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FOOD INDUSTRY WASTE MANAGEMENT: CURRENT STATUS, TECHNOLOGIES, VALORIZATION AND POLICY PATHWAYS: NARRATIVE REVIEW

Narrative Review

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ABSTRACT

Background: Food industry waste has emerged as a significant global concern, creating environmental, economic, and social challenges across theentire supply chain. These wastes, which include processing residues, packaging discards, and post-consumer fractions, contribute to greenhouse gas emissions, resource depletion, and public health risks if not effectively managed. At the same time, they represent an untapped resource for energy generation, nutrient recovery, and the production of high-value compounds, making their sustainable management crucial for both environmental protection and economic resilience.

Objective: The purpose of this review is to synthesize current evidence on food industry waste generation, characterization, treatment options, and valorization strategies. It aims to highlight recent technological advances, assess policy and market drivers, and identify barriers that hinder the transition toward circular food systems.

Main Discussion Points: Key themes include the scale and classification of global and regional food wastes, with particular emphasis on hotspots in fruit and vegetable processing, dairy, brewery, and meat industries. Treatment and valorization technologies discussed include anaerobic digestion, composting, thermal conversion processes, fermentation, extraction methods, and the use of by-products as animal feed. Recent innovations such as cold plasma, enzymatic hydrolysis, and multi-physics processing are evaluated for their potential scalability. Policy frameworks, regulatory measures, and economic instruments that facilitate waste reduction and valorization are critically examined, alongside case studies that illustrate successful applications.

Conclusion: Findings indicate that integrating prevention, redistribution, and technological valorization can substantially reduce environmental impacts while creating economic opportunities. Harmonized measurement frameworks, supportive policies, and market development for novel co-products are essential to accelerate progress. Future research should focus on standardized data collection, large-scale trials of emerging technologies, and policy models tailored to low-resource settings to ensure equitable global implementation.

Keywords: Food waste, Valorization, Circular economy, Anaerobic digestion, Policy frameworks, Narrative review.

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INTRODUCTION

Global food systems generate significant amounts of by-products and wastes throughout the supply chain, ranging from pre-harvest losses and processing residues to packaging waste and post-consumer discards. These waste streams often contain organic matter, nutrients, microorganisms, polymers, and contaminants, which if left unmanaged, contribute to greenhouse gas (GHG) emissions, resource depletion, and environmental pollution while simultaneously representing a considerable loss of economic value (1,2). The magnitude of this issue has gained increasing global attention as food waste has been linked not only to environmental degradation but also to public health concerns, food insecurity, and economic inefficiencies (3). Despite recognition of the scale of this problem, current strategies for managing food system wastes remain fragmented and uneven across regions. Studies have demonstrated that processing and manufacturing industries, retail outlets, and food service sectors contribute significantly to global waste volumes, yet a large proportion of these by-products are still disposed of through landfilling or incineration rather than being directed toward recovery or valorization pathways (4,5). While technologies such as anaerobic digestion, composting, and bio-refining have emerged as potential solutions, their adoption is inconsistent, limited by economic, technical, and regulatory barriers (6).

In addition to technical approaches, policy frameworks and market incentives play a decisive role in determining whether food system wastes are viewed as liabilities or resources. International initiatives promoting circular economy models and sustainable development have called for stronger regulatory measures, better infrastructure, and consumer awareness to reduce food loss and valorize unavoidable waste streams (7,8). However, substantial knowledge gaps remain in terms of quantitative global and regional estimates of waste generation, comparative efficiency of available treatment technologies, and the effectiveness of policy interventions across different socioeconomic contexts. This review is therefore undertaken to synthesize the current evidence on food system waste generation, quantify global and regional burdens, evaluate existing treatment and valorization strategies, and analyze policy and market instruments that can foster circularity. The objective is to provide a consolidated understanding of both the challenges and opportunities in transforming food system waste management into a sustainable and economically viable model (9).

Magnitude of the problem: global and regional data

The scale of food waste has emerged as a critical global challenge, with recent assessments estimating that over one billion tonnes of food waste are generated annually at the consumer, retail, and service levels (1). When combined with upstream losses in production and supply chains, the total wastage increases to approximately 1.3–1.6 billion tonnes, equivalent to nearly one-third of all food produced globally (2). Household-level contributions remain dominant, accounting for nearly 60% of food waste, followed by the food service sector at 28% and retail at 12% (3). On a per capita basis, waste generation ranges between 74 and 132 kg per person annually, although significant regional variations exist due to differences in socioeconomic status, infrastructure, and cultural consumption patterns (4). These statistics highlight the magnitude of inefficiency embedded within food systems and underscore the urgent need for interventions that address both environmental impacts and nutritional inequities.

