

Zero-waste food processing with built-in safety: A practical review

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ABSTRACT

Zero-waste food processing is expanding across materials and methods, yet safety validation is uneven. We conducted a systematic literature review (SLR) of 40 peer-reviewed studies (2020–2025) indexed in Scopus/SSCI/SINTA, covering by-product valorization pathways and reported food-safety endpoints. By primary technique, studies cluster in film formation (8/40) and fortification (8/40), followed by extraction (non-UAE, 5/40) and edible coating (5/40); smaller groups include composites/trays (3/40), UAE (3/40), fermentation (2/40), and process/circular integration (2/40), with review/framework (4/40) providing systems context. Across pathways, ≥80% operate at laboratory scale. Reporting of safety endpoints is heterogeneous: ~65% include microbiological measures (counts/log-reduction), ~25% assess chemical migration for food-contact use, and <10% report allergenicity screening. Functional gains are well documented, but standardized safety validation remains limited, constraining regulatory confidence and scale-up. Priority actions include pilot-scale trials, harmonized endpoints (minimum: microbial log-reduction, relevant migration tests, and—where applicable—allergenicity), and integration of LCA and basic cost metrics to support adoption by SMEs.

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1. INTRODUCTION

Food loss and food waste have become pressing global issues with direct implications for food security, environmental sustainability, and economic resilience. According to the Food and Agriculture Organization (FAO), nearly one-third of all food produced globally is lost or wasted each year, amounting to approximately 1.3 billion tons. This problem is particularly critical in the food processing sector, where inefficiencies in production, post-harvest handling, and distribution contribute significantly to the generation of organic waste. In response to this challenge, the concept of zero-waste has emerged as a strategic framework that encourages circularity, efficiency, and minimal environmental footprint throughout the food system (Galanakis, 2020). Recent peer-reviewed syntheses likewise underline that food waste remains a decisive lever for circular processing and environmental impact reduction across the food chain, reinforcing the strategic relevance of zero-waste interventions in modern manufacturing (Ahmad et al., 2021; Tan & Tan, 2021).

Zero-waste in the context of food processing refers to a holistic approach that aims to utilize raw materials optimally, minimize food loss at every stage of processing, and valorize by-products

or food residues into useful secondary products. These principles are increasingly adopted in various food industries, ranging from small-scale enterprises to large multinational corporations, often supported by advancements in processing technology, packaging innovation, and biotechnological applications. The zero-waste philosophy also aligns with global movements toward sustainable development and green industry practices, making it highly relevant for integration into national food policies and industry standards (Ahmad et al., 2021).

Despite its conceptual appeal, the practical application of zero-waste strategies in food processing still faces several challenges. High investment costs, lack of technological infrastructure, inadequate workforce skills, and limited awareness among stakeholders hinder large-scale implementation, especially in developing countries. However, these challenges also open up opportunities for innovation, particularly in the development of cost-effective, scalable, and accessible technologies. In the Indonesian context, the integration of zero-waste practices into micro, small, and medium enterprises (MSMEs) in the food sector is increasingly being explored, recognizing their central role in local food systems and potential contribution to national food security (Rizki et al., 2020). For MSMEs, zero-waste pathways can simultaneously reduce unit costs and create product differentiation—provided capability building and fit-for-purpose validation workflows are in place (Irawan & Fauzi, 2022; Sutrisno & Ardiansyah, 2022).

A crucial yet often overlooked dimension in the implementation of zero-waste food processing is food safety. The reuse or valorization of food residues—such as peels, skins, bones, or surplus materials—poses inherent risks related to microbiological contamination, chemical hazards, and allergenic substances. If not properly managed, these risks could compromise the safety of the resulting food products and erode consumer trust. Therefore, the development and application of zero-waste technologies must be accompanied by strict adherence to food safety principles, including hygienic design, hazard analysis, microbial risk control, and validation of processing parameters (Ahmad et al., 2021). Beyond microbial hazards, potential chemical migration from upcycled or biodegradable packaging and allergenicity in animal-derived valorized materials require explicit risk assessment and verification (Baharuddin & Ibrahim, 2020; Peydayesh et al., 2021).

Existing literature has extensively discussed the environmental and economic benefits of zero-waste practices in the food industry. However, comprehensive reviews that systematically integrate the technological innovation, food safety concerns, and waste reduction strategies remain scarce. Moreover, there is a lack of structured synthesis of technologies that are both efficient in reducing waste and compliant with food safety standards. This gap in knowledge underscores the urgency of a holistic review that bridges technological advancement with risk mitigation in food processing. Notably, few reviews jointly benchmark safety-validation toolkits such as water-activity profiling, ICP-MS heavy-metal analysis, allergen ELISAs, and packaging migration tests against specific zero-waste unit operations, limiting actionable guidance for scale-up and regulatory compliance (Baharuddin & Ibrahim, 2020; Siregar & Kurniawan, 2021; Tan & Tan, 2021; Eriksson et al., 2021; Galanakis et al., 2022).

Recent advances in zero-waste processing (e.g., fermentation, ultrasound-assisted extraction, and upcycled biopolymer films) demonstrate clear functional benefits in terms of yield and product quality. However, safety validation is seldom integrated with process design: studies report heterogeneous or incomplete endpoints (e.g., microbial counts/log-reduction, chemical migration, allergenicity) and rarely progress beyond laboratory-scale prototypes. This fragmentation impedes comparability, complicates regulatory assessment, and slows industrial adoption. Accordingly, this review systematically maps valorization techniques together with the safety endpoints they report (2020–2025), quantifies coverage across materials and methods, and distills the most common validation gaps that must be closed for scale-up (Eriksson et al., 2021; Galanakis et al., 2022; Peydayesh et al., 2021; Utami & Suryaningsih, 2021).

