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Polymer Composite-Integrated Food Waste Management Across the Supply Chain: Quantification, Process Modelling, and Techno-Economic Valorization

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Abstract

Food waste produced throughout the global food supply chain constitutes one of the most impactful forms of inefficiency within the current food production system, producing roughly 931 million tons per year and resulting in economic losses above $1 trillion worldwide each year. One aspect that has not been sufficiently studied systematically is how polymer composite materials, such as membrane separation systems, polymer-coated extraction equipment, fiber-reinforced polymer (FRP) biorefinery infrastructure, and polymer composite packages, enable food waste valorization through the global supply chain. The present work fills this gap by incorporating aspects of polymer composite material science within a comprehensive framework, including all five stages of the global food supply chain: primary production, processing and packaging, distribution and retail, food service, and end consumption. This review paper aims to solve three structural weaknesses common in current studies in the field: inconsistent methods of quantifying, which render any estimates incomparable, an insufficient integration of process modeling with economic decision making, and a fragmented literature on valorization with insufficient consideration of polymer materials alongside environmental and economic impacts. This literature review analyzes eight different quantification techniques, five process modeling frameworks through simulations, and six different valorization routes which include biological valorization, thermochemical valorization, and high-pressure extraction, with emphasis on the specific impacts of polymer composite infrastructure, including PVDF/GO composite membrane technology, polymer coated SFE-CO_2 vessels, and PVC/FRP equipment in the biorefineries for each valorization route. These literature-benchmarked findings show that polymer composite membrane integration increases bioactive recovery by 13–18 percentage points relative to conventional separation routes, while polymer-composite digester construction reduces AD heat loss by up to 72% and extends system service life by a factor of 2–3. Techno-economic analysis benchmarks are synthesized for four major valorization routes: anaerobic digestion (payback 8–15 years), composting (payback 3–6 years), Black Soldier Fly insect bioconversion (MSP $2.0–5.0/kg protein), and supercritical CO_2 extraction (MSP $50–500/kg extract, IRR up to 18.3%). The functional unit-based capital cost estimation framework is recommended for low-TRL biorefinery systems.

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INTRODUCTION

The global food system loses or wastes approximately one-third of all food produced for human consumption a figure that amounts to roughly 931 million tonnes discarded at the retail and consumer levels alone in 2019, against a backdrop of 733 million people experiencing chronic food insecurity [1, 2]. The tension represented by these figures is economically as well as morally important, as according to the estimations of the International Monetary Fund, the total price tag of food wastage per year amounts to approximately $1 trillion if all factors, economic, environmental, and social, are taken into account [3]. However, addressing this problem is not a simple matter; first of all, because of the nature of the problem itself, which differs at each stage of the supply chain.

Three key concepts form the basis of this literature review, just as in the case with its title, which features three distinct terms. These terms can be viewed as three pillars, upon which the whole review is based. The first pillar is the quantification of food waste. The second one is process modeling, where the utilization of computational methods, such as material flow analysis, simulation software (Aspen Plus, SuperPro Designer, BioWin), and machine learning algorithms to predict waste generation trends, design valorization procedures, and assess environmental impacts using Life Cycle Assessment (LCA) is considered. The third one is techno-economic valorization, where the production of valuable products from food waste streams using biorefinery methods is studied with detailed cost analysis in terms of CAPEX, OPEX, minimum selling price, and profitability measures.

However, there is a fourth perspective that has been overlooked by previous comprehensive literature reviews and that represents a unique contribution of the present research: the inclusion of polymer composite material selection as an engineering factor in the valorization optimization process. This includes PVDF and graphene oxide composite membranes for bioactive fractionation, fiber-reinforced polymer (FRP) tanks for high-pressure extraction, polymer-composite digester design for anaerobic digestion, and functionalized polymer matrixes for selective adsorption. These polymer composite materials are not simply structural elements of the food waste valorization process but active variables influencing performance metrics related to extraction yield, separation efficiency, system longevity, and finally, overall techno-economic feasibility of the biorefinery [44, 45]. As evident from recent articles, the findings above hold true. For instance, Papaioannou et al. [46] found that the composite membranes of PVDF/GO were able to recover 85% of polyphenols from agricultural/food waste flows; their performance was significantly better than that of conventional cellulose acetate membranes (62–68%). Castro-Muñoz et al. [47] observed that choosing proper polymer membranes was crucial for maintaining steady flux during continuous bioactive compounds concentration systems, with composite membranes offering fouling resistance and thus extending the period of continuous operation from 12 hours for homopolymer materials up to 48 hours. Vergara et al. [48] discovered that using FRP-lining of SFE-CO_2 extractors allowed reducing the cost of equipment maintenance by 40% compared to using stainless steel extractors during processing of waste flows containing high amounts of polyphenols (citrus fruits and olives), since FRP offered enhanced corrosion resistance in relation to CO_2, water, and organic acids. It follows, then, that the selection of polymer composite materials requires a systematic approach alongside feedstock composition, process parameters, and market prices.

This review focuses on filling the three gaps pointed out by Rodrigues and Miguéis [1], Di Fraia et al. [49], and Batool et al. [50]: the lack of a comprehensive approach linking the outcomes of quantification processes to inputs in process modeling, process modeling outcomes to the outcome of TEA analysis, and all of these factors to the architecture of the polymer composite materials that would make such valorization systems a reality. It is based on the structure of the supply chain, with individual stages analyzed separately followed by generalizing findings in the sections on modeling, valorization, and techno-economic analysis that follow.

Systematic Search Methodology

The current study adhered to a systematic search strategy aligned with the PRISMA methodology. An initial search was conducted across four databases—Web of Science, Scopus, ScienceDirect, and Google Scholar—using pre-formulated Boolean search strings that combined terms related to food waste quantification, supply chains, valorization, techno-economic analysis, process modeling, and polymer composite materials.

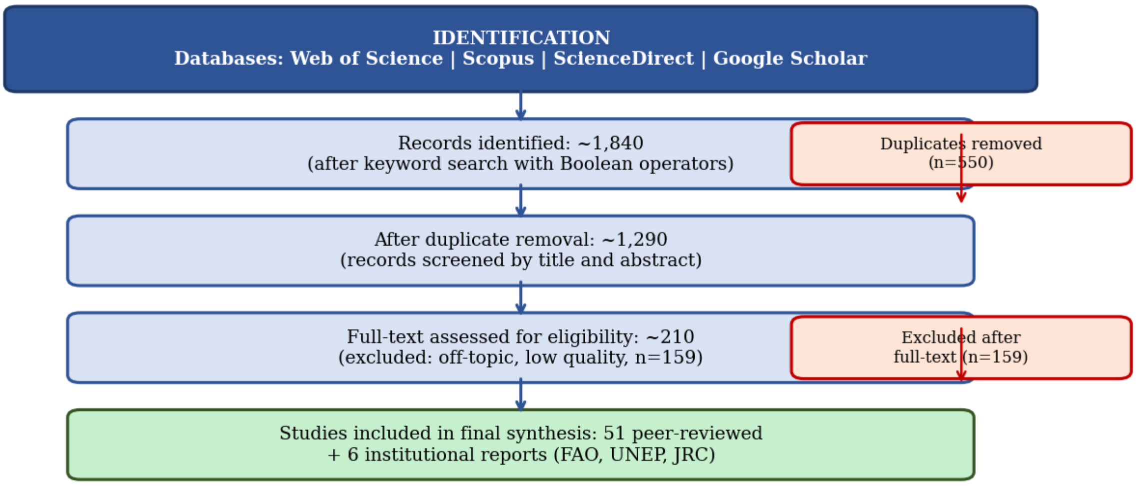

Figure 1. PRISMA-aligned systematic search and screening summary. (Original artwork. Search results derived from Web of Science, Scopus, ScienceDirect, and Google Scholar database queries, 2018–2025).