Classification of food industry wastes

Food industry wastes are diverse and can be classified according to their origin, composition, and hazard potential. By origin, they include processing residues, packaging discards, brewery and distillery effluents, fruit and vegetable pomace, and meat or seafood by-products (5). Composition-based categorization distinguishes between high-moisture organic fractions, lignocellulosic residues, fats/oils/greases, and synthetic packaging materials. Hazard-based classifications emphasize wastes that may carry contaminants, allergens, or persistent organic pollutants. Such classifications are essential for determining appropriate valorization strategies and regulatory requirements.

Typical compositions and hotspots

Processing plants represent hotspots of waste generation, with outputs varying by commodity type. Fruit and vegetable industries produce moisture-rich pomace high in fibers, sugars, and micronutrients (6). Meat processing facilities yield protein- and fat-rich offal with significant microbial risks, while the dairy sector generates whey, an underutilized but nutritionally valuable by-product. Grain

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milling and bakery industries create starchy residues that can be directed toward feed or fermentation. These compositional characteristics determine the suitability of waste streams for specific valorization pathways.

Treatment and valorization technologies

A broad spectrum of technologies has been developed to manage food industry wastes, each with specific benefits and limitations. Valorization approaches increasingly focus on resource recovery rather than disposal, aligning with circular economy principles (7). The main categories include source reduction and redistribution, anaerobic and aerobic biological treatments, thermal conversion, biochemical processing, and feed applications. Emerging innovations seek to overcome persistent barriers such as feedstock heterogeneity and regulatory constraints.

Source reduction and redistribution

Prevention remains the most effective strategy, with interventions targeting improved supply chain forecasting, cold chain maintenance, and innovative packaging solutions to extend shelf life (8). Redistribution through food banks and feed donation further reduces avoidable waste while enhancing food security. These approaches yield immediate social benefits but require infrastructure, policy support, and consumer participation.

Anaerobic digestion (AD)

AD is the most widely implemented technology for high-moisture organics, converting wastes into biogas and nutrient-rich digestate. Co-digestion with manure or energy crops improves stability and methane yields. However, challenges such as ammonia inhibition, foaming, and variable feedstock composition persist (9). Europe and North America lead in AD deployment, supported by policy incentives, whereas adoption in low- and middle-income countries remains limited due to high capital costs.

Composting and aerobic biological treatments

Composting remains a low-cost option, transforming organic wastes into soil conditioners. In-vessel and vermicomposting approaches provide enhanced control over microbial activity and nutrient recovery. Nevertheless, contamination with plastics and the need for pre-treatment remain obstacles (10). Aerobic treatments are particularly suited to decentralized waste streams but require careful management of carbon-to-nitrogen ratios.

Thermal conversion (incineration, gasification, pyrolysis)

Thermal technologies offer rapid volume reduction and energy recovery. Incineration with energy capture is established in high-income regions with stringent emission controls (11). Gasification and pyrolysis are emerging options that generate syngas, bio-oil, and biochar, with biochar providing additional benefits in carbon sequestration and soil amendment. However, cost, emissions management, and ash disposal remain major concerns.

Biochemical valorization: fermentation and extraction

Fermentation processes enable the production of bioethanol, volatile fatty acids, and single-cell proteins from carbohydrate-rich wastes. Similarly, extraction techniques recover antioxidants, polyphenols, and pigments, which are increasingly utilized in nutraceuticals and cosmetics (12). While promising, these processes are constrained by the need for clean feedstocks, market demand for recovered products, and regulatory approvals for novel food ingredients.

Use as animal feed

Utilizing wastes as animal feed is one of the oldest valorization practices, particularly for bakery residues, whey, and spent grains. However, strict safety regulations are necessary to prevent pathogen transmission and ensure nutritional adequacy (13). Advances in feed processing technologies have expanded the range of usable waste fractions, though cost and consumer acceptance remain barriers.

Emerging tech: cold plasma, enzymatic hydrolysis and multi-physics processing

Cutting-edge technologies such as cold plasma and enzymatic hydrolysis are being explored to break down complex polymers into fermentable sugars and bioactive compounds (14). Multi-physics processing that combines mechanical, thermal, and biological approaches is also being tested at pilot scales. Although these innovations hold significant promise, their scalability and economic viability are yet to be demonstrated.

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Environmental and economic assessment

Life cycle assessments (LCAs) consistently demonstrate that valorization strategies reduce GHG emissions compared to landfilling or uncontrolled dumping (15). AD, for instance, not only offsets fossil fuel use but also provides digestate that improves soil fertility. Economic analyses highlight that profitability depends on market conditions such as energy prices, policy incentives, and demand for co-products. The lack of standardized frameworks for assessing trade-offs remains a challenge.