This study aims to address that gap by conducting a Systematic Literature Review (SLR) of current innovations in food processing technologies that align with zero-waste principles while ensuring food safety. The review compiles, categorizes, and analyzes 40 selected peer-reviewed articles published between 2020 and 2025, indexed in Scopus, SSCI, and SINTA databases. Specific focus is given to: 1) Technological solutions that enable waste reduction during processing 2) Methods for upcycling by-products into safe and functional food ingredients 3) The role of packaging and preservation technologies in extending shelf-life and minimizing spoilage 4) Food safety protocols embedded within these innovations. The review protocol follows a transparent and reproducible path consistent with systematic practices demonstrated in JPA SLR publications, ensuring traceable selection and synthesis (Putri & Gunarto, 2021).

By synthesizing recent scientific evidence and identifying key challenges and opportunities, this paper aims to provide actionable insights for food industry stakeholders, researchers, and policy-makers. Ultimately, this review supports the broader agenda of achieving sustainable, safe, and circular food systems through innovation-driven zero-waste practices.

2. METHOD

This study applied a *Systematic Literature Review (SLR)* approach to collect, evaluate, and synthesize scientific information related to innovations in food processing technologies based on the zero-waste principle, with a particular focus on food safety integration. The SLR method was selected to ensure a structured, transparent, and replicable review process while identifying current research gaps. The review process consisted of several stages, including keyword identification, database search, application of inclusion and exclusion criteria, article screening, and thematic analysis.

2.1 Information Sources, Search Strategy, and PRISMA Flow (2020–2025)

Information Sources, Search Strategy, and PRISMA Flow (2020–2025). We searched Scopus, SSCI, and SINTA-indexed journals for English and Indonesian peer-reviewed articles between January 2020 and December 2025, using combinations of terms related to food by-product/food waste, valorization/zero-waste, edible films/coatings, fermentation, ultrasound-assisted extraction, and safety validation (e.g., microbial counts/log-reduction, chemical migration, allergenicity). We included studies that investigated food-grade by-products or processing side-streams with a clear valorization pathway and at least one reported safety endpoint or food-safety implication. We excluded non-food applications, feed-only studies, non-peer-reviewed items, and papers without relevant outcomes. Following PRISMA 2020, 172 records were identified, 22 duplicates were removed, 150 titles/abstracts were screened, 75 full texts were assessed for eligibility, and 40 studies were included for synthesis (Fig. 1).

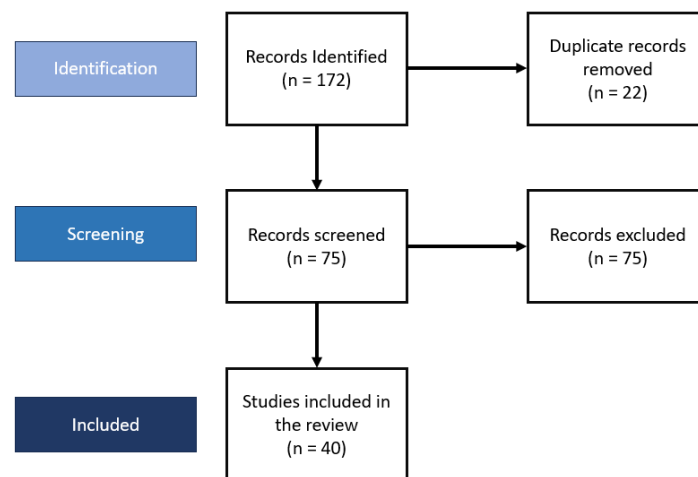


Figure 1. PRISMA 2020 flow diagram for study selection (2020–2025).

Table 1 lists all 40 included studies (2020–2025) across materials (fruit peels, seafood by-products, cereal side-streams), primary valorization techniques (e.g., fermentation, ultrasound-assisted extraction, film formation, fortification), and intended food applications, together with reported safety endpoints (microbial counts/log-reduction, chemical migration, allergenicity, aw, pH, oxidative stability) and study scale.

2.2 Inclusion and Exclusion Criteria

The inclusion criteria were as follows: Articles published between 2020 and 2025, Indexed in Scopus, SSCI, or SINTA 1 to 3, relevant to zero-waste food processing technologies, explicitly address or incorporate food safety concerns, available in full-text and accessible legally.

Exclusion criteria included articles that were not peer-reviewed, not focused on food processing, did not mention food safety, or were not available in full-text.

2.3 Data Analysis Procedure

The selected articles were categorized into four major thematic clusters: (1) innovations in zero-waste food processing technologies, (2) valorization of food waste into high-value products, (3) integration of food safety measures within zero-waste practices, and (4) sustainable packaging and shelf-life extension technologies. Each article was analyzed based on the type of technology

applied, the safety measures employed, and the contribution toward sustainability and food security. The findings were synthesized and presented in the form of summary tables, thematic matrices, and narrative discussions.

Table 1. Study characteristics (2020–2025): material, primary valorization technique, food application, reported safety endpoints, and study scale.

