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Review

From Urban Resource Sinks to Hubs of Materials for the Environment: Trade-Offs and Deployment Realities for Net-Zero Municipal Wastewater Systems

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Abstract: Municipal wastewater treatment plants (WWTPs) are major urban energy consumers but also contain recoverable resources, including organic chemical energy, wastewater heat, nutrients, and other recoverable materials. Harnessing these resources could contribute to net-zero urban development, yet full-scale performance often falls below theoretical potential because of influent variability, climatic constraints, and plant-wide process interactions. Moreover, energy neutrality does not imply carbon neutrality, as fugitive CH_4 and process N_2O emissions can offset the climate benefits of energy recovery. Recovered materials also face product-specific health, chemical, regulatory, and market barriers. This review suggests that future studies should shift the focus from maximizing theoretical resource recovery to evaluating whether its benefits persist under real-world energy, greenhouse gas (GHG), effluent-quality, safety, economic, and infrastructure constraints. Evidence from pilot- and full-scale studies and system-level assessments is synthesized to compare major recovery pathways, identify theory-practice gaps and critical trade-offs, and evaluate technology combinations with realistic decarbonization potential. It also highlights the need for plant-wide optimization, standardized benchmarking, uncertainty-aware life-cycle assessment, and enabling policy frameworks to advance low-carbon municipal wastewater treatment systems.

Keywords: municipal wastewater treatment; energy recovery; energy saving; carbon neutrality; resource circularity; sustainability; low-carbon systems

1. Introduction

Municipal wastewater treatment is now a key part of the urban sustainability transition. As urban populations continue to grow and carbon budgets become stricter, wastewater infrastructure should no longer be treated solely as a pollution-control service. It should be developed as an important asset within the water-energy-carbon-nutrient nexus. Conventional activated sludge systems still require high energy input. Aeration and sludge treatment consume most of the electricity, while many embedded resources are wasted rather than used to reduce energy demand or replace fossil fuels. Net-zero targets, circular economy policies, and higher energy prices now require integrated systems that recover value while keeping good effluent quality and public health [1].

This shift from simple pollutant removal to nexus optimization has already been achieved in engineering practice. Recent plant-wide audits show that keeping organic matter for anaerobic digestion (AD), recovering heat before discharge, and improving nitrogen removal can reduce net energy use and greenhouse-gas emissions. However, these benefits are not guaranteed. Effective recovery depends on matching technologies to local conditions rather than chasing the highest performance of individual processes.

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Gong et al. [2] evaluated data collected from approximately 50 full-scale and pilot-scale plants across various climate regions and with different treatment capacities. The findings show that achievable energy recovery in real systems is generally below the theoretical maximum. This difference is mainly associated with variations in influent conditions, changes in operating temperatures, and differences in sludge properties. Such findings help move the field from laboratory expectations toward more deployable solutions.

Although many studies focus on individual technologies, an important gap remains. Existing reviews discuss anaerobic membrane bioreactors (AnMBRs), mainstream anammox, wastewater-source heat pumps, and nutrient-recovery products, but rarely compare full-scale performance with theoretical limits. Plant-wide trade-offs among energy neutrality, carbon neutrality, cost, reliability, and public-health outcomes are also not fully addressed [3,4]. For example, anammox-based nitrogen removal can reduce aeration demand, but the need for a stable nitrite supply and temperature sensitivity still limit mainstream application [5]. City-block decentralization can support on-site reuse, but only when local demand is well matched [6]. Sulphide-driven partial denitrification-anammox is promising for energy neutrality, but long-term full-scale validation is still limited [7]. Beyond energy recovery, municipal wastewater treatment also provides opportunities to recover environmentally relevant materials, including phosphorus- and nitrogen-containing products and algal biomass. However, their contribution to circular and net-zero wastewater systems depends not only on recovery efficiency but also on product quality, environmental safety, downstream processing, and their ability to substitute for conventional products.

