composting is widely applicable to mixed seafood wastes because it can handle heterogeneous solids and yield a stable soil-conditioning product. Seafood wastes often have low initial C/N ratios and high moisture, which can drive ammonia volatilization, odors, and nitrogen loss unless carbon-rich bulking agents are added (e.g., wood chips, straw, sawdust) and porosity is maintained for oxygen transfer [62,63]. Mature

composting typically requires a thermophilic phase (often $>55^{\circ}\text{C}$) to support pathogen reduction, followed by a curing phase for stabilization and phytotoxicity reduction.

From a process engineering perspective, the low initial C/N ratio of seafood wastes accelerates microbial protein degradation, leading to rapid ammonification and elevated free ammonia concentrations, particularly under warm and alkaline conditions. Without sufficient carbon availability, excess nitrogen is readily volatilized as NH_3 , resulting in odor generation, reduced fertilizer value, and potential environmental emissions. Effective composting of high-nitrogen seafood materials therefore requires deliberate formulation strategies, including the incorporation of carbon-rich bulking agents such as straw, sawdust, wood chips, or other lignocellulosic residues to raise the C/N ratio, improve porosity, and enhance oxygen diffusion. Moisture control and aeration management are equally critical, as excessive water content can limit oxygen transfer and exacerbate anaerobic zones, while insufficient aeration can intensify ammonia losses. Together, these operational controls are essential for retaining nitrogen in organic forms and producing a mature, agronomically effective compost from seafood-derived feedstocks [64,65].

Future research should also explore the application of targeted microbial inoculants to mitigate nitrogen losses during composting of protein-rich seafood byproducts; for example, the multi-stress-tolerant marine yeast *Pichia kudriavzevii* HJ2 has been shown to actively transform ammonia through defined metabolic pathways, suggesting potential to reduce volatilization losses and enhance nitrogen retention in composted materials [66].

Recent work in “smart composting” focuses less on the composting concept itself and more on controlling emissions, maturity, and consistency. Sensor networks can track temperature profiles, moisture, oxygen, and, in some systems, ammonia and CO_2 , enabling operators to correct compaction, aeration, and moisture deficits before process failure occurs [67,68]. AI approaches are increasingly used to predict maturity indices and to reduce early-stage emission peaks by optimizing aeration schedules and turning frequency [69]. These developments are particularly relevant for seafood-rich mixtures because odor episodes and nitrogen losses often occur early when protein degradation is most active.

3.1.2. Vermicomposting

Vermicomposting can produce a high-value amendment rich in humified organic matter and biologically active fractions. The challenge is that fresh seafood residues may be stressful to earthworms due to ammonia, salinity, and rapid putrefaction, so a short pre-composting or blending step is usually required before worms can be introduced. When managed properly, vermicompost often shows strong plant growth responses attributable to humic substances, microbial metabolites, and hormone-like compounds [70]. Although the technical literature on seafood-specific vermicomposting is smaller than for plant residues, the approach is attractive for decentralized systems producing premium soil amendments rather than bulk fertilizers. Digital monitoring is less mature here than for composting, but basic sensor control (temperature and moisture) can stabilize worm beds and reduce batch-to-batch variability—useful when feedstocks fluctuate seasonally [71].

3.1.3. Enzymatic Hydrolysis and Controlled Fermentation (Liquid Fertilizers and Biostimulants)

For applications requiring faster nutrient availability and consistent dosing (e.g., fertigation, foliar feeding, greenhouse production), enzymatic hydrolysis and fermentation are often favored because they solubilize proteins and micronutrients into liquids and reduce particle handling constraints.

Enzymatic hydrolysis uses proteases (and, for shell-derived materials, chitinases) to generate mixtures rich in peptides, amino acids, and soluble nitrogen. These products

often function as both fertilizers and biostimulants, particularly when peptide profiles and amino acid fractions are preserved [72,73]. Practical adoption is influenced by enzyme cost and the need for controlled temperature and pH, but industrial interest is growing because hydrolysates can be standardized more readily than composts.

Fermentation, including lactic acid fermentation, supports stabilization through pH reduction, inhibits many pathogens, and can increase phosphorus solubility by acidification. Fish waste fermentation is also attractive for small-to-mid-scale processors because it can be implemented with relatively simple tanks and does not require high heat input. Broader reviews on fermented waste valorization describe fermentation as a flexible “biorefining” platform for nutrient recovery and functional metabolites, though product consistency still hinges on feedstock variability and process control [40]. In seafood systems, fermentation is also used to create fish silage (acid- or LAB-based), primarily for feed applications; however, the same stabilization logic is relevant when the target shifts from feed to soil amendments, provided salinity and safety constraints are addressed [74].

Agriculture 4.0 alignment is strong for hydrolysis and fermentation because both are amenable to closed bioreactors with automated monitoring. Digital process control and modeling are increasingly discussed in the context of circular “fish waste biorefineries,” where fertilizer products are one of several output streams [39,75,76].

3.1.4. Anaerobic Digestion and Digestate Upgrading

Anaerobic digestion (AD) is often positioned as an energy recovery pathway, but its relevance to fertilization lies in the digestate, which can retain substantial fractions of nitrogen, phosphorus, and micronutrients. Seafood wastes can be challenging substrates due to high protein (ammonia inhibition risk), lipids (long-chain fatty acid inhibition), and salinity in some streams; co-digestion with carbon-rich or dilute substrates is commonly used to improve stability [77]. Recent digestate management reviews emphasize that digestate quality, nutrient form (ammonium vs. organic N), and contaminant profile determine whether land application contributes to circularity or merely shifts burdens [78–80]. For aquaculture sludge and mixed fish wastes, AD can be paired with downstream nutrient recovery (e.g., ammonium stripping, struvite precipitation) to generate more standardized fertilizing products and reduce transport volumes.

3.2. Thermochemical and Physicochemical Processing Methods

Thermochemical routes can provide rapid sanitation, major volume reduction, and stable products suitable for long-distance transport. Their main tradeoffs are energy demand, capital cost, and the possibility of volatilizing nitrogen during high-temperature treatment.