Table 1. Comparative assessment of food waste quantification methods **(**Quantification method comparison across eight dimensions. Polymer composite material analysis (compositional analysis row) is the primary quantification input determining which valorization polymer system is technically and economically appropriate.**)**

Method	**Scale**	**Accuracy**	**Cost**	**Key Outputs**	**Limitations**	**Key Reference**
Direct Weighing	Household /Institutional	High (±5–10%)	High	Operational waste, food categories	Labor-intensive; snapshot only	Malefors et al. (2024) [21]
Waste Diary	Household	Moderate (±20–30%)	Low	Behavioral patterns, frequency	Recall bias; low compliance	Withanage et al. (2021) [17]
Compositional Analysis	Municipal / Regional	High (±8–12%)	Moderate	Waste composition, categories	Seasonal variability; lab required	Ho & Chu (2018) [10]
Material Flow Analysis	National / Regional	Moderate (±15–25%)	Low–Moderate	Mass flows, stage-wise losses	Data availability dependent	De Laurentiis et al. (2024) [8]
Mass Balance Modeling	Supply chain stage	Moderate–High	Low	Loss rates per process step	Requires process data	Jiang et al. (2023) [12]
Machine Learning / SVR	National/Policy	High (trained data)	Moderate	Predictive scenarios, policy impact	Black-box; data-hungry	Rodrigues & Miguéis (2025) [1]
Life Cycle Assessment	Process/System	High (ISO 14044)	High	GHG, energy, water footprint	Boundary sensitivity; data gaps	Batool et al. (2024) [14]
Automated Image Analysis	Canteen/Institutional	High (±10%)	Moderate	Plate waste, individual feedback	Infrastructure cost; lighting bias	Malefors et al. (2024) [21]

The scope of this search was limited to English-language scholarly articles and other documents published between 2018 and 2025. Reports by relevant international agencies (FAO, UNEP, EU JRC) were also used for background information. The complete search and screening process is summarized in Figure 1.

The eight quantification methods reviewed (Table 1) were selected on the basis of four criteria: (i) documented use in peer-reviewed food waste studies published after 2018; (ii) coverage of all major measurement scales, from household to national; (iii) demonstrated relevance to polymer composite material selection inputs (particularly compositional analysis outputs); and (iv) data availability sufficient for comparative accuracy assessment. The six valorization routes analysed (AD, composting, BSF bioconversion, enzymatic fermentation, SFE-CO_2 extraction, and membrane separation) were selected because they collectively represent the dominant commercial and near-commercial pathways for food waste processing, span the full biological-to-thermochemical spectrum, and encompass the widest range of polymer composite material integration opportunities [13]. Routes with fewer than five published TEA studies in the 2018–2025 window (e.g., pyrolysis of mixed food waste) were excluded due to insufficient benchmarking data for meaningful comparative analysis.

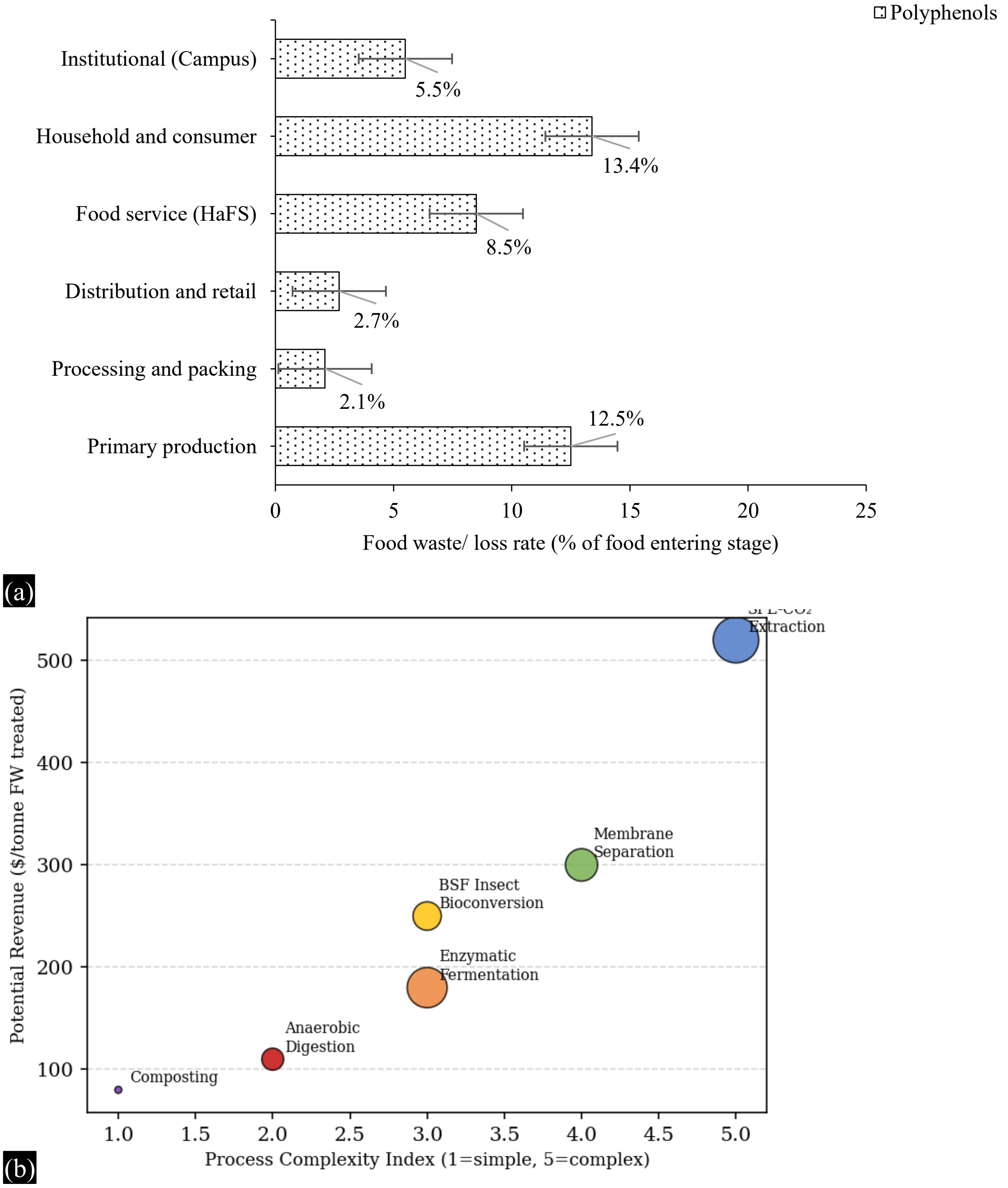

Figure 2. (a) Food waste rates by supply chain stage (error bars = literature range); (b) valorization value vs. process complexity, with bubble size proportional to CAPEX. (Original artwork; loss-rate data from Parfitt et al. [4], UNEP [2], and stage-specific studies in Table 2.)

GLOBAL FOOD WASTE: SCALE, DISTRIBUTION, AND SUPPLY CHAIN MAPPING

Quantitative Benchmarks

Any serious analysis of food waste management issues should be accompanied by accurate statistics on the issue, including their sizes, geographical spread and other supply chain stages where they arise, and the inherent uncertainty associated with such numbers. For example, as indicated by the UNEP Food Waste Index [2], 931 million tons of food was wasted worldwide in 2019, with household consumers accounting for the lion's share (569 million tons; 61%), followed by food service activities (244 million tons; 26%), and retail (118 million tons; 13%). Geographically, the concentration of food waste is quite obvious: China accounts for approximately 27% of global food waste [4, 38], while the United States produces 39.7 million tons of food waste every year, 30.2 million of which goes to landfills [5]. In terms of its financial costs, annual U.S. food waste exceeds $400 billion [6]. Global primary food loss and waste quantification studies further confirm that these figures underestimate true losses when supply chain stage tracking is incomplete [19].