This review synthesizes peer-reviewed literature identified through searches in Web of Science. Search terms included “municipal wastewater”, “energy recovery”, “carbon neutrality”, “anammox”, “heat recovery”, “nutrient recovery”, “life-cycle assessment (LCA)”, “techno-economic analysis (TEA)”, and related terms. Full-scale studies were defined as investigations conducted at operating wastewater treatment facilities. Pilot-scale studies involved dedicated pilot systems treating wastewater under specified operating conditions. Modeling studies were identified when reported results were primarily derived from mathematical simulation, mass or energy balances, or scenario analysis rather than direct full-scale measurements. LCA and TEA studies were identified by their assessment methods. Quantitative findings were interpreted according to their study scale, system boundaries, and operating conditions. This article argues that sustainable municipal wastewater treatment should not aim only at maximum theoretical resource recovery. Instead, a practical pathway is context-specific, engineering-realistic, and system-level, optimizing across energy, carbon, nutrients, infrastructure, and implementation constraints. By focusing on demonstrated performance, theory-practice gaps, and life-cycle trade-offs, this article provides a framework for utilities, engineers, and policymakers.

2. Current Status of Energy Flows and Recovery Potential

Municipal wastewater treatment plants (WWTPs) are increasingly considered not only as facilities with high energy demand but also as potential sources of renewable energy and urban resources. To enable this change, it is necessary to evaluate current energy consumption patterns, available recovery methods, the level of technology development, and interactions among different processes. This section reviews practical results obtained from full-scale plant assessments and pilot-scale investigations.

2.1. Main Energy Sinks in Municipal Wastewater Treatment

Aeration is usually the largest electricity consumer in WWTPs, accounting for approximately more than 50% of total energy consumption, followed by pumping and sludge treatment operations [8]. In conventional activated sludge systems, most aeration energy is used to transfer oxygen for organic matter oxidation and nitrification. This demand represents a particularly large proportion of total energy consumption when the wastewater contains a low concentration of organic matter. Plant-wide energy assessments show that influent chemical oxygen demand (COD) and wastewater temperature strongly affect energy distribution. When influent COD is low, aeration accounts for a larger share of total energy use. Under cold conditions, additional energy may also be required for heating and mixing [9]. Sludge-handling processes, including thickening, AD, and dewatering, account for about 20–30% of total energy consumption in WWTPs equipped with energy-intensive sludge management systems. Energy losses may occur through inefficient heat utilization and incomplete biogas recovery [10]. Conventional WWTPs typically consume approximately 0.3–0.6 kWh/m^3 of treated wastewater, which remains considerably higher than the theoretical minimum energy requirement [11].

2.2. Main Options for Energy Recovery and Reduction

Current strategies for improving plant energy performance should be distinguished according to whether they recover embedded energy or reduce the energy required for treatment. Chemical-energy recovery is primarily achieved through AD, co-digestion, combined heat and power (CHP), or anaerobic membrane processes, whereas mainstream anammox or shortcut nitrogen-removal processes primarily reduce electricity and external-carbon demand. In a scenario-based mass and energy balance analysis, Sarpong et al. [12] estimated that increasing COD removal during primary treatment by 10% reduced the total treatment energy requirement by 8.5% and increased recoverable energy by 8.8%. These values are model-derived scenario results rather than universal conversion factors, and the achievable benefit depends on influent wastewater characteristics, plant capacity, primary-treatment performance, and the configuration of the energy-recovery system.

Wastewater heat recovery is technically mature but highly site-specific because recoverable heat depends on wastewater flow and temperature, heat-pump performance, distance to heat users, and local heat demand. Mainstream anammox-based nitrogen removal provides a different type of benefit: energy saving rather than energy recovery. Compared with conventional nitrification–denitrification, theoretical aeration-saving ratios of approximately 47% for partial denitrification-anammox (PDA) and 63% for partial nitritation-anammox (PNA) have been reported [13,14]. These values represent theoretical process-level potential rather than directly measured plant-wide electricity savings. Actual performance depends on nitrite supply, temperature, biomass retention, influent characteristics, and process-control requirements.

