Journal of Food Science, Nutrition and Health Vol.4 Issue 1 EWA Publishing
Available Online: 23 July 2025 DOI: 10.54254/3029-0821/2025.25360

Closed-loop resource recovery technologies for food processing wastewater: construction of a three-level circulation system and synergy of economic and environmental benefits

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Abstract. The food processing industry generates large quantities of wastewater rich in organic matter and nutrients, which poses significant environmental pressures while also serving as a valuable resource carrier. The sector is transitioning from simple compliance-based discharge to an integrated management model of "reduction–reuse–resource recovery." For water reclamation, multi-layer membrane technologies have become the mainstream advanced treatment approach, significantly increasing reuse rates. Treated water can be used for cooling, washing, and even certain production processes, effectively reducing freshwater consumption. In terms of resource recovery, anaerobic digestion technology has matured and is widely applied for biogas production, while recovering high-value substances from wastewater has become a research focus. Nevertheless, challenges such as large fluctuations in wastewater composition, high treatment costs, and incomplete regulatory standards for reclaimed water and by-products (e.g., fertilizers) hinder wider adoption. Moving forward, it is essential to strengthen collaboration among industry, academia, and research institutions to develop more economical and adaptable integrated technological solutions, fostering closed-loop water resource management and promoting green, low-carbon development in the food processing industry.

Keywords: wastewater treatment, food processing, resource utilization

1. Introduction

1.1. Water resource stress and the circular economy context

With over 2 billion people worldwide facing water scarcity and industrial water usage accounting for nearly 20% of total withdrawals, the food processing industry—known for its high water consumption—has become a key focus area for water resource management. In response, policies such as the European Green Deal and China's "Water Ten Plan" are driving a systemic shift from traditional end-of-pipe wastewater treatment to resource-oriented recovery processes. This transformation is not only driven by stricter compliance requirements for COD, BOD, and nitrogen/phosphorus discharge limits, but also presents opportunities to reduce costs through water reuse (by 20–60%), generate biogas (meeting 10–30% of energy demand), and extract high-value by-products (such as PHA bioplastics and microalgae-based fertilizers). These approaches enhance corporate ESG performance and align with global investment trends favoring sustainable water management.

1.2. Characteristics of food processing wastewater

Food processing wastewater typically exhibits high organic loads and nutrient enrichment, along with significant fluctuations in water quality and quantity [1]. Additionally, it often contains inhibitory components—such as high salinity, disinfectant residues, antibiotics, or hormones—has a tendency to biodegrade rapidly, and may cause operational issues such as foaming and clogging due to suspended solids and colloidal substances. These complex pollution characteristics pose challenges for stable process control, but the wastewater's high water content (>90%), convertible organic matter, and nutrient salts (nitrogen and phosphorus) also offer substantial resource recovery potential. This includes water reuse, conversion to biogas energy, and extraction of high-value chemicals.

1.3. The inevitable shift: from "end-of-pipe treatment" to "source reduction + resource recovery + reuse"

Treating food processing wastewater represents a practical pathway toward circular resource utilization. Wastewater treatment facilities can remove or degrade harmful substances and convert organic materials and nutrients into biofertilizers or energy. This not only reduces environmental pollution and minimizes freshwater waste, but also enables the recovery of clean water for use in production processes—ultimately realizing water recycling and contributing to sustainable development [2].

The contradiction between the high resource potential of food industry wastewater and the high cost of end-of-pipe treatment is accelerating a systemic shift—from passive treatment to a restructured approach encompassing source separation, in-process control, and value-added end-use. This transition is driven by increasingly stringent regulations, breakthroughs in technological and economic feasibility, and mounting ESG pressures across the value chain. By transforming wastewater constituents into recoverable resources (water, energy, fertilizers), the industry can offset treatment costs and move along a green upgrade path aligned with the “dual carbon” goals—an approach that has now become a globally recognized solution.