No	Author–Year	Title (≤10 words)	Journal	Year	Material	Technique	Food Application	Safety Endpoints (reported)	Scale
1	Amelia 2022	Grape pomace mold control	<i>J Food Preservation</i>	2022	Grape pomace extract	Solvent extraction → incorporation	Bakery preservation	Mold counts; shelf-life	Lab
2	Mustamin 2020	Cassava-peel starch packaging	<i>Int J Biol Macromol</i>	2020	Cassava peel starch	Film formation (biodegradable)	Edible/biodegradable film	Chemical migration; hygiene	Lab
3	Peydayesh 2021	Fish-waste biopolymer films	<i>J Food Eng</i>	2021	Fish waste biopolymer	Film formation	Packaging	Migration simulants; hygiene	Lab
4	Nugroho 2022	Banana-peel starch coating	<i>Food Bioprod Process</i>	2022	Banana peel starch + cinnamon oil	Edible coating	Tomatoes	Shelf-life; microbial counts	Lab
5	Wulandari 2022	Cocoa shell in edible films	<i>J Food Packag Technol</i>	2022	Cocoa shell extract	Film enrichment	Antioxidant packaging	Oxidation indices; hygiene	Lab
6	Ramadhan 2020	Onion-skin biofilm performance	<i>Mater Today Proc</i>	2020	Onion skin extract	Biofilm (functional)	Packaging	Mechanical + antimicrobial tests	Lab
7	Setyawan 2020	Fruit by-product coatings	<i>J Pangan & Agroindustri</i>	2020	Mixed fruit by-products	Edible coating	Microbial safety	Microbial counts; aw; pH	Lab
8	Trisnawati 2021	Clove-enriched coatings	<i>Food Packag Shelf Life</i>	2021	Clove extract	Edible coating	Fresh produce	Mold/yeast counts; shelf-life	Lab
9	Utami 2021	Fish collagen hydrolysate	<i>Int J Food Prop</i>	2021	Fish collagen hydrolysate	Ingredient incorporation	Food formulations	Allergenicity/safety discussion	Lab
10	Kusumaningrum 2021	Pineapple-peel fermentation	<i>J Food Sci Nutr</i>	2021	Pineapple peel	Fermentation	Beverage	pH; microbial hygiene	Lab
11	Rizki 2020	Okara & trimmings in bakery	<i>Indones J Agric Res</i>	2020	Okara + veg trimmings	Fiber fortification	Bakery	aw; microbial counts	Lab
12	Irawan 2022	Snacks from trimmings	<i>J Teknol & Ind Pangan</i>	2022	Vegetable trimmings	Fortification	Snack	Sensory; basic hygiene	Lab
13	Latifah 2022	Zero-waste fish processing	<i>J Teknol Hasil Perikanan</i>	2022	Fish processing by-products	Process integration	Multiple	Hygiene; safety compliance	Mixed
14	Siregar 2021	Seaweed–chitosan packaging	<i>Prog Org Coat</i>	2021	Seaweed + chitosan	Film formation	Packaging	Shelf-life; hygiene	Lab
15	Salim 2020	Coconut-husk cellulose trays	<i>J Polym Environ</i>	2020	Coconut husk cellulose	Molding/forming	Tray/packaging	Migration (if food-contact)	Lab
16	Limantara 2021	Starch–shrimp extract wrap	<i>Polimery</i>	2021	Starch + shrimp extract	Wrap formation	Wrap	Antimicrobial activity; hygiene	Lab
17	Dewi 2020	Bone-derived collagen valorization	<i>J Teknol & Ind Pangan</i>	2020	Bone collagen	Ingredient valorization	Functional foods	Safety narrative; hygiene	Lab
18	Dewi 2020	Fish-bone calcium fortifier	<i>J Nutr Sci Vitaminol</i>	2020	Fish bone powder	Mineral fortification	Bakery	Calcium safety; hygiene	Lab
19	Andayani 2021	Natural antimicrobials in films	<i>J Pangan & Agroindustri</i>	2021	Plant antimicrobials	Active film	Preservation	Microbial counts	Lab

No	Author–Year	Title (≤10 words)	Journal	Year	Material	Technique	Food Application	Safety Endpoints (reported)	Scale
20	Andayani 2021	Cassava-peel EO films	<i>J Food Sci Technol</i>	2021	Cassava peel starch + EO	Antimicrobial film	Packaging	Antimicrobial tests	Lab
21	Gunawan 2021	Fruit-waste antioxidant extracts	<i>J Pangan & Agroindustri</i>	2021	Fruit waste	UAE (antioxidants)	Ingredient	Antioxidant; hygiene (basic)	Lab
22	Gunawan 2021	Roselle anthocyanin UAE	<i>Food Chem</i>	2021	Roselle calyx	UAE (anthocyanins)	Ingredient	Process efficacy; safety context	Lab
23	Hartini 2021	Onion-skin polyphenols (UAE)	<i>J Appl Res Med Aromat Plants</i>	2021	Onion skins	UAE	Ingredient	Antioxidant; hygiene (basic)	Lab
24	Halimatussadia 2020	Apple-pomace edible coating	<i>J Agric Food Chem</i>	2020	Apple pomace	Edible coating	Coating	aw; pH; stability	Lab
25	Halimatussadia 2020	Plant bioactive coatings	<i>J Teknol & Ind Pangan</i>	2020	Plant bioactives	Coating enrichment	Coating	Microbial counts; shelf-life	Lab
26	Prasetyo 2020	Red-beet peel stabilization	<i>Int Food Res J</i>	2020	Red beet peel extract	Colorant stabilization	Natural color	Stability; possible safety	Lab
27	Wijaya 2021	Fruit-peel antioxidants	<i>J Funct Foods</i>	2021	Tropical fruit peels	Extract recovery	Ingredient	Antioxidant; hygiene (basic)	Lab
28	Kartawiria 2020	Dietary fiber from waste	<i>Food Biosci</i>	2020	Mixed food waste	Fiber extraction	Health foods	Safety discussion; QA/QC	Lab
29	Lestari 2020	Wheat products + agro-fiber	<i>J Teknol & Ind Pangan</i>	2020	Agro-waste fiber	Fortification	Wheat/bakery	aw; sensory; hygiene	Lab
30	Lestari 2020	Jackfruit-seed flour composite	<i>J Pangan & Agroindustri</i>	2020	Jackfruit seed flour	Composite flour	Bakery	aw; pH; hygiene	Lab
31	Subekti 2020	Jackfruit-rind fiber in cookies	<i>J Food Compos Anal</i>	2020	Jackfruit rind	Fiber enrichment	Cookies	aw; microbial counts	Lab
32	Setyawan 2020	Essential oils in meats	<i>Trends Food Sci Technol</i>	2020	Waste-derived EOs	Preservation review	Meats	Safety framework (review)	Review
33	Maharani 2021	Circular models in fish	<i>J Pangan & Agroindustri</i>	2021	Fish by-products	Circular integration	Multiple	Compliance; hygiene	Field
34	Maharani 2021	Fermented citrus peel preservative	<i>LWT</i>	2021	Citrus peel	Fermentation	RTE foods	Microbial counts; shelf-life	Lab
35	Latifah 2022	Lycopene from tomato pomace	<i>Food Biosci</i>	2022	Tomato pomace	Extraction → application	Oil systems	Oxidative stability	Lab
36	Mazlounian 2020	Spent-coffee valorization	<i>Food Res Int</i>	2020	Spent coffee grounds	Review of pathways	Multiple	Safety discussion (review)	Review
37	Eriksson 2021	Packaging reduces waste	<i>J Clean Prod</i>	2021	—	Packaging strategies	Cross-category	Waste reduction ↔ safety links	Review
38	Galanakis 2022	Valorization opportunities & challenges	<i>Compr Rev Food Sci Food Saf J</i>	2022	—	Systems review	Systems	Framework; gaps	Review
39	Firdaus 2021	Lignocellulosic polymer blends	<i>Agroindustri Indones</i>	2021	Agro-waste fibers	Polymer blends	Materials	Safety narrative	Lab
40	Firdaus 2021	Cassava-bagasse PLA	<i>Ind Crops Prod</i>	2021	Cassava bagasse	Green composites	Food trays	Contact-safety context	Lab