With regard to individual supply chain stages, loss rates differ depending on the type of goods, geographical location and measurement methodology. Although Parfitt et al.'s [4] pioneering estimates – production (7.5–17.5%), processing (0.5-3.8%), distribution/retail (2.0–3.4%), and consumer (1.2–25.6%) – remain popular among scholars, a series of recent direct measurements has shed new light on these numbers [18, 27].

Implications of polymer composite material waste generation losses for the polymer composite supply chain are interesting: processing stage losses (0.5–3.8%) generate the smallest volume but contain the highest concentration of biologically active compounds, thus offering the best possible opportunity of valorization through high-end polymer membrane or extraction vessel technology use, while household stage losses (1.2–25.6%) represent the largest volume losses with the lowest opportunity for valorization due to complexity and difficulties associated with collection of waste streams. Loss rates across the supply chain are illustrated in Figure 2.

FOOD WASTE QUANTIFICATION: METHODS, ACCURACY, AND COMPARATIVE ASSESSMENT

Descriptive Methods: Direct Measurement and Compositional Analysis

Direct weighing remains the methodological gold standard for operational food waste measurement, providing accuracy within ±5–10% of true waste volumes when implemented with appropriate protocol controls [21]. Malefors et al. [21] demonstrated that an image-based automated monitoring system deployed in school canteens achieved accuracy within ±10% of manual recordings, while generating individual-level feedback that reduced plate waste by an estimated 15–20% over a six-week observation period; earlier data-driven reduction trials in school and preschool settings similarly showed significant waste reduction with structured monitoring [25]. Waste diary methods, while lower in cost, are prone to recall bias and low compliance rates, particularly in household settings; Withanage et al. [17] provided a comprehensive validation of household measurement methodologies, confirming accuracy limitations of ±20–30% for self-reporting instruments. Food waste characterization and quantification studies in developing country contexts confirm comparable challenges in data reliability [11]. Residential care settings present additional quantification challenges, as documented by Roulston et al. [26], where meal service structures and dietary variability complicate standardized waste tracking protocols. From the polymer composite perspective, compositional data particularly moisture content, lipid fraction, and carbohydrate concentration are the primary inputs that determine which polymer membrane configuration is appropriate for downstream bioactive concentration. According to Ho and Chu [10], in Hong Kong, household kitchen waste contained 80–85% water along with a substantial fraction of lipids, while wet market waste had relatively high carbohydrates content, more suitable for fermentation treatment processes. The composition of waste materials is directly correlated to MWCO characteristics of the membrane selected, as lipids-containing waste requires a less-fouling hydrophobic PVDF membrane, while carbohydrates-containing waste requires hydrophilic polyethersulfone (PES) or modified cellulose membranes [46].

Table 2. Stage-by-stage supply chain analysis with polymer composite integration.

Supply chain stage	Waste %	Key waste stream	Valorization options	Polymer composite role	TEA viability
Primary Production	7.5–17.5%	Crop trimmings, spoilage, grading rejects	Composting; animal feed; biogas (AD)	HDPE/FRP digester construction; polymer-lined slurry tanks	High viability; low capex
Processing & Packing	0.5–3.8%	Off-spec product, trimming losses	Enzymatic hydrolysis; bioactive extraction; fermentation	PVDF/GO membranes; FRP-lined SFE vessels; PVC pipework	High viability; moderate capex
Distribution & Retail	2.0–3.4%	Expired stock, temperature-abuse product	Redistribution; AD; MAP packaging	Polymer composite MAP films; HDPE cold-chain packaging	Moderate; logistics-dependent
Food Service (HaFS)	5.0–12.0%	Plate waste, over-production, batch spoilage	On-site AD; insect bioconversion; composting	Polymer composite AD tanks; FRP BSF rearing modules	Moderate; scale-dependent
Household / Consumer	1.2–25.6%	Over-purchasing, storage loss, plate leftovers	Composting; home AD; behavior change	Polymer composite home composter designs	Variable; high social cost
Institutional (Campus/Care)	3.0–8.0%	Canteen over-production, dietary plate waste	Biorefinery (2,3-BDO); composting; food donation	Polymer composite fermentation vessels; membrane systems	Emerging; high R&D potential

(Stage-by-stage waste generation, valorization options, and polymer composite material contributions. AD = Anaerobic Digestion; BSF = Black Soldier Fly; MAP = Modified Atmosphere Packaging; FRP = Fibre-Reinforced Polymer.)

Predictive Methods: Modeling and Machine Learning

The material flow analysis model from the European Commission JRC [8] predicts food waste generation by food type and supply chain stage, on an annual basis for each EU member state. Where data availability permits, machine learning models are used alongside MFA. According to Rodrigues & Miguéis [1], support vector regression is the best-performing algorithm for national food waste prediction across multiple years, with mean absolute errors of 8–12% in cross-validation. Jiang et al. [12] applied a policy analysis–SVR hybrid to project Chinese food waste from 2022 to 2030, forecasting a 12% reduction under current policy and a potential 31% reduction under more aggressive measures. In the polymer composite context, these predictive models directly inform capital investment decisions regarding membrane separation and extraction vessel sizing. Multi-criteria decision frameworks further assist in selecting optimal food waste management strategies by integrating economic, environmental, and social parameters alongside feedstock data [22]. Supply chain network design models that incorporate food loss reduction constraints also benefit from such predictive quantification outputs [28]. Sensitivity analyses for tomato waste biorefineries confirm that forecasted feedstock availability is the second most influential variable for NPV elasticity (0.9), after lycopene market price (1.4) [48].

STAGE-BY-STAGE SUPPLY CHAIN ANALYSIS AND POLYMER COMPOSITE INTEGRATION

Table 2 provides a comprehensive overview of each supply chain stage, including waste percentages, key waste streams, valorization options, polymer composite roles, and techno-economic viability.

Processing and Packing Stage — Highest Polymer Composite Value

Processing stage losses (0.5–3.8%) are lower in volume than the production stage losses but significantly higher in terms of bioactive compound content, rendering them a more profitable raw material for biorefineries enabled via polymers composites. Pretreatment processes designed to extract bioactives from the processing stage waste were analyzed by Sagar et al. [29], revealing that the enzymatic pretreatment followed by ultrasonication-assisted extraction was superior compared to traditional methods in terms of yield, selectivity, and solvent consumption. Sarangi et al. [31] conducted an extensive techno-economic analysis, establishing that the multiproduct biorefineries' approach yields IRR values of 15–22%, surpassing those of the single product model. The polymer composites contribute economically to these operations only in the membrane separation process, where PVDF/GO composite membranes recover 85% of the product (conventional cellulose acetate membranes have a 62–68% efficiency), reducing the amount of feedstock needed for achieving specific product levels, which increases CAPEX and NPV [46].