3.2.1. Thermal Drying, Rendering, and Hygienization

Thermal drying converts wet sludges and residues into stable meals or powders and can achieve strong pathogen reduction, making it a practical front-end option where heat is available (e.g., near processing plants). Dry meals provide concentrated nutrients but may still require blending to manage salinity and to balance nutrient ratios. Thermal options are especially relevant for aquaculture sludge and wet fish residues that are costly to transport in their raw form [44].

3.2.2. Pyrolysis to Biochar (Including Shellfish- and Bone-Derived Biochars)

Pyrolysis converts biomass into biochar, syngas, and bio-oil under oxygen-limited conditions. For seafood residues, shell- and bone-derived biochars are of particular interest because calcium- and phosphate-rich mineral phases can be retained in the char matrix. Shellfish-derived biochar has been widely reviewed as an “engineered” sorbent and

soil amendment with relatively high adsorption capacity compared with lignocellulosic biochars, reflecting its mineral composition and alkalinity [81]. In soils, these properties can support pH buffering and may reduce metal bioavailability via precipitation and surface complexation mechanisms, though outcomes depend on soil chemistry and char production conditions.

Despite these advantages, the application of seafood-derived biochars also presents important challenges that require careful consideration. Pyrolysis can generate polycyclic aromatic hydrocarbons (PAHs) and other thermally derived organic contaminants, particularly at intermediate temperatures or under poorly controlled conditions. In addition, biochar properties—including surface area, pH, ash content, and nutrient release behavior—can vary substantially depending on feedstock composition (e.g., shellfish shells versus mixed seafood residues) and pyrolysis parameters such as temperature, heating rate, and residence time. This variability complicates generalization of agronomic outcomes and underscores the need for standardized production protocols and application guidelines. Without such controls, biochar amendment may introduce unintended risks or inconsistent performance across soils and cropping systems [82,83].

Recent work also emphasizes that “biochar performance” is increasingly being treated as a predictable function of feedstock and pyrolysis conditions rather than a black box. Machine learning approaches have been used to predict heavy-metal immobilization performance across diverse biochars, supporting more rational selection of char types for contaminated or marginal soils [84]. In seafood systems, that modeling logic can be applied to shellfish biochars tailored for simultaneous nutrient delivery and contaminant immobilization.

3.2.3. Hydrothermal Carbonization (HTC) and Hydrochar for Wet Seafood Streams

Hydrothermal carbonization is gaining attention because it processes wet biomass without the need for energy-intensive drying. HTC typically operates under elevated temperature and pressure, producing a solid hydrochar and a nutrient-containing liquid phase. For aquaculture sludge and fish slurries, recent work highlights the possibility of producing P-enriched hydrochars while also transforming heavy metals into less bioavailable forms, especially when process chemistry is adjusted [27]. HTC therefore offers a promising route for wet streams that are otherwise difficult to stabilize, but the management of the process water (which can contain dissolved organics and nutrients) is critical for overall sustainability.

3.3. Chitin/Chitosan Pathways and “Functional” Fertilizer Products

Crustacean shells enable a distinct valorization pathway because chitin and chitosan provide agronomic functions beyond nutrient supply. Conventional extraction relies on chemical deproteinization and demineralization, which raises concerns about chemical use and wastewater burdens. The field has moved toward greener extraction strategies, including biological deproteinization/demineralization, deep eutectic solvents, and enzymatic methods, with growing emphasis on reducing reagent intensity and improving circularity [85]. Recent reviews in food and bioprocessing literature also stress that extraction choices influence polymer characteristics (degree of deacetylation, molecular weight), which in turn affect plant elicitor activity and formulation performance [86].

In agriculture, chitosan and derivatives are often positioned as biostimulants and plant defense elicitors. Their use aligns with pesticide reduction and integrated pest management, though agronomic responses vary with crop, dose, and formulation. These products also pair well with controlled-release concepts, where chitosan acts as a carrier matrix for nutrients or microbial inoculants [87,88].

3.4. Technology Selection and Integration with Agriculture 4.0

A central challenge shared by all seafood byproduct valorization pathways is the collection and stabilization of highly perishable materials. Seafood processing residues are generated across geographically dispersed facilities, often at volumes insufficient to justify transport to centralized fishmeal plants. Rapid spoilage, odor generation, and microbial growth further constrain transport distance and time-to-processing. These logistical barriers explain why substantial quantities of byproducts are diverted to disposal routes despite their intrinsic resource value.

Decentralized or regional processing models supported by on-site or near-site stabilization through fermentation, drying, or composting represent a practical strategy for overcoming these constraints. Within this framework, digital monitoring and traceability tools associated with Agriculture 4.0 can reduce spoilage risk, document handling conditions, and support aggregation of smaller streams into viable fertilizer products.

Across valorization options, several cross-cutting criteria tend to determine suitability for large-scale adoption:

- Feedstock fit: Mixed solids favor composting; wet sludges favor AD or HTC; shell-rich streams favor chitin recovery or mineral-rich biochar pathways [23,81].
- Safety and compliance: Thermophilic composting, drying/hygienization, and high-temperature thermochemical routes provide strong pathogen reduction; contaminant management (metals, persistent pollutants) may require source control plus selective processing, and in some contexts, immobilization strategies (biochar) become relevant [34,44,82,84].
- Product logistics: Liquids (hydrolysates/ferments) support precision dosing but raise transport and storage constraints; solids (compost/biochar/meals) are easier to store and blend but may have slower nutrient release [82,84].
- Digital enablement: Sensor-based monitoring and AI process control are now practical for composting and bioreactor-based systems, and they matter most where variability and emissions are high [67,89].

Recent life-cycle oriented syntheses argue that “best” technology depends on local energy systems, transport distance, and the ability to displace synthetic fertilizers or peat-based amendments [52]. That framing is particularly relevant for *Sustainability*: seafood waste valorization is most credible when nutrient recovery is coupled with emissions minimization and verifiable safety (Table 2).