2.3. Technology Maturity and the Gap between Practical and Theoretical Performance

As shown in Table 1, AD combined with CHP is currently the most mature energy-recovery option and has been applied widely at full scale. However, actual methane production is generally below theoretical estimates because COD capture is incomplete and operating conditions change over time. AnMBRs can increase methane recovery, but their wider use is limited by membrane fouling and the related cleaning and maintenance costs [15]. In these systems, membrane-based separation supports biomass retention and resource recovery, while membrane fouling, cleaning requirements, and associated energy consumption can reduce the overall environmental benefits. Therefore, membrane performance and operational requirements should be considered together when evaluating the net benefits of anaerobic treatment.

Wastewater heat recovery is commercially established in suitable settings. Its performance may decline during seasonal temperature changes, especially in colder climates [16]. Mainstream anammox has moved from pilot testing to a small number of full-scale applications [17]. Wider implementation is still restricted by unstable nitrite production and poor process performance at low temperatures [14,18].

Table 1. Representative performance and deployment characteristics of major resource-recovery and energy-saving pathways in municipal wastewater treatment.

Pathway and Resource Recovered	Evidence Type and Quantitative Benefit	GHG and Economic Trade-Offs	Deployment Maturity and Key Limitations	References
Organic-carbon capture and AD/CHP: biogas, electricity and heat	Modeling: a 10% increase in primary COD removal reduced total energy demand by 8.5% and increased recoverable energy by 8.8%.	Energy recovery can offset purchased energy, but CH_4 losses and N_2O emissions remain concerns. Economics depend on plant scale, CHP utilization and energy prices.	AD/CHP is mature and widely deployed; advanced COD up-concentration remains less established. Incomplete COD capture, gas losses, and competing downstream carbon demand remain important constraints.	[2,12,19,20]
AnMBR: methane and chemical energy	Experimental studies and reviews: Enhanced methane recovery; transferable net-energy benefits remain uncertain.	Dissolved methane can reduce climate benefits; membrane cleaning, replacement and methane management add costs.	Pilot to early demonstration for mainstream municipal wastewater; constrained by membrane fouling, cleaning energy, dissolved methane recovery, and low-temperature operation.	[15,16]
Wastewater heat recovery: thermal energy	Full-scale studies and Modeling: Highly site-specific, benefits depend on heat-pump performance, wastewater conditions and heat demand.	GHG benefits depend on electricity carbon intensity and the displaced heat source. Economics depend on electricity prices, coefficient of performance (COP) and heat utilization.	Commercially mature with full-scale applications, but seasonal variation and mismatch between heat supply and demand can undermine utilization.	[16,21,22]

Table 1. *Cont.*

Pathway and Resource Recovered	Evidence Type and Quantitative Benefit	GHG and Economic Trade-Offs	Deployment Maturity and Key Limitations	References
Mainstream anammox: nitrogen removal	Theoretical estimates: aeration savings of 47% for PDA and 63% for PNA	Lower aeration and external-carbon requirements can reduce indirect emissions, but N_2O must be assessed separately.	Mainly pilot/demonstration scale. Key constraints include nitrite-oxidizing bacteria (NOB) control, nitrite supply, low temperature, biomass retention, and polishing requirements.	[5,13,14,18]
Nutrient recovery: phosphorus, nitrogen and fertilizer products	Pilot-scale TEA: Material recovery rather than direct net-energy generation.	Fertilizer substitution may avoid emissions, while chemical consumption, transport and product upgrading add burdens. Economic feasibility depends on product value and market demand.	Selected pathways such as struvite recovery are established, but economics depend on chemical demand, product quality, market value, and regulatory acceptance.	[23–25]
Algae-based treatment: algal biomass and nutrients	Demonstration-scale study: a membrane-coupled high-rate algal pond treating urban wastewater required 0.29 kWh/m^3; N and P removal rates reached 11 and 1.6 g/m^3·d, respectively.	Potential nutrient substitution and biomass valorization benefits depend on downstream use; energy, harvesting and processing affect lifecycle-performance.	Emerging/demonstration scale; land requirement, solar availability, seasonal productivity, biomass harvesting, and product markets remain major constraints.	[26,27]
Integrated plant-wide optimization: coordinated energy and resource recovery	Modeling: carbon footprint decreased by 40% despite a 31% reduction in energy recovery in one mitigation scenario.	Outcomes are sensitive to system boundaries, process interactions, assumptions and operating scenarios.	System-level strategy rather than a single technology; constrained by process interactions, uncertainty, and control complexity.	[9,20,28]