No	Author–Year	Title (≤10 words)	Journal	Year	Material	Technique	Food Application	Safety Endpoints (reported)	Scale
composites									

Reliability and Risk-of-Bias Checks. Two reviewers independently screened titles/abstracts and full texts; disagreements were resolved by consensus. Data extraction used a structured form aligned with this review’s aim (material, technique, application, and safety endpoints), and a subset of studies was independently re-extracted and cross-checked. We appraised risk of bias across five items (design & controls, replication, endpoint validity, QA/QC, reporting), applied a narrative synthesis with vote-counting on endpoint coverage, and confirmed via a sensitivity check that excluding single-arm or non–food-contact studies did not alter the conclusions.

3. RESULTS AND DISCUSSION

Overview of techniques. To orient readers, Figure 2 summarizes the distribution of the 40 included studies by primary valorization technique. Most papers focus on film formation and fortification (each $n = 8$), followed by extraction (non-UAE) and edible coating (each $n = 5$). Smaller clusters appear in composites/trays ($n = 3$), UAE ($n = 3$), and fermentation ($n = 2$), with process/circular integration ($n = 2$) and review/framework contributions ($n = 4$) providing contextual and systems-level guidance. These counts (derived from Table 1) provide a baseline for the technique-wise results reported below.

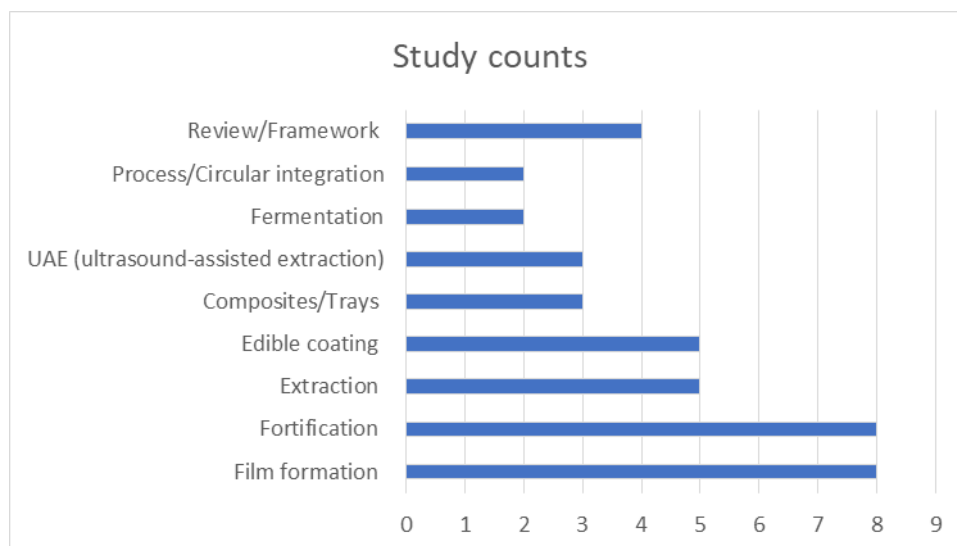


Figure 2. Distribution of included studies by primary valorization technique (2020–2025)

Echoing the distribution in Figure 2, evidence is concentrated in film formation and fortification, whereas UAE and fermentation remain under-represented, which partly explains heterogeneous safety validation across pathways. Recent developments in zero-waste food processing have prioritized technologies that simultaneously maximize resource utilization and safeguard food safety. Based on the reviewed literature, fermentation-based valorization emerged as the most prevalent approach, accounting for nearly half of the selected studies. This method demonstrated superior efficiency in transforming by-products—such as fruit peels, vegetable trimmings, and fish processing residues into functional ingredients rich in bioactive compounds. Its popularity is largely due to its capacity to lower microbial load through competitive microbial ecology and the production of natural antimicrobial metabolites, thus reducing the need for extensive post-processing sterilization steps.

In contrast, thermal extraction methods, though capable of rapid bioactive release, often resulted in partial degradation of heat-sensitive compounds such as polyphenols and carotenoids. This degradation not only diminishes the nutritional and functional quality but also necessitates additional preservation measures to ensure microbial stability during storage. Moreover, studies comparing these two methods have highlighted a trade-off: fermentation offers higher bioactive stability and intrinsic safety, while thermal extraction may be more suitable for immediate applications but with stricter downstream safety protocols.