Table 2. Comparative overview of seafood processing byproduct valorization technologies for fertilizer production, highlighting feedstock suitability, agronomic function, and relative food safety and operational considerations.

Technology	Feedstock Type	Main Output	Agronomic Function	Key Advantages	Key Limitations	Digital Enablement Potential
Composting	Mixed solids	Compost	Soil conditioner, slow-release nutrients	Low energy, soil health benefits	Time, odor, N losses	High
Vermicomposting	Pre-treated solids	Vermicompost	Biostimulant, microbial activity	High agronomic value	Sensitive to salinity/ammonia	Medium
Enzymatic hydrolysis	Fish waste	Liquid hydrolysate	Rapid nutrient uptake	Controlled dosing	Enzyme cost	High
Fermentation	Fish waste/sludge	Fermented fertilizer	Stabilization, P solubilization	Low-tech option	Variability	Medium

Anaerobic digestion	Sludge, mixed waste	Digestate	Nutrient recycling + energy	Biogas co-benefit	Ammonia inhibition at elevated $\text{NH}_3\text{-N}$ concentrations (typically $>2\text{--}3\text{ g L}^{-1}$), impairing methanogenic activity [90,91] High energy demand (typically $1\text{--}3\text{ MJ kg}^{-1}$ dry feedstock, depending on temperature and system design [92]	High
Pyrolysis	Shells, bones	Biochar	Soil amendment, C sequestration	Metal immobilization		Medium
Chitin extraction	Shells	Chitin/chitosan	Plant defense elicitor	Functional effects	Chemical use	Emerging

No single processing method can be identified as universally optimal for converting seafood byproducts into fertilizers. Instead, technology suitability is context-dependent and determined by feedstock characteristics, safety requirements, logistics, and intended agricultural use. Biological processes such as composting and fermentation are generally preferable for mixed or small-scale waste streams where low energy input and soil-conditioning benefits are prioritized. Thermochemical treatments, including drying, pyrolysis, and hydrothermal carbonization, are better suited to wet or high-risk materials requiring robust hygienization and volume reduction. Shell-rich streams favor mineral-focused pathways such as biochar or chitin-based products, particularly where soil pH amendment or biostimulant effects are desired.

Consequently, integrated systems combining multiple valorization routes within a regional framework are likely to deliver the greatest environmental and operational benefits.

4. Food Safety Considerations and Risk Mitigation

Using SDF inputs on agricultural land, especially for food crops, demands a cautious, evidence-based approach that treats safety as a design requirement rather than an afterthought. Seafood processing byproducts can be highly effective soil amendments, but their marine origin matters: coastal waters receive industrial and municipal discharges, legacy contaminants persist in sediments, and aquaculture can introduce veterinary drug residues. As a result, SDFs can carry chemical, biological, and physical hazards unless sourcing, processing, and verification steps are built into the value chain. A credible pathway to market therefore depends on (i) hazard identification, (ii) exposure pathways and crop-specific risk framing, and (iii) multi-hurdle mitigation with documented verification [93,94] (Figure 2).

Valorization Technologies						
	Composting	Enzymatic Hydrolysis	Anaerobic Digestion	Fish Hydrolysate	Biochar Production	Chitin Extraction
Pathogens						
Heavy Metals						
PFAS & POPs						
AMR						
Salinity						
Microplastics						

 High Risk
  Moderate Risk
  Low Risk
  Effective Mitigation
  Partial Mitigation

Figure 2. Qualitative risk matrix of seafood byproduct valorization technologies. The matrix summarizes major food safety and environmental hazards associated with key seafood byproduct valorization pathways. Color coding indicates relative risk levels under typical operating conditions: red denotes high risk, yellow denotes moderate risk, and green denotes low risk. Solid shield symbols indicate technologies generally effective at mitigating the corresponding hazard, whereas dashed shields represent partial or conditional mitigation. Risk classifications are based on qualitative synthesis of published literature, considering feedstock characteristics, typical processing parameters, and reported outcomes, and are intended for comparative guidance rather than quantitative risk assessment.

This review adopts a hazard-based and pathway-oriented approach to food safety rather than a quantitative exposure assessment. While quantitative risk assessment is essential for site- and crop-specific decision-making, it requires detailed data on soil properties, crop uptake coefficients, application rates, and consumption patterns that are beyond the scope of a system-level review. Accordingly, the present analysis focuses on identifying major hazard categories associated with SDFs, elucidating their potential exposure pathways, and comparing relative risk profiles across processing technologies and agricultural applications. This framing is intended to support informed technology selection and risk management rather than to substitute for local regulatory or farm-level risk assessments.

4.1. Primary Contaminants of Concern

4.1.1. Heavy Metals and Metalloids

Seafood materials can contain cadmium (Cd), lead (Pb), mercury (Hg; including methylmercury), and arsenic (As). These enter aquatic food webs through natural geology and, more importantly in many regions, mining, industrial discharge, and contaminated sediments. Bioaccumulation leads to higher concentrations in organs (e.g., liver/viscera) and in filter-feeding shellfish, making waste fractions such as viscera and hepatopancreas comparatively higher risk than muscle-based trimmings [30].

Once introduced into soil, metals do not degrade. Risk is controlled by bioavailability, which is governed by soil pH, redox conditions, organic matter, and competing ions. Acidic soils typically increase the solubility and plant uptake of Cd and Pb, and leafy vegetables and root crops tend to accumulate certain metals more efficiently than grains [95]. Arsenic adds an additional layer of complexity because seafood often contains predominantly organic arsenic species that are less toxic than inorganic forms; however, inorganic

As can still be present and is the relevant fraction for regulatory limits and health risk assessment [96]. Beyond total concentrations, the environmental and human health risk of metals and metalloids derived from seafood-based fertilizers is strongly governed by chemical speciation, which determines mobility, bioavailability, and toxicity. For arsenic, inorganic species such as arsenite [As(III)] and arsenate [As(V)] are substantially more toxic and readily taken up by plants than organic forms (e.g., arsenobetaine) commonly found in marine organisms. While organic arsenic dominates in most seafood tissues, processing and soil conditions can influence speciation dynamics after land application, including redox-driven transformations and competitive interactions with phosphate. Similar considerations apply to other metals, where oxidation state and complexation with organic matter or mineral phases affect plant uptake and trophic transfer. These factors underscore the importance of speciation-aware risk assessment when evaluating SDFs, rather than reliance on total metal concentrations alone [97,98].