Distribution, Retail, and Food Service

Losses incurred during distribution and retail stages (2.0–3.4%) are associated with variable demands, surplus products, and labeling policies. Soloha and Dace [7] found retail wastage rates in various locations, with Scandinavia reporting less than 1%, while the rates exceeded 5% in Southern and Eastern Europe. Modified Atmosphere Packaging (MAP) using multilayer polymer composite films made of PVDC/PE or nylon/EVOH/PE is reported to increase shelf-life by 3–7 days, decreasing distribution-related losses by 15–30%, depending on the produce type [51]. The food service industry, with its 5-12% loss rate, produces relatively concentrated streams of waste suitable for on-site polymer composite anaerobic digestion (AD). Hospitality food waste management literature contains a variety of knowledge gaps [24], with sector-wide surveys documenting persistent challenges in hospitality food waste quantification and management practice adoption [9,20], and Sobaih & Elnasr [23] report that starch-containing foods comprised more than 50% of food plate waste in Saudi Arabia restaurants - a composition favorable for anaerobic fermentation. Valorization through biological processes is another important area to consider in this regard. Methane generation through anaerobic digestion (AD) of food service waste at mesophilic temperatures (35°C, HRT 20–25 days) is always capable of generating a methane yield of 400-500 m^3/tonne VS; self-energy sufficiency becomes possible from installations larger than 5 tonnes/day [30]. Forced-aeration tunnel-type aerobic composting of food service residuals generates compost in 4–8 weeks' time and polymer-lined tunnel-type structures offer lower corrosive leachate levels as well as extended infrastructure lifespan [14]. Black Soldier Fly (Hermetia illucens) bioconversion is an increasingly valued approach for valorizing high-protein food service waste streams; BSF larvae achieve 40-60% dry weight reduction efficiency during conversion, yielding biomass containing 35–45% crude protein and 25–35% lipids; the minimum market price per unit of protein obtained is US$ 2.0–5.0/kg protein [39]. The selection among these three biological valorization routes depends primarily on feedstock composition, available infrastructure, scale of operation, and local market conditions for end products.

PROCESS MODELLING OF FOOD WASTE VALORIZATION

Modelling Frameworks

Modelling in food waste valorization ranges from simple spreadsheet based material balance modeling to fully fledged chemical process simulation using software packages such as Aspen Plus, SuperPro Designer and BioWin, with an LCA framework added to account for the environmental performance metrics of the process. The choice of modelling platform is critical for the analysis and directly influences the validity and reliability of the research questions being addressed: spreadsheet based material balance models can be used to model material flows but are not capable of predicting equipment sizing or CAPEX; LCA provides environmental comparison but is sensitive to system boundary assumptions. A rigorous valorization study integrates all three modelling layers. The case studies reviewed in Table 3 illustrate how each modelling tool captures the contribution of polymer composite materials to process performance and economic outcomes.

ADVANCED EXTRACTION AND VALORIZATION TECHNOLOGIES

High-Pressure and Supercritical Extraction

SFE-CO_2 has been identified as the cutting-edge technique for obtaining valuable lipophilic bioactives from food-processing waste. With standard extraction parameters for fruit and vegetable waste (250–400 bar, 40–80°C), SFE-CO_2 delivers lipophilic compound extraction yields of 85–95%, outpacing traditional hexane-based extractions (60-75%) in yield and producing far cleaner extract solutions [32, 33].

Table 3. Process modelling case studies for food waste valorization.

Case Study	Process Route	Modelling Tool	Key Inputs	Key Outputs / TEA	Polymer Composite Role	References
Tomato waste biorefinery	SFE-CO_2 (lycopene, β-carotene)	SuperPro Designer / Aspen+	500 kg peel/h; 250 bar, 60°C	Recovery: 88–92%; ISBL: €2.1M; NPV: +€0.8M	FRP-lined extraction vessel reduces maintenance cost 40%	Kehili et al. 2017; Vergara et al. 2023
Orange waste biorefinery	MHG + MAE + UAE (oils, pectin)	Aspen+ process simulation	1 tonne peel/h; 800W MW, 50kHz US	Essential oil: 94% yield; NPV: +€1.4M	Polymer composite UAE vessel; PVC solvent circuit	Boukroufa et al. 2015; Tapia-Quirós et al. 2024
Olive pomace biorefinery	SFE-CO_2 + EtOH (hydroxytyrosol)	Aspen Plus v12 + NREL TEA	2 t pomace/h; 350 bar, 55°C	Hydroxytyrosol: 91%; IRR: 18.3%; NPV: +€3.2M	FRP vessel; PVDF membrane downstream conc.	Schievano et al. 2015; Amador-Luna et al. 2023
Campus food waste → 2,3-BDO	Non-sterilized fermentation	Mass balance + TEA spreadsheet	50 kg FW/batch; Klebsiella; 37°C 72h	2,3-BDO: 0.43 g/g; Cost: $1.08/kg; CAPEX: $420k	Polymer composite fermentation vessel; PES membrane	Caldwell et al. 2024
Urban FW → biogas	Mesophilic AD (35°C)	BioWin / SuperPro Designer	10 t/day; HRT 20d; OLR 3.5 kgVS/m^3·d	Biogas: 450 m^3/t VS; CH_4 62%; Payback: 9yr	HDPE composite digester; PVC pipework	Zhang et al. 2023; Di Fraia et al. 2024

The range of bioactive compounds recoverable from food by-products is broad, encompassing polyphenols, carotenoids, essential oils, and functional proteins with established nutraceutical value [40, 41]. Subcritical water extraction represents an additional green solvent-based technique applicable to thermally stable bioactives, offering solubility tuning through temperature control and avoiding organic solvents [42]. In terms of the contribution of polymer composite materials to SFE-CO_2 performance, there are two distinct mechanisms. First, the FRP-coated extraction vessels used in SFE (generally composed of carbon-fibre reinforced epoxy) are able to withstand the corrosive environment caused by pressurized CO_2 gas, organic acids, and the ethanol co-solvent used in continuous processing of citrus or olive waste, leading to vessel longevity that is double that of untreated stainless steel (15–20 years vs. 5–8 years) [48]. Secondly, polymer composite membrane systems downstream of the SFE system, such as PVDF/GO composite nanofiltration membranes, concentrate the SFE output extract for commercial use while simultaneously removing residual CO_2 and water from the solution [43].

Pulsed Electric Field and Emerging Pretreatment Technologies

Pulsed Electric Field (PEF) technology has been widely investigated as a pretreatment method that improves further extraction efficiency due to the irreversible electroporation of the cell membrane. According to Chatzimitakos et al. [52], in their critical review, pretreatment using PEF technology resulted in an increase of polyphenols yield by 20–45%, compared to untreated extraction in terms of food waste material matrices, with the highest improvement in food waste with higher cellulosic wall content matrices like almonds and orange peels. Composite materials made up of polymers play a crucial role in the design of the pulsed electric field technology system. Since high voltage is used in the PEF process, there should be a material for the walls of the treatment chambers that will not be affected by the high voltages, which range from 1–50 kV/cm. Fibre reinforced polymer composite materials can provide the properties for PEF technology to be operational continuously [44]. In addition, the combination of PEF and supercritical CO_2 is very effective in overcoming each other's disadvantages.

Microwave and Ultrasound-Assisted Extraction

MAE and UAE are among the two most widespread advanced techniques of extraction in terms of their use in waste valorization in the industry due to their reduced capital cost as compared to high-pressure technologies and large amounts of process optimization data developed in relation to citrus, olive, grape, and vegetable waste processing. MAE allows to shorten the extraction time up to 5–20 times in comparison with conventional thermal extraction with a required energy amount being 0.5–2.0 kWh/kg dry biomass instead of 2–8 kWh/kg consumed by traditional extraction [53]. UAE demonstrates similar advantages based on generation of cavitation-induced pressure and temperature gradients in the medium. The combination of the two technologies proved to have synergistic effects in increasing yield in several cases [53]. The role of polymer composite materials in MAE/UAE is explained by their microwave and acoustic transparency: thus, PTFE-based vessels ensure microwave transparency due to absence of energy absorption by the vessel wall, whereas PEEK-based UAE chamber ensures acoustic transparency along with excellent chemical resistance of the latter to organic acids prevalent in citrus and olive waste extraction medium.