2.4. Integration of Different Recovery Pathways

Greater benefits may be obtained when energy-recovery technologies are coordinated through whole-plant optimization. For instance, chemically enhanced primary treatment or high-rate contact stabilization can capture more influent organic matter and increase the amount of COD available for AD. These approaches may also support early-stage heat recovery because the wastewater still contains relatively high thermal energy before treatment [19,22,29]. After most organic matter has been removed, mainstream anammox or partial denitrification-anammox can reduce the aeration demand for nitrogen removal. The electricity saved from aeration may then support heat-pump operation or sludge-processing activities. Nutrient-recovery methods, including struvite precipitation and biosolids upgrading, connect energy management with material recovery. These technologies may improve digestate quality and lower the energy required for product transport [24,25]. Full-scale process modeling suggests that integrated approaches can transform conventional WWTPs from net energy consumers into systems approaching energy neutrality. However, successful implementation requires balancing the interactions among processes. For example, capturing excessive organic matter for methane production can leave insufficient carbon for conventional denitrification unless shortcut nitrogen-removal processes are also introduced [20,28]. Overall, individual energy recovery technologies have reached a relatively high level of maturity. Nevertheless, their maximum benefits have yet to be fully realized through integrated, plant-wide design and operation strategies.

3. Engineering Realities, Trade-Offs, and Contextual Limitations

Full-scale applications often fall short of their theoretical potential. This section describes the main causes of this gap and evaluates trade-offs related to energy, greenhouse gas emissions, nutrient recovery, cost, reliability, and public health (Figure 1). It also considers how site-specific conditions affect the selection of suitable technologies.

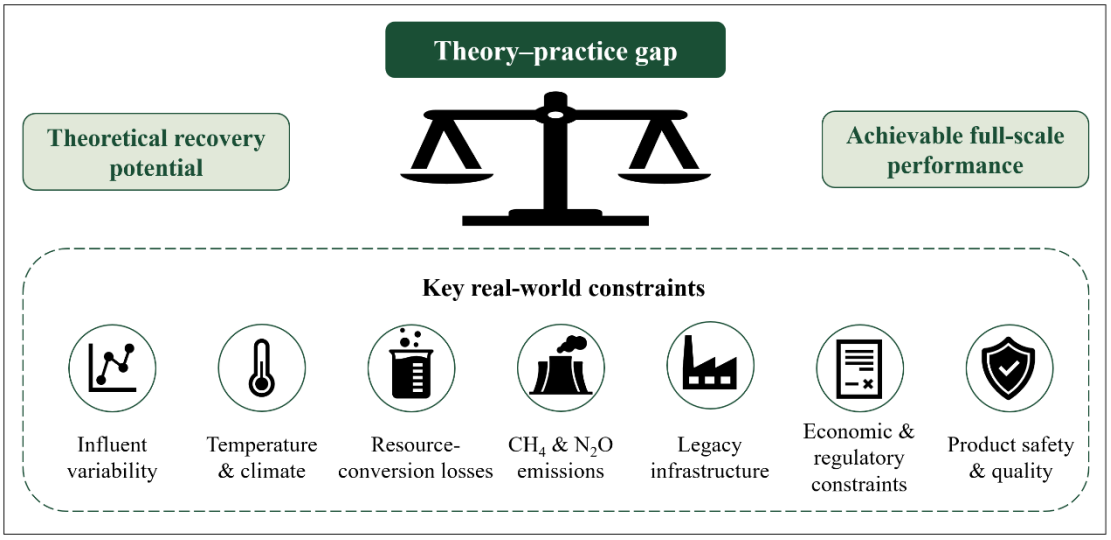


Figure 1. Conceptual illustration of the gap between theoretical resource-recovery potential and achievable system-level performance in municipal wastewater treatment.