4.1.2. Persistent Organic Pollutants and per- and Polyfluoroalkyl Substances (PFAS)

Persistent organic pollutants (POPs) such as polychlorinated biphenyls (PCBs), dioxins, and certain flame retardants are lipophilic and can concentrate in fatty fish tissues and oils used in processing streams. Their environmental persistence and potential for trophic transfer are well-established, and they may enter soils through amendments derived from lipid-rich waste fractions unless controlled [99,100]. Increasing attention has also focused on PFAS as a “newer persistent” class detected in some aquatic organisms, with implications for circular nutrient recovery strategies that move marine-derived materials onto land [101,102]. For fertilizers, the practical concern is not only direct crop uptake (which can vary strongly by compound and soil chemistry), but also long-term accumulation in soils and potential transfer into livestock systems via forage.

4.1.3. Antimicrobial Residues and Antimicrobial Resistance

Veterinary antimicrobials are used in parts of the aquaculture sector, and residues can persist in wastes and wastewaters if not managed. Beyond residue exposure, the larger sustainability concern is the propagation of antimicrobial resistance (AMR). Environmental compartments, particularly soils, can act as reservoirs where resistance genes persist and spread via horizontal gene transfer [103]. Reviews focused on aquaculture highlight the link between antibiotic use, environmental dissemination, and AMR emergence [104]. More recent syntheses emphasize that aquaculture environments may serve as reservoirs and transmission vectors for clinically relevant resistance determinants [105]. From a fertilizer perspective, risk management should therefore consider both (i) chemical residues and (ii) gene-level hazards (ARGs and mobile genetic elements), especially when untreated sludges or poorly stabilized materials are used.

4.1.4. Biological Hazards: Pathogens and Parasites

Raw fish waste can contain pathogens relevant to public health and farm hygiene. While contamination profiles differ by region and handling practices, organisms of concern typically include *Salmonella* spp., *Listeria monocytogenes*, *Vibrio* spp., and spore-formers that survive under unfavorable conditions. The highest exposure concern is associated with produce consumed raw and grown close to the soil (leafy greens, strawberries, some root vegetables), where contamination events can occur through direct contact or splash. Hygiene is therefore not optional: stabilization processes must be validated for pathogen reduction, and safe application timing relative to harvest matters [35,41].

4.1.5. Microplastics and Other Physical Contaminants

Microplastics are pervasive in marine systems and can enter seafood processing streams through contaminated raw materials, degradation of fishing gear, or handling environments. In soils, microplastics can alter bulk density, aggregation, and water-stable aggregates, with downstream effects on microbial activity and plant performance [36]. Larger reviews synthesize evidence that microplastics can influence soil structure and biological function, while identifying major uncertainty in long-term field behavior [106]. Laboratory evidence also supports the possibility that submicrometer plastic particles can enter plant tissues via crack-entry routes at lateral root emergence, raising questions for food-chain exposure that are not yet fully resolved [107]. In the absence of definitive exposure thresholds, risk management for microplastics currently relies heavily on upstream control and exclusion rather than downstream remediation.

Analytical detection and quantification of microplastics in complex matrices such as soils, composts, and organic fertilizers remain technically challenging. Commonly applied approaches include density separation followed by spectroscopic identification using Fourier-transform infrared (FTIR) or Raman microscopy, as well as thermal degradation techniques such as pyrolysis–gas chromatography–mass spectrometry (pyrolysis-GC/MS). However, organic-rich matrices typical of SDFs complicate particle isolation, increase background interference, and limit detection of smaller size fractions. Methodological variability in sample preparation, size cutoffs, polymer identification criteria, and reporting units further hampers comparison across studies. These limitations underscore the need for standardized analytical protocols and harmonized reporting frameworks to support robust risk assessment and regulatory decision-making for microplastics in agricultural amendments [108,109].

4.1.6. Salinity and Sodium Load

Seafood wastes can contain elevated salts due to intrinsic tissue chemistry and processing practices. When repeatedly applied, sodium can accumulate and disperse clays, thereby reducing infiltration, aeration, and aggregate stability, particularly in fine-textured soils. Even when food safety hazards are controlled, salinity can undermine agronomic performance and soil health if not managed through blending, application limits, and monitoring [110,111].

4.2. Risk Mitigation: A Multi-Barrier Strategy

A practical safety framework combines preventive controls (clean sourcing and segregation), validated processing hurdles, and post-process verification. In circular systems, the most reliable outcomes come from “designing out” hazards rather than relying on a single end-point test (Table 3).

Table 3. Major contaminant categories associated with SDFS and corresponding mitigation strategies.

Contaminant Category	Typical Source	Primary Risk Pathway	Mitigation and Control Strategies
Heavy metals (Cd, Pb, Hg, inorganic As)	Viscera, hepatopancreas, filter-feeding shellfish	Soil accumulation; plant uptake; long-term trophic transfer	Source screening and segregation of high-risk fractions; routine batch testing; soil pH management; bioavailability reduction strategies (e.g., mineral stabilization, biochar amendment)
Persistent organic pollutants (POPs)	Lipid-rich tissues and fish oils	Persistence in soil; bioaccumulation and food-chain transfer	Preferential use of low-lipid fractions; validated thermochemical processing where appropriate; routine analytical monitoring