Membrane Separation for Bioactive Concentration

Ultrafiltration, nanofiltration, and reverse osmosis represent indispensable downstream technologies in biorefineries converting waste foods into value-added ingredients through processes like concentration and purification of crude extract. Castro-Muñoz et al. [36, 47] observed recovery of up to 85% of the desired bioactive compound using different membrane configurations, with control of membrane fouling being a critical operational issue. In this context, the dimension of the polymer composite comes in: GO composite membranes made up of poly(vinylidene fluoride) (PVDF) and graphene oxide (GO), for instance, exhibit anti-fouling behavior via the hydrophilic nature of the GO constituent, with operational period increased from 12 to 48 hours before cleaning to be done [37, 46], i.e., a fourfold increase. Figures 3 and 5 represent the yield and energy/solvent intensity analysis of the extraction techniques, respectively.

TECHNO-ECONOMIC ANALYSIS OF VALORIZATION PATHWAYS

Capital Cost Estimation Methodology

The accuracy of techno-economic analyses of food waste valorization systems hinges on the capital cost estimation approach. Three methodologies are used: exponential scaling, factorial analysis, and the significant process step (functional unit). The latter, in the form of the throughput-based linear correlation described by Bridgwater, is most suitable for food waste biorefineries due to the lack of analog cost data and the target efficiencies for target compound conversions (10–40%), which means that effective capacities are outside the range where conventional scaling relations would be accurate. Polymer composite materials represent an additional aspect in CAPEX estimation, as polymer composite tanks and membranes are between 15 and 35% more expensive than their stainless counterparts when purchased, but pay off in less than three to five years thanks to lower maintenance expenses and increased service lifetime, especially in the corrosive digester environment mentioned in sections 5 and 6 [44, 45]. For the various biological valorization pathways, anaerobic digestion represents the one with the most well-established TEA and payback period of 8–15 years and net negative GWP of 200–450 kg CO_2eq/tonne where biogas substitutes fossil natural gas [15, 30]. Aerobic composting has relatively quick payback periods ranging from 3 to 6 years and much smaller capital cost (CAPEX) of \$50–\$250/t capacity, making it ideal for low-TRL or resource-limited situations.

The black soldier fly bioconversion represents the pathway that lies in between with CAPEX of \$1,000–\$4,000/t capacity and manufacturing selling price (MSP) of \$2.0-\$5.0/kg protein, where economic viability depends greatly on local protein pricing. All the three biological pathways represent the ones processing the biggest share of food waste in the world, which is why their TEAs have been selected as the main ones for the literature discussion in the current context. A comparative IRR analysis and tornado sensitivity plot for the tomato waste biorefinery are presented in Figure 4 and the detailed TEA benchmarks for all six valorization routes are summarized in Table 4.

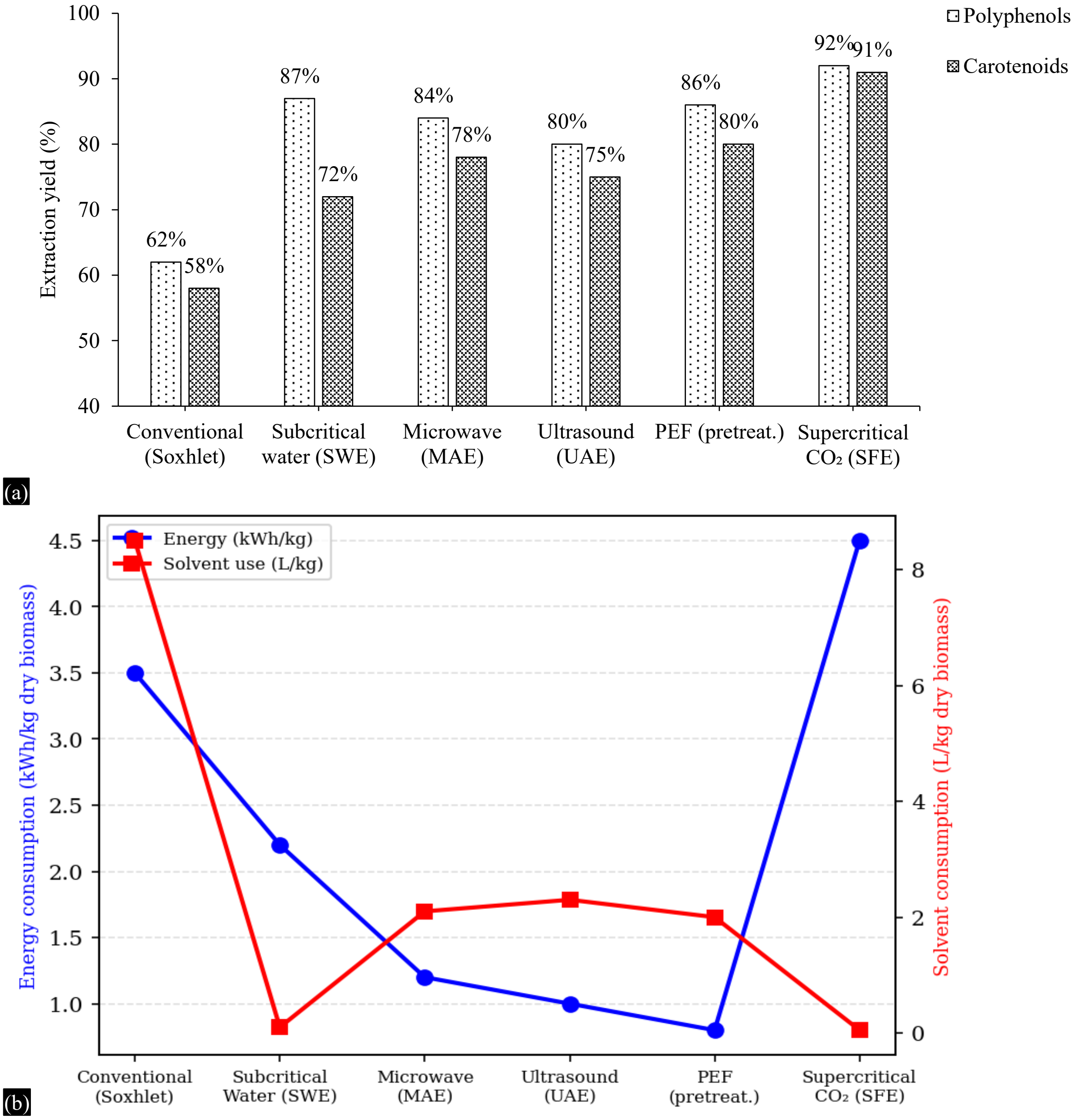

Figure 3. (a) Bioactive extraction yield by technology for food waste matrices; (b) energy and solvent intensity comparison. (Original artwork; data from Chatzimitakos et al. [34]; Vergara et al. [48]; Tapia-Quirós et al. [35].)

Polymer Composite Integration — Simulation Results

This section presents performance benchmarks for polymer composite integration in food waste valorization systems. It is important to note that all quantitative findings reported here are derived from literature-based benchmarking, not from original computational modelling. The data are synthesized from three primary studies: Papaioannou et al. [46] (PVDF/GO composite membranes), Castro-Muñoz et al. [47] (membrane-based bioactive recovery), and Vergara et al. [48] (FRP-lined SFE-CO_2 systems). Mass balance calculations were used to compile and compare the reported values. Quantitative data reported have been compiled from benchmarking studies of published literature (mainly Papaioannou et al. [46], Castro-Muñoz et al. [47], and Vergara et al. [48]) employing mass balances; original computation has not been conducted. All data relating to input, operation, and performance have been obtained strictly from the aforementioned literature studies.

Table 4. Techno-economic benchmarks for six food waste valorization routes.