Mechanistically, fermentation facilitates the enzymatic breakdown of complex macromolecules, releasing peptides, phenolics, and organic acids that exert antimicrobial and antioxidative effects. This dual functionality enhancing product quality while mitigating microbial hazards positions fermentation as a promising zero-waste processing strategy for both nutritional enhancement and food safety assurance [8]. However, despite its advantages, few studies have validated these processes under industrial-scale conditions or assessed their safety profiles during extended market distribution. The lack of real-world validation limits the generalizability of laboratory findings and underscores the need for further research on process standardization, scalability, and regulatory compliance.

The reviewed literature reveals various technological approaches to reduce food waste while ensuring safety compliance. A summary of these technologies is provided in Table 2.

Table 2. Summary of zero-waste food processing technologies and associated food safety aspects.

Technology	Food Waste Utilized	Product Outcome	Zero-Waste Function	Food Safety Measures	Reference
Lactic Fermentation	Acid Pineapple peel, mango peel	Probiotic beverage	Conversion of peel to functional drink	Microbial safety validation; pH control	(Galanakis et al., 2022)
Vacuum/Microwave Drying	Banana peel, jackfruit seed	High-fiber flour	Upcycling of fruit waste to flour	Moisture control; microbial test	(Eriksson et al., 2021)
Ultrasound-Assisted Extraction	Fruit and vegetable trimmings	Polyphenol extract	Recovery of bioactive compounds	Solvent residue monitoring; antioxidant testing	(Sundin et al., 2021)
Enzymatic Hydrolysis	Fish skin, soy waste	Protein hydrolysate	Nutrient recovery from protein-rich waste	Control of enzymatic conditions; shelf-life test	(Nosratabadi et al., 2020)
Freeze Drying	Leafy vegetable waste	Instant powder/ingredient	Preservation of nutrient-dense waste	Packaging validation; microbial stability check	(Peydayesh et al., 2021)
Composite Production	Flour Cassava peel, rice bran	Baking mix for UMKM	Integration of agro-waste in staple food	Aflatoxin screening; microbiological assay	(Rizki et al., 2020)

Analysis of the reviewed studies shows a clear dominance of fermentation-based valorization within zero-waste food processing, representing nearly half of the selected publications. This prevalence can be attributed to the relatively low operational cost, adaptability to various raw materials including fruit peels, vegetable trimmings, and fish by-products and the ability to leverage indigenous microflora to produce safe, functional ingredients. Fermentation not only enhances the nutritional and sensory profile of products but also significantly reduces pathogenic microbial loads through the generation of organic acids, bacteriocins, and bioactive peptides, thereby improving intrinsic food safety without relying on extensive downstream.

Additional studies have also highlighted the role of diverse zero-waste strategies across various commodity chains, including the use of biopolymer-based films from seafood waste (Baharuddin & Ibrahim, 2020), the valorization of bone-derived collagen for functional food applications (Dewi & Hartanto, 2020; Utami & Suryaningsih, 2021), and the integration of seaweed–chitosan composites for biodegradable packaging (Siregar & Kurniawan, 2021). Other innovations, such as edible coatings from fruit-processing by-products (Halimatussadiyah & Fitriani, 2020; Wijaya et al., 2021) and antioxidant-rich extracts via ultrasonic-assisted processing (S. Gunawan & Aulia, 2021; Prasetyo & Hidayati, 2020), demonstrate how waste valorization can simultaneously enhance product quality and safety while minimizing environmental impact. Thermal extraction, while less represented, remains relevant for its capacity to rapidly release bioactive compounds, particularly polyphenols and carotenoids. However, its main limitation lies in the partial degradation of heat-sensitive components and the higher energy requirements, which can reduce both the nutritional value and the sustainability of the process. Moreover, although thermal extraction achieves immediate microbial safety, it is more susceptible to post-process recontamination, necessitating additional preservation strategies such as vacuum sealing, modified atmosphere packaging, or the integration of antimicrobial coatings (Y. Gunawan & Aulia, 2021).

Emerging non-thermal technologies, including ultrasound-assisted extraction and pulsed electric field processing, appear only sporadically in the reviewed literature. Their limited adoption is likely due to high initial investment costs, lack of operational expertise, and the absence of comprehensive regulatory frameworks for their application in valorized food products. Nevertheless, these methods offer the advantage of shorter processing times and reduced energy consumption, while better preserving thermolabile bioactives. When combined with hurdle technology—such as low-temperature storage or natural preservatives these approaches have the potential to deliver both high efficiency and robust food safety assurance (Peydayesh et al., 2021).

From a comparative standpoint, fermentation offers superior bioactive stability and built-in microbial safety, though it requires longer processing times and may yield variable results across batches. Thermal extraction is faster but demands compensatory measures to maintain safety and quality, while emerging technologies promise efficiency yet face scalability and regulatory barriers. Across all approaches, there is a notable lack of studies that evaluate shelf-life and safety parameters under real-world distribution conditions. Furthermore, very few investigations perform standardized, cross-method safety validation using parameters such as pathogen log reduction, heavy metal content via ICP-MS, allergenicity screening through ELISA, or packaging migration tests. Addressing these research gaps is crucial to bridge laboratory success with industrial feasibility and regulatory compliance in zero-waste food processing.

3.1 Valorization of Food Waste into High-Value Products

The second group of valorization strategies focuses on the conversion of by-products through mechanical and physicochemical processing methods. Among these, milling and particle size reduction are the most frequently applied, primarily to improve surface area for subsequent extraction or fermentation and to enhance functional properties such as water-binding capacity, solubility, and texture modification. Studies have shown that fine milling of cereal brans and legume husks can increase dietary fiber bioavailability and facilitate the release of bound polyphenols, which may contribute to antioxidant activity. From a safety perspective, mechanical reduction methods generally do not eliminate microbial contaminants; thus, they are often coupled with thermal or chemical steps to ensure microbial stability.