2. Advanced treatment and water reuse technologies for food processing wastewater

2.1. Mainstream mature technologies

The resource recovery technology system for food processing wastewater has evolved into a coordinated matrix designed for staged value capture. Primary recovery employs physical separation methods such as dissolved air flotation and centrifugation to rapidly intercept suspended oils and proteins, transforming waste materials into commodity-grade intermediates. Secondary conversion relies on high-efficiency anaerobic digestion to selectively convert dissolved COD into methane energy (1 kg COD ≈ 3.5 kWh electricity), significantly offsetting treatment energy costs. High-value purification involves coupled processes including membrane separation, crystallization, and biorefining to extract long-chain value from trace components in the wastewater. This three-level technology system must be embedded within a “plant-scale micro-loop and industrial park-scale macro-loop” spatial framework. At the plant level, reclaimed water is reused for washing operations, while biogas powers steam boilers. At the park level, digested sludge is converted into organic fertilizer supplied to farms, and high-purity recovered salts are provided to nearby chemical plants. This reorganization of material flows breaks through the scale limitations of single technologies, ultimately achieving triple Pareto optimization: in the value chain dimension (absorbing treatment costs with 40% water reuse cost reduction and >80% energy self-sufficiency), in the carbon footprint dimension (achieving 90% sludge reduction and indirect emissions mitigation), and in the commercial dimension (generating revenues from derived resources).

2.2. Classification and analysis of key current technologies

2.2.1. Pollutant component control technologies

Given the high organic content, oils, and colloidal pollutants in food industry wastewater, technological development has focused on enhanced pretreatment and targeted component separation.

Physicochemical separation technologies (such as dissolved air flotation and centrifugation) can efficiently capture suspended oils and proteins, but their efficiency declines in the presence of emulsified oils (particle size < 20 μm) and polysaccharide–protein colloids [3]. To address this, innovative methods such as enzymatic pretreatment (protease/pectinase) and pulsed electric fields (PEF) have been introduced, which hydrolyze colloids or disrupt emulsion micelle structures, significantly improving oil recovery rates and reducing membrane fouling.

For wastewater with low carbon-to-nitrogen ratios ($C/N < 10$), bioaugmentation techniques employ electron donors such as zero-valent iron (Fe^0) to enhance interspecies electron transfer during anaerobic digestion, overcoming limitations in conventional methane yield.

2.2.2. Water resource reclamation and reuse technologies

Membrane technology has become the core platform for advanced treatment and reuse, with ultrafiltration (UF)–reverse osmosis (RO) combinations now the industrial mainstream [4].

Advantages: These systems achieve over 95% organic matter rejection, producing water suitable for cooling, washing, and certain process uses, effectively reducing freshwater consumption.

Challenges: Membrane fouling (especially from colloidal and dissolved organic matter) and scaling in high-salinity wastewaters limit operational stability and economic feasibility. Countermeasures include developing anti-fouling modified membranes (e.g., hydrophilic coatings), coupling with pretreatment processes (such as enzymatic hydrolysis and ozonation), and adopting Internet of Things (IoT) solutions for real-time flux monitoring and optimized cleaning protocols.

2.2.3. High-value resource recovery technologies

Resource recovery has expanded from single-path energy conversion to multi-chain "energy–nutrient–chemical" approaches, but remains constrained by concentration thresholds and separation energy demands.

Energy conversion: High-efficiency anaerobic reactors (e.g., EGSB/IC) convert dissolved COD into biogas (1 kg COD ≈ 0.35 m³ CH_4), though they must address inhibition from long-chain fatty acids (LCFAs) [5].

Nutrient recovery: Struvite crystallization can achieve 90% phosphorus recovery but requires economic thresholds of PO_4^{3-} > 80 mg/L [6]. Strategies to address this include regional co-treatment of multiple wastewater sources (e.g., mixing starch and brewery wastewaters to increase substrate concentrations) or coupling with electrochemical technologies (such as bipolar membrane electrodialysis) to enhance selectivity.