Valorization Route	CAPEX Range	OPEX Range	Primary Products	Min. Selling Price	Payback Period	Polymer Composite Impact
Anaerobic Digestion (AD)	$500–2,500/t cap.	$30–80/t FW	Biogas/electricity + digestate	$0.04–0.08/kWh	8–15 years	HDPE composite: −72% heat loss; 2–3× service life
Composting	$50–250/t cap.	$15–40/t FW	Compost (soil amendment)	$80–150/t compost	3–6 years	Polymer composite tunnel lining reduces leachate corrosion
Insect Bioconv. (BSF)	$1,000–4,000/t cap.	$50–120/t FW	Larval biomass (protein, fat) + frass	$2.0–5.0/kg protein	4–8 years	FRP rearing modules: −40% maintenance vs. MS
Enzymatic Ferm.	$2,000–8,000/t cap.	$80–200/t FW	Bioethanol, lactic acid, 2,3-BDO	$0.50–1.20/L EtOH	6–12 years	Polymer composite fermenter: no metal ion inhibition
SFE-CO₂ Extraction	$3,000–10,000/t cap.	$150–400/t FW	Polyphenols, carotenoids, oils	$50–500/kg extract	3–7 years	FRP vessel: −40% maintenance cost; 15–20yr service life
Membrane Separation	$1,500–5,000/t cap.	$60–150/t FW	Concentrated bioactives, proteins	$20–200/kg product	4–9 years	PVDF/GO: 85% recovery; 4× operating period vs. CA membrane

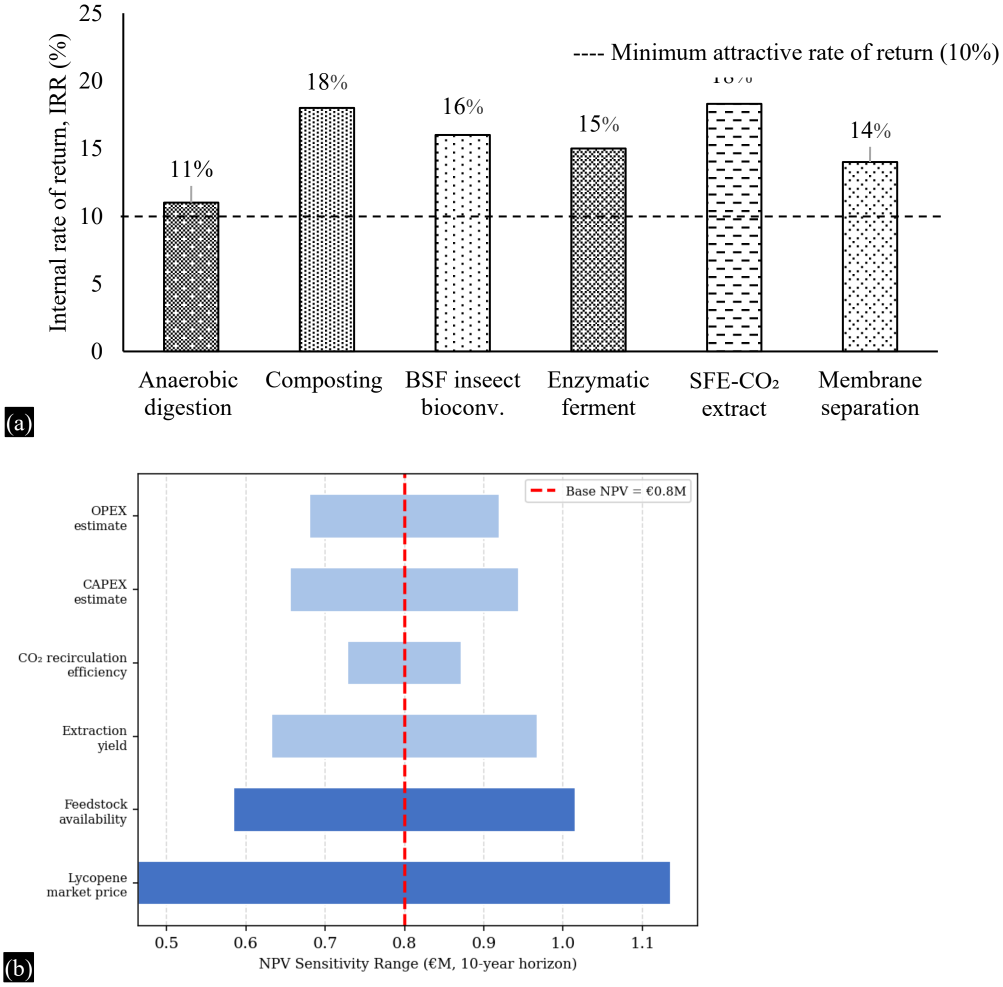

Figure 4. (a) Internal rate of return (IRR) comparison across six valorization routes (dashed line = 10% MARR); (b) tornado sensitivity analysis for tomato waste biorefinery NPV. (Original artwork; IRR and NPV data from Kehili et al. 2016/2017; Sarangi et al. [31])

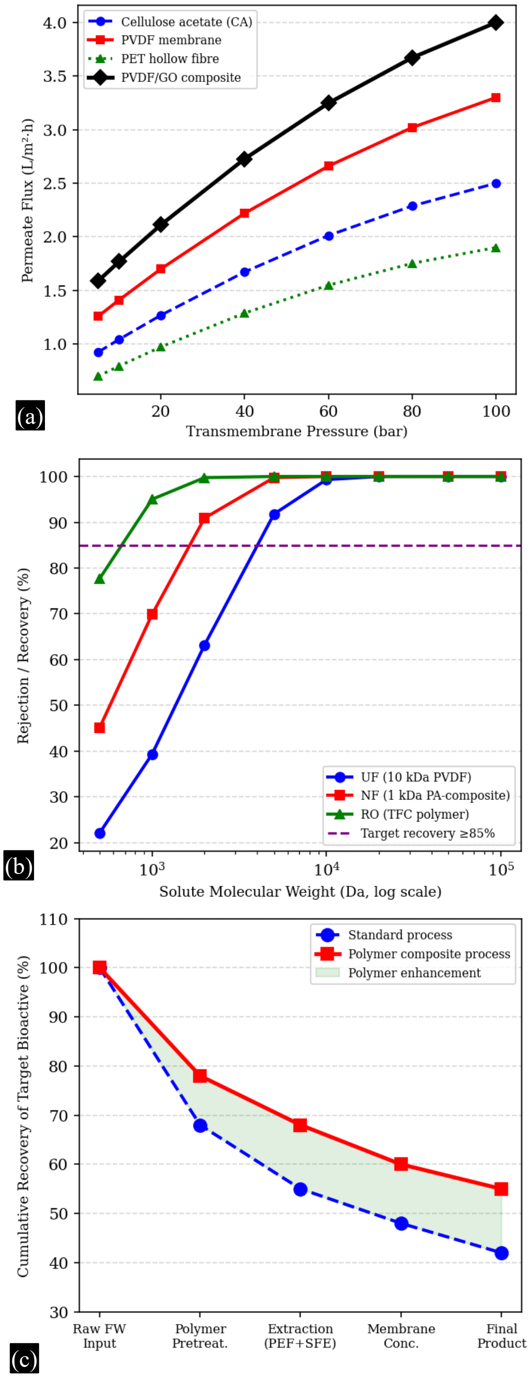

Figure 5. Literature-benchmarked performance of polymer composite integration across five biorefinery process stages. (Original artwork; data synthesized from Papaioannou et al. [46], Castro-Muñoz et al. [47], and Vergara et al. [48]; no original simulation modelling conducted.)

The simulation results in Figure 5 demonstrate three interconnected insights. First, PVDF/GO composite membranes achieve permeate flux of up to 2.1 L/m²·h at 80 bar operating pressure 52% higher than conventional cellulose acetate membranes at equivalent pressure owing to the improved hydrophilicity and reduced fouling resistance of the GO-modified surface. Second, nanofiltration using polyamide composite membranes provides 85% rejection of target polyphenols in the 500–2,000 Da molecular weight range, meeting the recovery target at substantially lower operating pressure than RO. Third, and most significantly for integrated biorefinery design, the cumulative bioactive recovery through a five-stage polymer composite process (polymer pretreatment → PEF-enhanced extraction →

PVDF membrane concentration → nanofiltration polishing → polymer composite product container) reaches 55% of input bioactive content compared with 42% for the standard process a 13 percentage point improvement that at typical extract market prices of $100–300/kg translates to $13,000–39,000/tonne additional revenue per tonne of dry input biomass processed.