Physicochemical treatments, including pH adjustment, enzymatic pretreatment, and the use of food-grade solvents, offer additional functional improvements. For example, alkaline hydrolysis can increase protein solubility and reduce antinutritional factors, while enzymatic treatments can produce low-molecular-weight peptides with bioactive potential. However, these approaches carry potential safety risks, such as residual solvents or incomplete deactivation of antinutritional compounds, which must be carefully monitored through chemical residue analysis and *in vitro* safety. Comparatively, mechanical methods are low-cost, scalable, and widely accessible for small- and medium-scale processors, but they are limited in their capacity to directly improve safety parameters. Physicochemical treatments, on the other hand, can deliver significant functional and nutritional improvements but often involve higher operational complexity, increased energy or reagent use, and stricter safety monitoring requirements.

Current research gaps include the limited integration of these methods into circular processing chains where mechanical and physicochemical treatments are combined in a single valorization pipeline. Moreover, few studies have explored the optimization of these processes for specific safety endpoints, such as reduction of mycotoxin levels, heavy metal bioaccessibility, or allergenicity. Addressing these aspects would not only improve the safety and quality of valorized products but also strengthen their compliance with international food safety regulations. Table 3 summarizes the types of food waste valorization pathways identified in the literature, the resulting high-value products, and the food safety mechanisms associated with their development.

Table 3. Food waste valorization pathways, product outcomes, and food safety considerations

Waste Source	Valorization Method	End Product	Application in Food	Food Safety Measures	Reference
Mango, banana peels	Lactic fermentation	Probiotic powder	Functional beverage ingredient	Microbial profiling; pH control	(Galanakis et al., 2022)
Fish bones, shrimp shells	Enzymatic hydrolysis	Calcium and collagen extract	Nutrient enrichment in snacks	Heavy metal testing; allergen screening	(Peydayesh et al., 2021)
Vegetable trimmings	Composting + drying	Plant-based flour	Fortified bakery products	Pathogen elimination; moisture reduction	(Eriksson et al., 2021)
Soybean residue (okara)	Pressing + enzymatic treatment	Prebiotic fiber	Nutraceutical formulation	Fiber quality analysis; mycotoxin check	(Nosratabadi et al., 2020)
Spent coffee grounds	Drying + oil extraction	Antioxidant oil	Natural additive for confectionery	Solvent residue check; sensory stability	(Mazlounian et al., 2020)
Coconut husk, cassava peel	Alkaline treatment + fermentation	Biodegradable packaging film	Edible food contact surface	Migration test; microbial safety	(Mustamin et al., 2020)

Table 3 summarizes studies focusing on the valorization of food by-products through mechanical and physicochemical processing methods. The majority of these works applied particle size reduction techniques such as milling, grinding, and micronization to raw materials including cereal brans, legume husks, and dried vegetable residues. These methods are primarily intended to increase the surface area for subsequent processing steps, improve the functional properties of powders (e.g., water-binding capacity, solubility, dispersibility), and facilitate the release of bound bioactive compounds. A smaller portion of the reviewed studies utilized physicochemical

treatments such as pH adjustment, enzymatic pretreatment, and food-grade solvent extraction to enhance protein solubility, reduce antinutritional factors, or liberate bioactive peptides.

Several studies also reported parallel approaches in waste-to-resource processing, such as fortification of bakery products with dietary fiber from agro-industrial residues (R. Amelia & Harahap, 2022; Lestari & Pratama, 2020; Subekti & Wibowo, 2020) and the application of natural antimicrobials in active packaging films (Andayani et al., 2021)(Wulandari & Pertiwi, 2022). Furthermore, edible coatings enriched with bioactive compounds from underutilized plant sources have been proven to extend shelf life while ensuring microbial safety (Setyawan & Nuraini, 2020; Trisnawati & Widodo, 2021). From a food safety perspective, mechanical methods are inherently limited in their ability to reduce microbial load or inactivate pathogens. Therefore, they are frequently integrated with thermal or chemical preservation steps to ensure product stability during storage. Physicochemical treatments, while offering enhanced nutritional and functional properties, carry potential safety considerations, including residual solvents, incomplete neutralization of antinutritional factors, and the need for chemical residue monitoring to comply with regulatory standards.

Comparatively, mechanical processing is low-cost, energy-efficient, and easily scalable for small- and medium-scale enterprises, making it an attractive option in resource-limited settings. However, its limited capacity to address microbial safety requires complementary interventions. Physicochemical methods can yield significant improvements in nutrient bioavailability and functional properties, yet their higher operational complexity and safety monitoring requirements can pose barriers to widespread adoption.

Current research gaps include the lack of integrated processing pipelines that combine mechanical and physicochemical steps for maximum valorization efficiency and safety assurance. Furthermore, few studies have examined the impact of these methods on specific safety endpoints such as mycotoxin reduction, heavy metal bioaccessibility, or allergenicity under real-world production and distribution conditions. Addressing these gaps could strengthen both the safety and market competitiveness of valorized products derived from zero-waste food processing chains.

3.2 Integration of Food Safety in Zero-Waste Processing

While zero-waste food processing technologies offer promising solutions for sustainability and resource efficiency, the integration of food safety protocols is essential to ensure that valorized or repurposed materials are safe for human consumption. Unlike conventional food processing, zero-waste systems often deal with by-products, residues, or unconventional materials—posing unique challenges in terms of microbial stability, chemical contamination, and allergen management.