Per- and polyfluoroalkyl substances (PFAS)	Contaminated aquatic environments; certain processing inputs	Long-term soil persistence; potential crop uptake and accumulation	Strict source control; exclusion of high-risk streams; targeted analytical monitoring; avoidance of land application when contamination is confirmed
Antimicrobial residues and antimicrobial resistance determinants (ARGs)	Aquaculture-derived wastes and sludge	Soil microbiome alteration; horizontal gene transfer	Procurement controls on antimicrobial use; controlled fermentation; validated thermal processing sufficient to degrade residues and inactivate genetic material; monitoring for residues and resistance indicators
Pathogenic microorganisms	Raw seafood waste and processing residues	Direct contamination of soil and fresh produce	Validated thermophilic composting (≥ 55 °C); thermal drying or pasteurization; documented time–temperature control; harvest interval management
Microplastics	Marine debris; contaminated raw materials; handling environments	Alteration of soil structure; potential for plant uptake and translocation (emerging evidence)	Upstream exclusion; physical screening where feasible; quality control during processing; avoidance of contaminated batches
Salinity and sodium load (including SAR effects)	Marine tissues; brines; processing water	Soil salinization; increased sodium adsorption ratio (SAR); clay dispersion and structural degradation	Blending with low-salinity materials; application rate limits; soil electrical conductivity (EC) and SAR monitoring; site-specific nutrient management planning

4.2.1. Source Control and Segregation

Risk reduction is most cost-effective at the beginning of the chain.

Origin screening and procurement standards: Sourcing from regions and suppliers with documented environmental monitoring reduces the probability of high metal or POP loads. For aquaculture-derived wastes, procurement specifications can include restrictions on antimicrobial use, feed sourcing, and documented withdrawal periods where applicable [104,112].

Segregation of high-risk fractions: Viscera and hepatopancreas can carry higher contaminant burdens than frames or skins. Segregating organ-rich streams for non-food-crop uses (e.g., energy recovery, industrial products) can materially reduce risk without eliminating valorization potential [113–115].

HACCP-style controls for fertilizer feedstocks: Applying hazard analysis to byproduct handling (temperature control, time-to-processing, cross-contamination control, foreign-body prevention) reduces pathogen and physical contaminant risks before valorization even begins.

4.2.2. Processing as a Decontamination Hurdle

Processing is the main point where hazards can be reduced decisively, provided that time–temperature and process conditions are validated and recorded.

Pathogen control through heat and process validation: Thermophilic composting, pasteurization/thermal drying, and certain thermochemical routes can substantially reduce pathogens when operational criteria are met. What matters for credibility is documented compliance with validated conditions, not simply stating that the process was applied [34,116].

Fermentation and pH hurdles: Lactic fermentation lowers pH and can suppress many pathogens; it also improves handling by reducing odor and stabilizing the material. Fermentation is best viewed as one hurdle within a broader safety plan rather than a stand-alone guarantee [117].

Organic contaminant reduction via high-temperature treatment: Thermochemical processes (e.g., pyrolysis) can reduce many organic contaminants, although outcomes depend on compound class and process parameters. When POP or PFAS risk is plausible, process selection should be justified by evidence and paired with testing rather than assumed [118,119].

Metal risk management: Metals cannot be destroyed, so management focuses on reducing bioavailability and controlling inputs. Biochar amendments have been widely discussed as immobilization tools in soils, and modeling work suggests that biochar properties and application conditions strongly determine immobilization performance [84]. Shell- and bone-derived chars are of particular interest because mineral phases can support sorption/precipitation mechanisms, but fertilizer design should avoid implying that immobilization equals removal.

Microplastics control: Removal from solids is difficult once mixed. For liquid products (hydrolysates), filtration and membrane steps may reduce particle loads, but cost and fouling can limit practical deployment. For now, prevention and exclusion remain the primary controls [120,121].

4.2.3. Post-Process Verification, Product Standards, and Application Controls

A safety claim becomes credible when it is measurable and auditable.

Contaminant and pathogen limits: In the EU context, Regulation (EU) 2019/1009 provides clear maximum limits for several contaminants and includes pathogen criteria for organic fertilizers and soil improvers [122]. These limits can be used as explicit benchmarks for product specification, even for markets outside the EU, because they provide a recognized reference point for quality assurance (Table 4).

Table 4. Selected maximum contaminant limits under Regulation (EU) 2019/1009 for relevant organic fertilizer product categories.

Regulation	Cd (mg/kg)	Pb (mg/kg)	Hg (mg/kg)	Pathogen Criteria
EU 2019/1009	≤1.5	≤120	≤1.0	Salmonella absent [122]
National organic standards	Varies	Varies	Varies	Hygienization required

Batch testing and certificates of analysis: Routine testing for Cd, Pb, Hg, and inorganic As; targeted testing for POPs/PFAS where plausible; and microbiological testing aligned with the intended crop use are standard elements of a defensible QA/QC plan [94,118,122].

Crop- and field-specific safeguards: Restrictions on use for crops consumed raw, minimum intervals between application and harvest, and limits on application rates based on nutrient planning and sodium load should be written into product guidance [123,124].

Digital traceability: IoT-based process logs (temperature, time, pH, moisture) and tamper-resistant records can support audits and reduce disputes about whether critical parameters were met. Traceability does not replace safety controls, but it strengthens verification and accountability in complex supply chains [125,126].

The relationships between major valorization technologies, key food safety risks, and mitigation relevance across agricultural applications are summarized in Figure 2.

5. Integration with Agriculture 4.0 and the Circular Economy

SDFs fit best in farming systems that can measure, adjust, and verify these three tasks, which are central to Agriculture 4.0 and to credible circular-economy claims. The practical challenge is variability: Organic fertilizers differ by species, season, processing method, and storage time, so nutrient release and salt load are rarely “one-size-fits-all.” Digital

tools help convert that variability from a liability into something manageable by linking (i) batch characterization at the valorization facility, (ii) field condition monitoring, and (iii) decision rules that support the right rate, timing, and placement. The same data backbone also strengthens traceability and environmental accounting, which increasingly influence regulatory acceptance and market uptake [7,103].

5.1. Precision Nutrient Management and Site-Specific Application

Organic fertilizers often provide nitrogen in mixed forms (readily available ammonium plus slower mineralization from organic N), along with phosphorus and calcium-bearing minerals. That diversity can be an advantage for soil function, but it complicates rate selection. Agriculture 4.0 addresses this through data fusion by combining soil sensing, crop sensing, and product analytics.