Policy, regulation and market instruments

Successful waste management requires supportive policy instruments. Examples include landfill bans, mandatory source segregation, extended producer responsibility (EPR), and financial incentives for renewable energy recovery (16). Market-based instruments such as pay-as-you-throw schemes encourage behavioral change at the household level. Harmonized monitoring tools, including the Food Waste Index, are critical for benchmarking progress.

Case studies and sector-specific considerations

Brewery and distillery

Breweries generate large volumes of spent grains rich in protein and fiber, commonly used as feed or substrates for fungal fermentation. Recent studies highlight their potential for producing biomaterials and enzymes (17).

Dairy

The dairy sector's whey by-product has transitioned from a disposal problem to a valuable input for producing protein concentrates and lactose-derived chemicals. Advances in membrane technologies have further improved recovery efficiency (18).

Fruit and vegetable processing

Pomace from fruit and vegetable processing contains polyphenols, fibers, and pectins, which are extracted for use in food additives and nutraceuticals. Drying and extraction technologies have enhanced the viability of these valorization routes (19).

Technical and implementation challenges

Despite technological advances, significant barriers persist. These include logistical difficulties in collecting perishable wet wastes, contamination with packaging materials, fluctuating feedstock quality, and limited markets for digestate or compost (20). Additionally, regulatory hurdles surrounding novel feed and food products constrain commercialization. Access to capital investment is another limiting factor, particularly in low-income regions.

Data sources, metrics and monitoring

Reliable data remain essential for designing effective interventions. Global datasets such as the FAO Food Loss Index and UNEP Food Waste Index provide standardized metrics, while national inventories and facility-level surveys contribute to regional assessments (5). Key indicators include waste mass (tonnes), per capita generation (kg/year), carbon footprint (CO_2-eq/tonne), and economic recovery value. However, disparities in methodologies complicate global comparisons, underscoring the need for harmonized reporting frameworks.

CRITICAL ANALYSIS AND LIMITATIONS

The existing literature on food waste management and valorization provides important insights but is characterized by several critical limitations that restrict the strength and generalizability of its conclusions. A key issue lies in the lack of standardized reporting methods across regions and value chains. Different studies employ varying definitions of food waste, diverse system boundaries, and inconsistent metrics, which complicates comparison and synthesis of results at a global level (10,11). This methodological heterogeneity leads to uncertainty in estimating both the scale of food losses and the effectiveness of interventions. Another important limitation is the frequent reliance on small-scale or pilot studies when evaluating pretreatment and valorization technologies. While such studies demonstrate technical feasibility, their scalability to industrial levels remains uncertain. For example, enzymatic hydrolysis and plasma-assisted technologies show promising laboratory outcomes but have yet to be validated under real-world operational conditions where mixed and contaminated food waste streams dominate (12). The absence of robust field-scale trials limits confidence in their long-term

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economic and environmental viability. The integration of digital technologies such as artificial intelligence (AI) and the Internet of Things (IoT) for supply-chain optimization has been widely proposed but remains underrepresented in empirical research. Most available studies are either conceptual frameworks or case-specific applications, often conducted in high-income regions with advanced infrastructure. This creates a risk of selection bias, as findings may not reflect realities in low-resource settings where refrigeration, transport, and monitoring infrastructures are limited (13,17). Moreover, there is limited exploration of potential confounding factors, such as energy requirements of digital tools themselves, which may offset some sustainability gains.

Market development for novel valorization products—including volatile fatty acids, single-cell proteins, and biochar—represents another underexplored area. Although laboratory studies have confirmed their functional properties and potential health or agricultural benefits, the literature often neglects market acceptance, regulatory approval, and consumer perception (14,18). This omission creates a gap in understanding how promising bioproducts can transition into commercially viable commodities. The lack of long-term follow-up data further limits evaluation of their scalability and safety. Publication bias also appears to influence the field, as studies frequently highlight the benefits of valorization pathways while underreporting inconclusive or negative results. For instance, failures of anaerobic digestion plants due to ammonia inhibition or economic non-viability are less frequently documented than successful pilot demonstrations (19). This selective reporting may create an overly optimistic impression of technological readiness. Variability in measurement outcomes adds further complexity. Some studies focus primarily on waste mass reduction, while others emphasize energy recovery, greenhouse gas mitigation, or nutrient recycling. Without harmonized indicators, it becomes challenging to compare performance across technologies or regions. The generalizability of findings is also restricted, as much of the empirical evidence is concentrated in Europe and North America, with limited data from Asia, Africa, and Latin America where the majority of food production and waste occurs (20). Overall, while the literature has expanded rapidly in recent years, it remains fragmented and uneven. There is a clear need for harmonized global reporting frameworks, large-scale trials of emerging technologies, and policy designs tailored to low-resource contexts. Addressing these gaps is essential to ensure that strategies for food waste reduction and valorization are not only scientifically robust but also socially equitable and practically implementable worldwide.