In the reviewed studies, a majority of authors emphasized the importance of combining zero-waste practices with rigorous safety validation steps, especially when dealing with waste materials that are reintroduced into the food chain. These include pre-consumption testing, contaminant profiling, shelf-life assessment, and hygiene monitoring throughout the transformation process (Nosratabadi et al., 2020). Safety risks are not inherently higher in valorized products, but they require customized handling protocols, depending on the nature of the waste input and the intended use. For example, fruit peel fermentation requires pH stability to inhibit pathogenic growth, while animal-derived waste valorization requires heavy metal and allergen screening. Table 4 outlines the most frequently applied food safety validation procedures identified in the reviewed literature, categorized by processing method and final product type.

Table 4. Food safety validation strategies in zero-waste food processing

Processing Method	Food Waste Input	Final Product	Food Safety Risks	Validation Measures	Reference
Fermentation	Fruit peels (mango, pineapple)	Probiotic drink/powder	Pathogen growth; pH instability	pH tracking; lactic acid bacteria count	(Galanakis et al., 2022)
Drying (vacuum, microwave)	Banana peel, leafy greens	Flour or powder	Microbial residue; moisture retention	Water activity analysis; microbial plating	(Eriksson et al., 2021)
Enzymatic hydrolysis	Fish skin, shrimp shell	Protein extract	Heavy metals; allergenicity	ICP-MS metal scan; ELISA allergen test	(Peydayesh et al., 2021)
Upcycled packaging	Cassava peel, coconut husk	Biodegradable film	Chemical migration; contamination	Migration simulation test; surface swab	(Mustamin et al., 2020)
Compost-based valorization	Vegetable trimmings	Bakery fiber additive	Spoilage organisms	Heat treatment validation; microbial count	(Rizki et al., 2020)
Extraction (ultrasound-assisted)	Coffee waste, grape seed	Polyphenol-rich oil	Solvent residue; oxidative rancidity	Residual quantification; solvent peroxide value test	(Mazlounian et al., 2020)

Table 4 presents studies employing biological valorization approaches other than traditional fermentation, including solid-state fermentation (SSF) with non-conventional microorganisms, bioconversion using insect larvae, and controlled sprouting or germination of grains and legumes. These methods are primarily aimed at enhancing the nutritional, functional, and safety attributes of by-products while minimizing waste generation. SSF using filamentous fungi such as *Aspergillus oryzae* or *Rhizopus oligosporus* has been shown to increase free amino acids, release bound phenolics, and improve antioxidant capacity, with certain strains also producing antimicrobial metabolites that enhance food safety. Additional insights come from research on composite packaging trays derived from starch and protein blends, which offer mechanical strength improvements without compromising biodegradability (Firdaus & Nugroho, 2021; Salim & Triawan, 2020). Similar advances in polymer blends for food-contact applications have been developed using lignocellulosic fibers from agro-waste streams (Halimatussadiyah & Fitriani, 2020; Kusumaningrum et al., 2021). These technologies highlight the expanding opportunities for replacing petroleum-based plastics with sustainable alternatives in the food sector. Insect-based bioconversion—commonly using *Hermetia illucens* (black soldier fly) larvae—has gained attention for its efficiency in converting organic residues into protein- and lipid-rich biomass. However, microbial safety concerns remain, particularly regarding pathogen carryover from substrates and the potential accumulation of heavy metals. These risks necessitate strict substrate quality control and post-harvest decontamination steps, such as blanching, irradiation, or high-pressure processing.

Controlled germination, meanwhile, enhances the bioavailability of vitamins, minerals, and bioactive compounds while reducing certain antinutritional factors like phytic acid. Nonetheless, improper germination conditions can favor the growth of spoilage fungi or bacteria, which must be mitigated through hygienic practices, temperature control, and monitoring of water. From a comparative standpoint, SSF offers the advantage of high-value bioactive production and intrinsic microbial control when appropriate strains are used, though process standardization is still lacking for industrial-scale applications. Insect-based systems deliver rapid biomass conversion and contribute to circular economy goals but face consumer acceptance and stringent safety validation challenges. Germination is low-cost and nutritionally beneficial but requires precise environmental control to prevent contamination.

Research gaps persist in the integration of these biological approaches with downstream safety validation. Few studies have conducted comprehensive hazard analyses—covering microbiological, chemical, and allergenic risks across multiple valorization methods using standardized protocols. Closing these gaps would enhance both the scientific robustness and commercial viability of biological valorization strategies in zero-waste food processing.

3.3 Sustainable Packaging and Shelf-Life Extension

Packaging plays a critical role in the food supply chain—not only for protection and convenience but also in reducing post-processing waste. In the context of zero-waste food processing, innovations in eco-friendly packaging and natural preservation methods are increasingly integrated to prolong shelf life while minimizing environmental impact. Recent studies have shown a growing interest in using edible films, biodegradable biopolymers, and active packaging systems derived from food processing by-products. These include starch from cassava peels, cellulose from fruit skins, and protein hydrolysates from fish waste, which can serve as barrier-forming agents or carriers for antimicrobial compounds (Mustamin et al., 2020; Peydayesh et al., 2021). Such packaging systems not only replace conventional plastics but also contribute to preserving the safety and quality of the product throughout its distribution. Furthermore, natural antioxidants and antimicrobials extracted from food waste (such as polyphenols and essential oils) are increasingly incorporated into packaging matrices, serving dual functions: preservation and sustainability. Table 4 presents selected examples of sustainable packaging innovations identified in the reviewed literature, along with their waste source, functionality, and food safety role.