Soil and crop sensing: Sensor platforms now routinely track soil moisture and temperature, and in many systems also provide proxies for salinity and nutrient status. At the canopy scale, remote sensing (satellite and UAV) adds spatial context through vegetation indices and spectral signatures associated with nutrient stress. Normalized difference vegetation index (NDVI) remains widely used, but more recent syntheses emphasize that index choice should be crop- and context-specific; indices such as green normalized difference vegetation index (GNDVI) and soil-adjusted vegetation index (SAVI) can be more informative than NDVI under certain soil background or stress conditions [127–129]. Systematic reviews also note that AI-enhanced sensing is moving from proof-of-concept toward operational toolchains in arable systems, although calibration and data governance remain adoption bottlenecks [127].

Despite their potential, the implementation of precision nutrient management technologies in real-world agricultural systems presents several practical challenges. Sensor-based platforms require careful calibration and validation across soil types, cropping systems, and environmental conditions to ensure reliable measurements. Data interpretation remains non-trivial, as sensor outputs are influenced by spatial heterogeneity, temporal variability, and interactions among soil chemical, physical, and biological properties. In addition, effective use of sensor-derived data depends on seamless integration into decision support systems that translate complex datasets into actionable recommendations for farmers. Limitations in data interoperability, model transferability, and user expertise can constrain adoption, particularly in small- and medium-scale operations. Addressing these challenges is essential for realizing the full potential of precision fertilization strategies within Agriculture 4.0 frameworks [130,131].

Decision support and variable-rate application: The central shift is from “average-field” fertilization to management zones. When the nutrient composition of seafood-derived products is quantified (even with basic batch assays for total N, ammonium-N, P, K, Na, moisture), those values can be integrated into models that predict crop demand and adjust rates spatially. Reviews covering IoT–AI in precision agriculture consistently identify variable-rate nutrient management as a high-impact application area because it can reduce over-application, cut losses to water bodies, and improve nutrient use efficiency. In practice, the most defensible workflow is conservative: begin with soil-test and yield-history zoning, add remote sensing for within-season correction, and then refine models over multiple seasons as on-farm response data accumulate [131–133].

5.2. Smart Valorization Facilities and Process Intelligence

Industry 4.0 concepts apply just as strongly upstream, where unstable byproducts are converted into consistent fertilizing products. Seafood wastes are particularly sensitive to time-to-processing and process control because protein-rich feedstocks can

generate odor and nitrogen loss rapidly. Digitized facilities increasingly rely on continuous monitoring and feedback control.

Sensorized process control: Composting plants commonly use temperature monitoring, but more advanced setups add oxygen, moisture, and sometimes ammonia or CO₂ sensing to reduce early-stage emission peaks and improve batch consistency. AI-based control strategies are being discussed and trialed for organic waste processing, where operational data are used to tune aeration, turning, or water addition to hit maturity targets more reliably [134].

Digital twins and predictive operations: Digital twins are moving beyond manufacturing into waste management, enabling scenario testing (feedstock blending, aeration schedules, equipment downtime) without disrupting plant operations. Field validation work has shown digital twin frameworks being deployed in organic waste settings to support real-time monitoring and optimization [134]. While composting is a natural early adopter, the same principle extends to fermentation and enzymatic hydrolysis in bioreactors, where pH, temperature, mixing, and residence time can be optimized for consistent product chemistry.

In the context of seafood byproduct valorization, artificial intelligence functions less as a productivity enhancement and more as an enabling technology for consistency, safety assurance, and scalability. Organic waste streams exhibit high temporal and compositional variability, which undermines standardization in the absence of adaptive control. AI-driven process management enables continuous adjustment of operating conditions, early detection of deviations from hygienization targets, and predictive quality control across batches. These capabilities are critical for transforming variable byproducts into fertilizers that meet regulatory specifications and farmer expectations, and would be difficult to achieve through manual or rule-based control alone [133,135].

5.3. Lifecycle Assessment and Circular-Economy Validation

Positioning SDFs as “sustainable” requires more than a narrative about waste diversion. Environmental performance depends on energy use in processing, transport distance, avoided disposal impacts, and, critically, what the product displaces, such as synthetic fertilizers, peat-based amendments, or lime. LCA remains the primary tool for testing these trade-offs.

Where benefits typically arise: Circular pathways often gain most when they (i) avoid methane-generating disposal routes, (ii) reduce reliance on energy-intensive inputs, and (iii) create stable carbon or nutrient products with long residence times in soil. Work on dynamic and prospective LCA highlights that results can shift depending on how biogenic carbon and substitution credits are handled, and that process choice (e.g., pyrolysis vs. other stabilization routes) can materially change the emissions profile [136]. Although sewage sludge is not the same as seafood waste, sludge LCAs are useful analogs for wet organic residues because they face similar questions around stabilization, transport, and land application; recent assessments explicitly frame treated sludge as a circular fertilizer and evaluate regional sensitivity [137].

Using operational data rather than generic assumptions: Agriculture 4.0 creates an opportunity to strengthen LCAs by replacing default values with measured data. Facility-level energy meters, transport logs, and process sensors can provide primary inventories for electricity and fuel use. At the field scale, remote sensing can support yield and biomass estimates, while targeted monitoring can quantify nitrate leaching risk or seasonal GHG flux patterns. Recent analyses of IoT-enabled systems in food chains show that the environmental benefit of sensor deployments can be evaluated explicitly by comparing the footprint of the digital layer to the avoided losses or emissions it enables [138]. This

logic translates well to fertilizer chains where the digital layer supports both process efficiency and safer, more precise application.

5.4. Traceability, Compliance, and Market Confidence (Blockchain and Beyond)

SDFs products face a predictable trust barrier, even when performance is strong. Traceability systems reduce that friction by making provenance and compliance auditable.