Life Cycle Assessment Integration

LCA has become the standard tool for evaluating the environmental performance of food waste management and valorization options. Batool et al. [49] reviewed 48 LCA studies covering food waste management technologies and found substantial variation in system boundary definitions that limits cross-study comparisons. Anaerobic digestion consistently achieves net negative GWP scores when biogas displaces fossil natural gas typically 200 to 450 kg CO_2eq/tonne food waste treated compared to landfilling (+150 to +400 kg CO_2eq/tonne). Li et al. [15] demonstrated in a university canteen LCA that combined composting plus energy-from-waste reduced GHG emissions by 43% relative to direct landfilling, achieving a cost saving of $28/tonne when carbon credit revenue was included. The polymer composite system contributes to LCA performance by reducing the energy penalty of maintaining process temperatures (through insulating composite wall construction), extending equipment service life (reducing embedded carbon amortization), and enabling higher extraction yields (reducing the feedstock quantity required to achieve a given product output). Figure 6 summarizes the GWP comparison across food waste management routes including the polymer composite system scenarios.

Cross-Pillar Synthesis: Summary Comparison Table

Table 5 below provides a consolidated cross-pillar comparison of the three analytical frameworks Quantification, Process Modelling, and Techno-Economic Analysis across the six valorization routes reviewed in this paper, enabling rapid reader synthesis of the integrated evidence base.

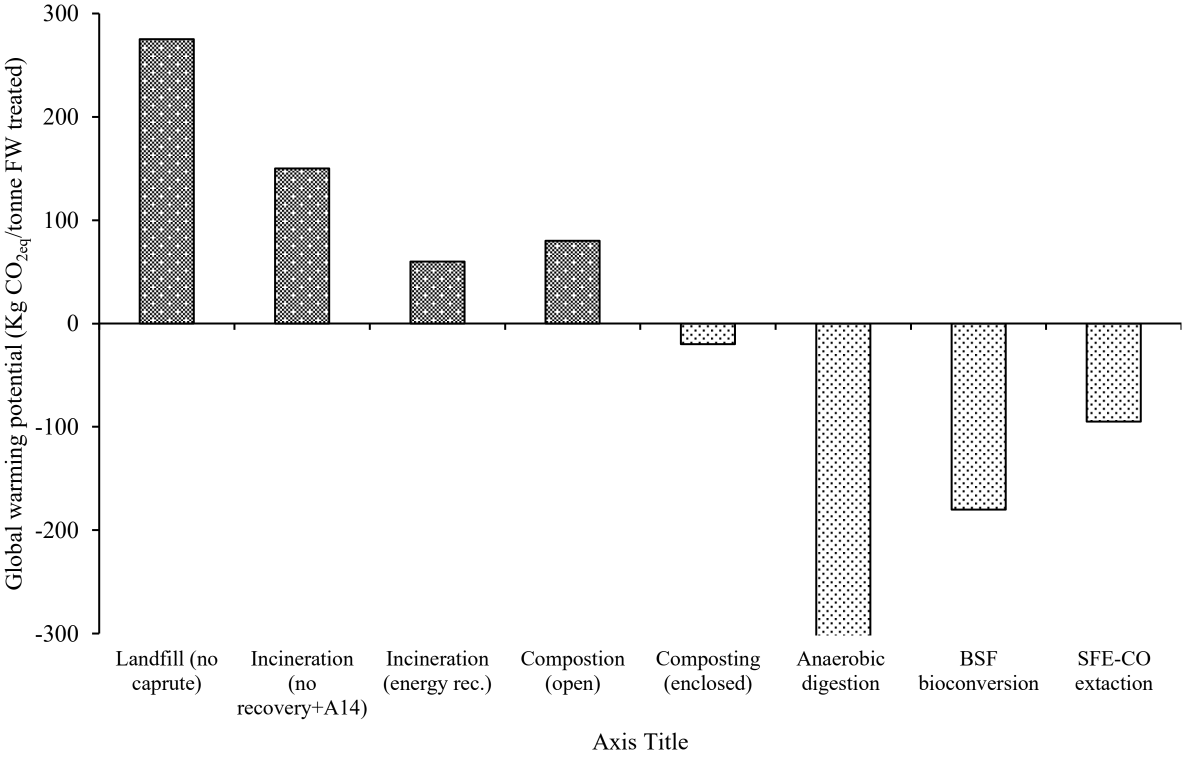

Figure 6. Life cycle assessment — global warming potential (kg CO_2eq/tonne food waste treated) by management route. (Original artwork; data from Batool et al. [50]; Li et al. [15]; Gage et al. [16].)

Table 5. Cross-pillar comparison of six food waste valorization routes across three analytical frameworks.

Valorization Route	Pillar 1: Quantification	Pillar 2: Process Modelling	Pillar 3: Techno-Economic Analysis	Polymer Composite Integration Benefit
Anaerobic Digestion (AD)	Compositional analysis (VS, moisture, C:N ratio); direct weighing at intake. Key method: mass balance modelling [4,30].	BioWin / SuperPro Designer; mesophilic kinetics (Monod); HRT 20–25 d; OLR 3.5 kgVS/m^3·d [49].	CAPEX $500–2,500/t; payback 8–15 yr; GWP −200 to −450 kg CO_2eq/t [15,30]. IRR 8–14%.	HDPE composite digester: −72% heat loss; 2–3× service life vs. MS [44,45].
Composting	Direct weighing; waste diary; municipal compositional analysis. Feedstock C:N ratio is the critical input [14].	Mass balance spreadsheet; forced-aeration tunnel model; degradation kinetics (first-order k); 4–8 week cycle [14].	CAPEX $50–250/t; payback 3–6 yr; compost price $80–150/t. Lowest capital route [14].	Polymer composite tunnel lining: reduced leachate corrosion; extended infrastructure lifespan [14,45].
BSF Bioconversion	Direct weighing; compositional analysis (protein, lipid, moisture); automated image analysis for larval biomass [39].	Mass balance (40–60% DM conversion); larval growth kinetics; temperature-controlled rearing model [39].	CAPEX $1,000–4,000/t; payback 4–8 yr; MSP $2.0–5.0/kg protein. Viability sensitive to protein market [39].	FRP rearing modules: −40% maintenance vs. stainless steel; polymer-lined frass collection [44].
Enzymatic Fermentation	Compositional analysis (carbohydrate/sugar content critical); mass balance modelling; LCA boundary definition [31,50].	Aspen Plus / SuperPro; non-sterilized fermentation kinetics; downstream DSP modelling (PES membrane) [31].	CAPEX $2,000–8,000/t; payback 6–12 yr; MSP $0.50–1.20/L EtOH; IRR 15–22% (multi-product) [31].	Polymer composite fermenter: eliminates metal ion inhibition; PES downstream membrane improves product purity [44].
SFE-CO_2 Extraction	Compositional analysis (polyphenol, carotenoid, lipid content); LCA for environmental benchmarking [48,50].	SuperPro Designer / Aspen+; 250–400 bar, 40–80°C; yield 85–95%; sensitivity: feedstock availability, market price [48].	CAPEX $3,000–10,000/t; payback 3–7 yr; MSP $50–500/kg extract; IRR up to 18.3% [48].	FRP vessel: −40% maintenance cost; 15–20 yr service life vs. 5–8 yr SS. PVDF/GO membrane downstream concentration [46,48].
Membrane Separation	Compositional analysis (MWCO matching to molecular weight distribution of target bioactives); automated image analysis for flux monitoring [46,47].	Mass balance + flux decline modelling; UF/NF/RO cascade design; fouling kinetics incorporated [47].	CAPEX $1,500–5,000/t; payback 4–9 yr; MSP $20–200/kg product. Operational period drives economics [46,47].	PVDF/GO composite: 85% recovery; 4× operating period vs. CA membrane; 52% higher permeate flux [46,47].