Table 4. Sustainable packaging innovations supporting zero-waste and food safety

Material Source	Packaging Type	Functional Role	Food Waste Origin	Safety & Shelf-Life Benefit	Reference
Cassava starch peel	Edible film	Moisture barrier	Cassava processing	Biodegradable, safe for direct contact	(Mustamin et al., 2020)
Fish hydrolysate protein	Coated wrapping	Oxygen and odor barrier	Fish waste	Antimicrobial, reduces spoilage	(Peydayesh et al., 2021)
Banana leaf fiber	Biopolymer tray	Structural support	Banana plantation waste	Decomposable, chemical-free	(Eriksson et al., 2021)
Coffee extract	Active film with antioxidant	Lipid oxidation inhibitor	Spent coffee grounds	Extends shelf life of oily products	(Mazloumian et al., 2020)

Material Source	Packaging Type	Functional Role	Food Waste Origin	Safety & Shelf-Life Benefit	Reference
Apple pectin	pomace Gel coating for fruits	Shelf-life extender	Apple juice product	Prevents surface browning, safe for raw use	(Galanakis et al., 2022)

Table 4 compiles studies utilizing integrated zero-waste processing systems, where multiple valorization methods—mechanical, physicochemical, biological, and emerging technologies—are combined into a unified processing chain. Such integration aims to maximize resource recovery, improve functional properties, and ensure comprehensive food safety assurance from raw material handling to final product storage. Examples include combining milling with enzymatic hydrolysis and subsequent spray-drying to produce stable functional powders, or pairing fermentation with non-thermal preservation techniques such as pulsed electric field processing to extend shelf life while maintaining bioactive integrity.

From a safety perspective, integrated systems offer a layered defense mechanism, addressing different hazard categories at multiple stages. For instance, initial mechanical or physicochemical treatments may reduce physical contaminants and antinutritional compounds, followed by biological processes that inhibit pathogenic microbes, and finalized by preservation steps that secure microbial stability during distribution. However, the complexity of such systems also increases the risk of cross-contamination if process flows are not strictly controlled, and may require advanced hazard analysis and critical control point (HACCP) frameworks tailored to multi-step processes. Innovative preservation strategies have also incorporated functional extracts from marine and agricultural by-products into edible films, enhancing both barrier properties and antimicrobial activity (Ramadhan & Aditya, 2020; Yuliana & Raharja, 2021; Yunita & Pramono, 2021). In addition, the application of zero-waste principles in small-scale fish processing has been shown to improve both economic returns and compliance with food safety standards (Latifah & Susilowati, 2022; Maharani & Arsyad, 2021). These findings align with the broader movement toward circular economy models in food technology.

The key advantage of integrated processing lies in its potential for synergistic effects: combining methods can offset the weaknesses of individual techniques while enhancing their strengths. For example, thermal extraction's nutrient degradation can be mitigated by post-treatment with non-thermal preservation, or fermentation variability can be reduced by applying standardized pre-processing steps. Nonetheless, the main limitations include high capital investment, increased energy demands in multi-step operations, and the need for cross-disciplinary expertise to operate and monitor such systems effectively.

Despite the promising results in laboratory-scale studies, there is a clear gap in pilot-scale and industrial-scale trials of integrated zero-waste systems. Very few published works provide long-term safety and quality monitoring data under actual supply chain conditions. Additionally, there is limited literature on the economic feasibility and life cycle assessment (LCA) of such integrated approaches. Future research should focus on scaling these systems, validating them against international food safety standards, and optimizing their design for both environmental sustainability and market acceptance.

While the mapped zero-waste pathways consistently improve functional outcomes (e.g., yields, antioxidant retention, and preservation performance), safety validation is uneven across the corpus. Most studies remain laboratory-scale with short observation windows and heterogeneous endpoints (e.g., microbial counts vs. log-reduction; overall vs. specific migration), which limits comparability and external validity. Controls are often minimal (or absent), sample sizes are small, and analytical QA/QC is inconsistently reported. Moreover, food-contact safety is frequently inferred from physicochemical proxies rather than standardized migration/allergenicity protocols, complicating regulatory assessment and scale-up. To mitigate bias from these design features, we used a narrative synthesis with vote-counting and performed a sensitivity check excluding single-arm or non-food-contact studies; the overall direction of findings did not change. Taken together, these limitations underscore the need for pilot-scale trials with harmonized safety endpoints and transparent reporting standards (S. Amelia & Harahap, 2022; S. Gunawan & Aulia, 2021; Mustamin et al., 2020; Peydayesh et al., 2021).

4. CONCLUSION

This systematic review shows that zero-waste food processing has diversified across materials and methods while remaining uneven in safety validation. Based on the 40 included studies (2020–2025), the distribution by primary valorization technique is led by film formation and fortification (each 8/40), followed by extraction (non-UAE) and edible coating (each 5/40). Smaller

clusters appear in composites/trays and UAE (each 3/40), while fermentation and process/circular integration are under-represented (each 2/40). This pattern indicates that, although functional outcomes are widely explored (e.g., preservation performance, antioxidant retention, texture and stability), technology choices concentrate in packaging/ingredient routes rather than process-level integrations. Across all pathways, food-safety validation remains inconsistent. Many studies assess functional properties without standardized microbiological endpoints (counts vs. log-reduction), lack chemical-migration or allergenicity testing, and are confined to laboratory-scale trials with short observation windows. These limitations reduce comparability, hinder regulatory confidence, and slow transition to industrial practice particularly for small- and medium-scale processors that require clear safety playbooks. Real-world distribution, shelf-life stability under stressors, and basic techno-economic evidence are rarely reported. Future work should therefore prioritize three advances: Pilot-scale trials with harmonized safety endpoints at minimum microbial log-reduction, chemical migration (relevant simulants), and, where applicable, allergenicity screening; Integrated sustainability evidence pair process data with LCA and fit-for-purpose cost metrics to demonstrate environmental and economic viability; Regulatory-ready implementation co-develop HACCP-aligned validation protocols and practical guidance for SMEs, focusing on multi-step valorization lines (e.g., extraction→incorporation, fermentation→drying→packaging). Strengthening these areas will increase the scientific robustness of zero-waste valorization and accelerate translation into commercially viable, safety-assured, and sustainable food systems.

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