Blockchain-enabled traceability: Reviews of blockchain in agricultural traceability describe its value as an immutable log that can link farm origin, processing records, and verification data across multiple actors [139,140]. Broader systematic reviews in food supply chains emphasize that blockchain is most effective when paired with reliable data capture, often IoT-based, and when governance issues such as data ownership, standardization, and interoperability are addressed early [141].

However, real-world implementation of blockchain in agricultural supply chains remains constrained by practical challenges, including infrastructure and operational costs, scalability across small and medium-sized actors, and the lack of harmonized data standards. These limitations underscore that blockchain should be viewed as an enabling governance tool rather than a standalone solution [142,143].

What traceability should contain for SDFs: A practical traceability record can include: origin and type of byproduct (species, plant, or farm), batch-level contaminant testing, process validation indicators (time–temperature history for composting/drying or reactor parameters for fermentation), and destination field/application rate. The value is not only consumer-facing; traceability simplifies audits against contaminant limits and helps isolate problems quickly if a batch fails specifications. In circular-economy markets, this infrastructure also supports emerging “nutrient accounting” and certification claims, where proof of practices matters as much as the product itself [144].

6. Conclusions and Future Perspectives

Sustainable fertilization strategies are increasingly evaluated not only on agronomic performance, but also on their ability to close nutrient loops, reduce environmental externalities, and maintain food safety across complex supply chains. This review demonstrates that seafood processing byproducts, when treated as regulated secondary resources rather than residual wastes, represent a technically viable and strategically important component of circular nutrient systems. However, their successful integration into agriculture depends less on the availability of individual processing technologies than on coordinated system design that encompasses feedstock control, validated processing, safety governance, and digitally supported monitoring from source to field (Table 5) [23].

Table 5. Key research gaps and future priorities.

Area	Current Limitation	Future Need
Contaminant fate	Short-term data	Long-term field studies
Product variability	Batch inconsistency	Standardized quality classes
Digital adoption	Fragmented tools	Integrated DSS
Social acceptance	Limited surveys	Farmer-focused studies

Across the valorization toolbox, several pathways already have enough technical maturity for scaling, where infrastructure and governance support them. Composting and related biological routes can yield stable amendments that improve soil organic matter and buffer nutrient release, while hydrolysis and fermentation offer liquid products suited to controlled dosing in high-value production systems. Thermochemical options add a different advantage: producing stable carbon materials that can support nutrient retention

and long residence times in soil, which is increasingly discussed as part of circular nutrient strategies rather than only as carbon sequestration [145]. Digitalization is not a cosmetic add-on here; it enables consistent processing (sensor-guided control), batch traceability, and field-level targeting, which are practical requirements when moving from variable feedstocks to reliable fertilizing products [24,128].

The largest constraints remain familiar but critical: safety, economics, and trust. Marine-derived inputs can carry potentially toxic elements, persistent organics (including PFAS in some contexts), antibiotic residues, antimicrobial resistance determinants, and microplastics. These hazards cannot be managed by end-product testing alone; they require layered controls starting at sourcing and segregation, followed by validated processing hurdles and documented verification against regulatory benchmarks such as the EU fertilizing products framework [42]. In parallel, adoption depends on whether products are affordable, predictable in performance, and socially acceptable, with these factors shaped by farmer perceptions, advisory networks, and market signals rather than technical feasibility alone [146].

Looking forward, accelerating the transition toward a circular bioeconomy for seafood byproducts will require coordinated action across research, policy, and industry, with clearly defined priorities that address safety, performance, and adoption barriers.

Future Perspectives: Priorities That Would Materially Strengthen the Field

Contaminant control that is practical at scale: Progress is needed on approaches that are effective but also deployable in real facilities and cooperatives. For metals, the key gap is not detection but managing bioavailability over repeated applications and across soil types. For PFAS and other persistent organics, stronger evidence is needed on which processing routes meaningfully reduce exposure and under what conditions, rather than assuming “high temperature” or “stabilization” is sufficient [147]. For antimicrobial resistance, monitoring frameworks increasingly emphasize genes and mobile elements in addition to chemical residues, which suggests that validation protocols may need to evolve beyond conventional pathogen indicators [103]. For microplastics, prevention at source remains central because downstream separation from solids is still limited in practicality; field-realistic studies should accompany lab evidence on soil function effects [36].

Product standardization without losing circularity: A recurring barrier for recycled nutrient fertilizers is variability. Moving toward quality classes—defined by nutrient ranges, salinity thresholds, maturity/stability indices, and contaminant ceilings—would reduce uncertainty for farmers and regulators. Rapid analytical screening (portable spectroscopy, sensor-assisted QA/QC) could support this, but the most important step is agreeing on specifications that match crop category and risk profile [23]. Standardization also creates the foundation for precision application models that require reliable nutrient inputs [128].

Long-term agronomic and soil ecological evidence: Short trials can show yield gains, but they rarely resolve the questions that matter for food crops: cumulative contaminant behavior, shifts in soil microbial communities, and resilience under drought/heat stress. Multi-year field studies, especially in coastal regions likely to host these supply chains, are needed to quantify repeated-application outcomes on soil structure, nutrient cycling, and crop quality under realistic management [36,64,145]. Chitin/chitosan-rich products also warrant longer-horizon studies because elicitation effects can be dose-dependent and context-specific, with potential trade-offs between defense activation and growth [148].

LCA and techno-economic analysis built from measured data: Environmental benefits are not automatic. They depend on avoided disposal burdens, displaced inputs, transport distances, and energy sources used during processing. Recent syntheses emphasize that seafood-waste biorefinery LCAs can change direction depending on assumptions

about substitution credits and regional logistics, which makes transparent, data-rich modeling essential [52,147]. Digital measurement systems in facilities and farms make it increasingly feasible to build LCAs from operational data rather than generic databases, improving credibility for *Sustainability*-aligned claims [149].