IMPLICATIONS AND FUTURE DIRECTIONS

The evidence synthesized in this review holds important implications for practice, policy, and future research. In clinical and public health contexts, the findings underscore the indirect but significant role of food system waste in influencing population health outcomes. Poorly managed food waste streams contribute to environmental pollution, greenhouse gas emissions, and microbial contamination, all of which are linked to increased burden of respiratory, gastrointestinal, and non-communicable diseases (21). Thus, integrating food waste reduction and valorization strategies into broader health promotion frameworks can support preventive care by reducing exposure to environmental risk factors and improving food and nutrition security, particularly in vulnerable populations. From a policy-making perspective, the review highlights the urgency of developing harmonized reporting methods and metrics across regions and value chains. Current fragmentation in data collection impedes accurate cross-country comparisons and undermines global accountability (22). Policies must move beyond general waste management regulations and incorporate specific frameworks that incentivize food waste reduction, valorization, and circular economy practices. This includes creating supportive environments for scalable pretreatment technologies, ensuring safety standards for novel feed and food applications, and designing regulatory pathways for emerging valorization products such as volatile fatty acids, single-cell protein, and biochar (23). Furthermore, policy design must be tailored to the realities of low-resource settings where infrastructure for refrigeration, storage, and transport is limited. Context-sensitive strategies such as decentralized anaerobic digestion or community-based redistribution programs may prove more feasible and equitable in such environments (24).

The review also brings into focus several unanswered questions that should guide future research. There is a clear need for standardized methodologies to ensure reliable reporting of waste volumes and outcomes of interventions. Moreover, gaps remain in the scalability of pretreatment technologies for mixed and contaminated waste streams, which continue to represent a major bottleneck. While digital innovations such as artificial intelligence and the Internet of Things are increasingly advocated for supply-chain optimization, empirical evidence on their real-world implementation, energy trade-offs, and long-term sustainability remains sparse (25). Similarly, the market acceptance, regulatory approval, and safety evaluation of novel valorization products are poorly documented, creating uncertainty around their integration into mainstream applications. Future research must therefore adopt more rigorous and inclusive study designs. Large-scale, longitudinal trials are required to validate the performance and economic viability of emerging technologies under diverse operational conditions. Comparative studies across regions should be prioritized to ensure findings are generalizable beyond high-

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income settings, with particular attention to low- and middle-income countries where food insecurity and waste coexist at critical levels. Mixed-methods approaches that combine life cycle assessment with social and economic evaluation will be vital in capturing the multi-dimensional impacts of interventions (26). Incorporating digital monitoring tools in future studies can further improve data quality, but such tools must be evaluated for accessibility, scalability, and equity. In sum, the implications of this review emphasize that addressing food system waste is not solely a matter of environmental management but an essential component of advancing public health, achieving sustainability goals, and fostering resilience in global food systems. The future of research lies in harmonizing data, validating scalable technologies, and embedding equity-driven policy interventions that ensure solutions are adaptable across diverse global contexts.

CONCLUSION

This review demonstrates that a combination of prevention, redistribution, and technological valorization represents the most effective pathway to mitigate the environmental and economic burden of food industry wastes. Evidence consistently shows that source reduction and redistribution can immediately decrease waste volumes while enhancing food security, whereas advanced valorization technologies such as anaerobic digestion, fermentation, and biochemical extraction provide opportunities to recover energy, nutrients, and high-value co-products. Although the existing literature supports the potential of these interventions, variability in methodologies, limited large-scale validation, and regional disparities reduce the overall strength and generalizability of current evidence. Practical recommendations include the adoption of harmonized reporting frameworks, the scaling of safe and cost-effective technologies, and the development of supportive policy and market incentives that can embed circularity within food systems. Future research must focus on standardized global metrics, field-scale trials of emerging technologies, and equity-oriented policies that ensure adaptability to low-resource settings, thereby advancing sustainable, resilient, and health-promoting food systems worldwide.

AUTHOR CONTRIBUTION

Author	Contribution
Muhammad Usama Aslam*	Substantial Contribution to study design, analysis, acquisition of Data Manuscript Writing Has given Final Approval of the version to be published
Esha Aslam	Substantial Contribution to study design, acquisition and interpretation of Data Critical Review and Manuscript Writing Has given Final Approval of the version to be published
Muhammad Shahbaz*	Substantial Contribution to acquisition and interpretation of Data Has given Final Approval of the version to be published

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