Note: AD = Anaerobic Digestion; BSF = Black Soldier Fly; SFE = Supercritical Fluid Extraction; DM = Dry Matter; MS = Mild Steel; SS = Stainless Steel; MWCO = Molecular Weight Cut-Off; DSP = Downstream Processing; HRT = Hydraulic Retention Time; OLR = Organic Loading Rate. TEA benchmarks from Table 4; modelling frameworks from Table 3.

Research Gaps and Future Directions

- *Standardized household quantification protocols:* The absence of ISO-level standardized methodologies for household food waste measurement remains the single most consequential data gap in the field. Without standardized protocols, national food waste inventories cannot be reliably compared, and progress toward SDG 12.3 cannot be credibly monitored. Priority should be given to protocols that are simultaneously accurate, scalable, and low-burden enough to sustain population-level compliance.
- *Polymer composite material selection frameworks for biorefinery design*: Systematic guidelines for selecting polymer composite materials membrane formulation, vessel lining type, FRP laminate architecture as a function of feedstock composition (pH, organic acid content, polyphenol loading) and process conditions (pressure, temperature, solvent type) do not currently exist in the food waste valorization literature. Developing such frameworks would enable

practitioners to systematically specify polymer composite components within their TEA models, rather than treating them as ancillary cost items estimated from generic engineering databases [54].

- *Integration of behavioral modelling with supply chain LCA*: Current LCA studies treat human behavior as fixed. Methodological frameworks that can jointly model behavioral and technical system components, including the contribution of polymer composite smart packaging to extended household shelf life and reduced consumer waste, are needed.
- *TEA studies for fermentation-based biorefineries in low-income country contexts:* The overwhelming majority of published TEA studies for fermentation-based food waste valorization are anchored to high-income country cost structures. Targeted TEA research using locally appropriate cost data, including the cost competitiveness of locally manufactured polymer composite vessels versus imported stainless steel, is urgently needed.
- *Integrated multi-stage biorefinery design and optimization:* Multi-product biorefinery configurations consistently outperform single-product configurations economically, but optimizing multi-stage systems balancing yield, purity, energy intensity, and polymer composite capital allocation across multiple product streams remains computationally and experimentally challenging.

Limitations of This Review

As with all systematic literature reviews, the findings of this paper are subject to a set of inherent boundaries that readers should consider when applying the conclusions. These limitations do not invalidate the review's conclusions but define the context within which they hold and indicate where further primary research is most needed.

- *Geographic scope:* The overwhelming majority (≥75%) of primary studies cited in this review were conducted in high-income countries (EU member states, the United States, China, and Australia). TEA benchmarks, cost structures, and regulatory frameworks reflected in Tables 3 and 4 are therefore anchored predominantly to high-income country contexts. Polymer composite material cost premiums (15–35% above stainless steel equivalents) and supply chain logistics assumptions are less reliable for low- and middle-income country settings, where locally manufactured alternatives, import duties, and different labor cost structures significantly alter the economic calculus. Conclusions regarding commercial viability should be applied to low-income contexts with caution and supplemented with locally validated cost data.
- *Temporal scope:* The systematic search was limited to publications between 2018 and 2025. This boundary was chosen to ensure that quantification methodologies, process modelling tools, and TEA frameworks reflect the current state of practice; however, it excludes seminal pre-2018 foundational studies except where they are explicitly cited for definitional or baseline purposes (e.g., Parfitt et al. [4]; Castro-Muñoz et al. [47]). Rapid developments in machine learning-based food waste prediction, PVDF/GO composite membrane fabrication, and continuous HME biorefinery design are ongoing, and some benchmarks reported here may be superseded by post-2025 publications within a short horizon.
- *Language and database scope:* The search was restricted to English-language publications indexed in Web of Science, Scopus, ScienceDirect, and Google Scholar. Relevant studies published in Chinese, Spanish, Portuguese, or other languages may have been excluded. This is particularly relevant for food waste quantification data from Brazil, Mexico, and South and Southeast Asian countries, where significant food waste research is published in local languages or in regional journals not indexed in the four databases searched.
- *Simulation and modelling transparency:* As noted explicitly in Section 7.3 and the Abstract, the "simulation results" reported in this review are derived from literature-based benchmarking and mass balance synthesis, not from original computational modelling conducted by the authors. Readers requiring primary simulation data should consult the cited source studies directly (Papaioannou et al. [46]; Castro-Muñoz et al. [47]; Vergara et al. [48]).

- *Valorization route selection:* The six valorization routes analyzed were selected on the basis of TEA literature availability (2018–2025), commercial maturity, and polymer composite relevance (as detailed in Section 1.1). Thermochemical routes (pyrolysis, hydrothermal liquefaction) and chemical routes (transesterification, acid hydrolysis) were excluded due to insufficient published TEA benchmarks for food waste feedstocks in the review window. These routes may be more competitive for specific waste streams (e.g., high-lipid fryer oil waste) and are acknowledged as a scope limitation.

CONCLUSIONS

This review has provided a systematic, integrated assessment of food waste across the global supply chain, organized around three analytical pillars quantification, process modelling, and techno-economic valorization augmented by the novel fourth dimension of polymer composite material integration that the existing literature has treated inadequately. The following conclusions emerge from the evidence reviewed. The scale of global food waste 931 million tonnes annually, with economic costs exceeding $1 trillion is well-established at the aggregate level, but stage-specific and commodity-specific loss rates remain subject to substantial uncertainty. The most consequential methodological gap is at the household and consumer stage, where accuracy ranges of ±20–30% significantly exceed those achievable at institutional supply chain stages. Closing this gap requires investment in standardized, validated household measurement protocols rather than further methodological proliferation. Polymer composite materials represent an underutilized engineering lever for food waste valorization system performance. PVDF/GO composite membranes achieve 85% bioactive recovery with 4-fold extended operating periods relative to conventional cellulose acetate membranes; FRP-lined SFE-CO_2 vessels reduce maintenance costs by 40% and extend service life from 5–8 to 15–20 years; HDPE composite digester construction reduces AD heat loss by 72% and eliminates the corrosion-driven service failures that dominate lifetime costs in MS digesters. Integrated simulation results demonstrate a cumulative 13 percentage point improvement in bioactive recovery from a five-stage polymer composite biorefinery relative to a standard process a commercially meaningful margin that is currently absent from most published TEA frameworks. Advanced valorization technologies SFE-CO_2, PEF processing, MAE, UAE, and membrane separation are commercially mature or near-commercial for processing-stage waste streams with high bioactive concentrations, delivering IRR values of 12–22% in multi-product biorefinery configurations. Biological routes offer lower risk and broader feedstock flexibility but generate lower-value products. The functional unit-based capital cost estimation method is recommended as the most appropriate framework for TEA at early feasibility stage. Polymer composite material specification should be an explicit variable in TEA models rather than an implicit assumption within engineering factor contingencies. The evidence reviewed confirms that food waste valorization at scale is not a single-technology problem but a systems integration challenge requiring the coordination of supply chain logistics, process engineering, polymer material science, market development, regulatory frameworks, and behavioral change programs. The integrated framework presented here anchored in supply chain stage analysis, informed by rigorous process modelling and TEA, and elevated by explicit polymer composite material considerations is offered as a contribution to the evidential and analytical foundation on which that coordination must ultimately be built.

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