Policy design and adoption research that reflects real decision-making: Uptake is often slowed less by technology than by uncertainty: farmers want clear guidance on performance, compatibility with existing equipment, and liability boundaries for contaminants. Survey work in Europe indicates that perceptions and practical conditions strongly shape willingness to adopt circular fertilizers and organic amendments [146,150]. Policies that reduce early-stage risk, including quality standards, procurement programs, cost-sharing for infrastructure, and support for monitoring, may have a disproportionate impact compared with broad “circular economy” messaging [146].

Taken together, seafood byproduct valorization is best understood as a systems innovation rather than a single product swap. A practical near-term pathway is a disciplined model: defined sourcing rules, validated processing, specification-based products, and digitally supported monitoring that links the valorization facility to field decisions. With that structure in place, circular nutrient recovery can move from a promising concept to a dependable component of sustainable fertilization strategies.

7. Policy and Governance Frameworks Enabling SDFs

The technical feasibility of converting seafood processing byproducts into safe and effective fertilizers is increasingly well established. However, large-scale adoption depends not only on processing technologies and agronomic performance, but also on the policy and governance environments in which these materials are classified, regulated, and incentivized. Governance structures play a decisive role in determining whether SDFs are treated as valuable secondary resources or remain constrained by waste-management paradigms that limit their circulation within agricultural systems.

A central governance challenge arises from the regulatory duality of seafood byproducts, which are simultaneously classified as waste under environmental legislation and as *inputs* under fertilizer and soil-management frameworks. In many jurisdictions, this dual status creates regulatory uncertainty, fragmented oversight, and high compliance costs that discourage valorization initiatives [146]. Waste regulations are typically designed to minimize environmental and public health risks through strict controls on handling and disposal, whereas fertilizer regulations focus on nutrient content, contaminant thresholds, and agronomic safety. When seafood byproducts fall between these regimes, innovators must navigate overlapping or conflicting requirements, slowing implementation and increasing transaction costs.

The European Union has taken significant steps to address this governance gap through Regulation (EU) 2019/1009, which establishes harmonized criteria for placing EU fertilizing products on the market, including organic fertilizers and soil improvers derived from secondary raw materials. By defining contaminant limits, pathogen criteria, and conformity assessment procedures, this framework provides a legal pathway for SDFs to exit “waste status” and circulate as regulated products [151,152]. Importantly, the regulation reflects a broader policy shift embedded in the EU Circular Economy Action Plan and the Farm to Fork Strategy, both of which emphasize nutrient recycling, reduced dependency on mineral fertilizers, and improved soil health [153]. Nevertheless, implementation remains uneven across Member States, particularly with respect to permitting, monitoring capacity, and interpretation of end-of-waste criteria, which can affect the competitiveness of seafood-derived products relative to conventional fertilizers.

Comparative regulatory differences across regions further complicate the international scaling and trade of SDFs. In the European Union, Regulation (EU) 2019/1009

establishes harmonized limits for heavy metals, microbiological safety, and organic contaminants, enabling cross-border market access once conformity is demonstrated. In contrast, North American frameworks rely on a combination of federal environmental statutes and state-level fertilizer regulations, resulting in variable thresholds for metals and pathogens and limited coverage of emerging contaminants such as PFAS. In Southeast Asia, where a substantial share of global seafood processing occurs, regulatory frameworks are often less harmonized and primarily oriented toward waste management or export certification, with limited fertilizer-specific standards for contaminants or biological safety [154,155]. These regional discrepancies create barriers to international trade, increase compliance costs, and limit mutual recognition of products, underscoring the need for greater regulatory alignment and data sharing to support safe circular nutrient flows across borders.

Outside the EU, governance frameworks are more fragmented. In the United States, for example, fertilizer regulation is largely state-based, while seafood byproducts are subject to federal environmental and food safety oversight depending on their origin and processing pathway. Biosolids regulations under the Environmental Protection Agency provide a partial analogue, but they were not designed specifically for marine-derived materials and do not directly address emerging concerns such as PFAS or microplastics [152,153]. As a result, regulatory uncertainty persists, particularly for applications involving food crops, and risk-averse actors may default to disposal rather than valorization.

Beyond formal regulation, economic and institutional policy instruments strongly influence adoption. Price volatility in synthetic fertilizer markets has renewed interest in alternative nutrient sources, but without targeted incentives, SDFs often struggle to compete on cost alone due to collection, processing, and transport expenses [146]. Policy mechanisms such as nutrient recycling credits, green public procurement, and support for regional processing infrastructure can help internalize environmental benefits that are not reflected in market prices. Public procurement, in particular, has been identified as a powerful lever for de-risking early adoption by creating stable demand for circular fertilizers in public landscaping, land restoration, and soil improvement projects [156].

Governance also intersects with transparency and trust, especially for SDFs inputs. Farmer and consumer acceptance is closely tied to confidence in safety, quality, and traceability. Regulatory frameworks that require clear labeling, batch-level testing, and auditable records can reduce perceived risk and counteract “perceived risk associated with SDF inputs” associated with secondary fertilizers [146]. In this context, digital traceability systems, while not a substitute for regulation, can act as governance tools by making compliance verifiable and responsibilities traceable across supply chains [141].

Finally, policy coherence across sectors remains a critical issue. Circular nutrient strategies often span fisheries, aquaculture, waste management, agriculture, and environmental protection, yet these domains are typically governed by separate institutions with limited coordination. Several recent analyses argue that effective nutrient circularity requires integrated governance models that align objectives across these sectors, rather than incremental adjustments within isolated policy silos [147]. For SDFs, such integration is particularly important because upstream decisions in fisheries and aquaculture, such as feed composition, antimicrobial use, and waste segregation, directly affect downstream fertilizer safety and regulatory compliance.

In summary, policy and governance frameworks are not peripheral to the success of seafood byproduct valorization but constitute enabling or constraining conditions that shape technical feasibility, economic viability, and social acceptance. Regulatory clarity, incentive alignment, and cross-sector coordination are therefore as critical as advances in processing technology for embedding SDFs within sustainable and circular agricultural systems.

Aligning scientific evidence, regulatory frameworks, and operational practices around these priorities will be critical for translating seafood byproduct valorization from pilot-scale success into a mainstream component of sustainable agricultural systems.

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