Chemical extraction: Technologies such as volatile fatty acid (VFA) refining and whey protein nanofiltration concentration are seeing increasing application. Microbial electrolysis cells (MECs) can simultaneously achieve VFA separation and hydrogen production, reducing energy consumption by over 60% compared to traditional distillation [7].

2.2.4. System integration challenges and innovation directions

Current technological bottlenecks include insufficient adaptability to multi-component interference, high economic scale thresholds, and the absence of standardized product specifications.

Integrated process design needs are increasingly evident, as in "anaerobic digestion–membrane concentration–electrochemical refining" tri-generation systems capable of simultaneously recovering water, energy, and nutrients.

Regional-scale circular models that promote inter-plant material exchanges (e.g., returning digested sludge as fertilizer to farms, supplying high-purity recovered salts to chemical facilities) help overcome the scale limitations of single-enterprise resource recovery.

Finally, intelligent control systems (using AI algorithms to optimize operational parameters) and targeted detoxification technologies (such as thiol-modified materials for heavy metal removal) are essential to support the safe and compliant use of recovered products.

3. Current challenges and development trends

3.1. Multi-level challenges

Technical challenges: Adapting to and maintaining stable treatment performance for highly variable wastewater quality (in terms of composition and concentration); operational issues such as membrane fouling/scaling and microbial process efficiency.

Economic challenges: High initial investment and operational maintenance costs for technologies and equipment; the need to better balance the value and cost of recovered products (water, energy, chemicals).

Policy and regulatory challenges: Incomplete standards for reclaimed water quality and safety regulations (especially where it contacts food production); regulatory certification and market access barriers for recovered products (fertilizers, chemicals).

3.2. Future priorities and trends

Technological optimization and integration: Develop processes with greater robustness to water quality fluctuations; explore optimal combinations of multiple technologies (e.g., anaerobic–aerobic–membrane–microalgae/crystallization) in integrated approaches.

Cost reduction: Develop fouling-resistant, durable membrane materials (e.g., modified membranes); design high-efficiency, low-energy recovery systems (such as the potential of microbial fuel cells); create low-cost, efficient functional materials (e.g., novel adsorbents).

Intelligent management: Apply Internet of Things (IoT) and Artificial Intelligence (AI), including machine learning (ML), to optimize process control (automated parameter adjustments based on online monitoring), enable predictive maintenance, and improve overall system efficiency.

Policy support and standardization: Promote the development and improvement of reclaimed water quality standards and resource product certification; explore incentive policies (such as discharge fee reductions and resource recovery subsidies) to encourage adoption by enterprises.

Demand-driven customization: Design tailored resource recovery solutions based on specific needs of individual enterprises or regional clusters (e.g., irrigation water, organic fertilizer, steam requirements).

4. Conclusion and outlook

Food processing wastewater, rich in organic matter and nutrients, is increasingly viewed not as an environmental burden but as a reusable resource carrier. Current technology systems—including membrane separation, anaerobic digestion, and resource recovery—have shifted the industry from end-of-pipe treatment toward a "reduction–reuse–resource recovery" circular model, delivering significant reductions in freshwater consumption and enabling energy generation. However, large-scale adoption remains constrained by wastewater quality variability, treatment costs, and the lack of standardized resource product specifications.

Future development must focus on multi-dimensional, coordinated upgrades as a core strategy: Technological dimension: Develop smart, integrated processes with strong adaptability to water quality fluctuations and optimized cost-effectiveness (e.g., membrane–electrochemical–biorefinery integration); Industrial dimension: Build closed-loop "water–energy–fertilizer" cycles through industrial-park-level material and energy exchange to achieve regional resource coordination; Policy dimension: Advance safety certification for reclaimed water and establish green standards for by-products. Through a three-pronged approach of technological innovation, industrial restructuring, and institutional support, the food processing industry can ultimately achieve sustainable water resource utilization and progress toward carbon neutrality goals.

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