3.1. Differences between Theoretical and Practical Performance

Theoretical calculations usually assume stable and ideal conditions. Real WWTPs, however, operate under changing COD loads, temperatures, and sludge biodegradability. For this reason, actual methane production is commonly below the theoretical value. A fraction of organic matter may be oxidized or lost during primary treatment, while some remains in the treated effluent. In AnMBR systems, membrane fouling increases operational energy demand [30], while the performance of wastewater heat recovery varies with temperature, flow, and seasonal heat demand [15,21]. Mainstream anammox can achieve lower energy savings than expected because nitrite production is unstable and anammox biomass may be washed out under cold operating conditions [18]. These factors show that practical engineering and operational constraints remain major barriers to realizing theoretical recovery potential.

Deployment experience further shows that promising pilot performance does not necessarily translate directly into full-scale implementation. At WWTP Dokhaven, mainstream PNA achieved effective nitrogen removal under stable conditions, but long-term stability remained a key constraint on scale-up [31]. Similarly, the one-year pilot study of Zheng et al. [18] showed that NOB suppression and ammonium removal could deteriorate when operating conditions changed, requiring coordinated control of dissolved oxygen, residual ammonium, and free nitrous acid (FNA)-based sludge treatment. These experiences indicate that deployment readiness depends not only on nominal energy-saving potential, but also on process stability, disturbance recovery, and operational control under variable conditions.

3.2. Energy Neutrality, Carbon Neutrality, and System-Level Trade-Offs

Energy neutrality does not imply carbon neutrality. Energy neutrality is an operational energy-balance concept defined within a specified WWTP boundary, in which imported electricity and heat are balanced against usable energy recovered on site or exported. Biogas-derived electricity and wastewater heat are therefore treated as energy recovery, whereas reductions in aeration, pumping, and chemical use represent energy savings. Net energy generation is achieved only when usable recovered or exported energy exceeds operational demand.

Carbon neutrality, by contrast, depends on the greenhouse-gas accounting framework and system boundary. Operational inventories distinguish direct process emissions, particularly CH_4 and N_2O, from indirect emissions associated with purchased energy and other inputs, whereas life-cycle assessment may additionally include upstream production, infrastructure, sludge management, and downstream substitution credits. The treatment of biogenic CO_2 and avoided emissions from exported electricity, recovered heat, or fertilizer substitution should therefore be stated explicitly. Consequently, a WWTP may approach energy neutrality while retaining a substantial positive carbon footprint. In the long-term monitoring results of Li et al. [20], biogas energy recovery offset 39.5% of total emissions, whereas N_2O from secondary treatment accounted for 62.3%, highlighting that energy recovery alone does not ensure carbon neutrality.

Other resource-recovery strategies introduce additional system-level trade-offs. Struvite and related nutrient-recovery products can support phosphorus recycling, but their agricultural use requires product-specific safety and quality assessment, potentially increasing treatment and monitoring costs [32]. Their environmental value also

depends on product purity, contaminant profiles, and suitability for the intended application. Accordingly, the benefits of material recovery should be assessed alongside downstream processing requirements, potential substitution of conventional products, and any environmental or health risks associated with recovered materials. Likewise, mainstream anammox can reduce aeration demand, but its benefits depend on stable process control and effluent performance under variable loading. Therefore, net-zero wastewater systems should be optimized across energy, greenhouse-gas emissions, resource recovery, effluent quality, safety, and operational reliability rather than for any single performance metric.

3.3. Geographical, Climatic, and Infrastructural Dependencies

In cold regions, mainstream anammox can maintain good performance with longer sludge retention times or by coupling partial denitrification. However, low temperatures usually reduce the achievable energy savings. Wastewater heat recovery is more favorable in densely populated cities, where influent is relatively warm and local heat demand remains stable. In rural areas or regions with large seasonal temperature changes, heat-pump efficiency and infrastructure utilization are often lower [21]. High-rainfall areas with dilute wastewater benefit more from up-concentration of organics before anaerobic treatment. In contrast, high-COD industrial-municipal mixtures favor co-digestion. In addition, old infrastructure imposes significant limitations: many centralized plants with gravity sewers and large activated-sludge tanks require substantial capital investment to install high-rate contact stabilization or membrane bioreactors. Overall, no recovery route is suitable for all situations. Technology selection should consider local temperature, sewer design, influent characteristics, and the configuration of the existing treatment plant [16].

3.4. Implications of Centralized and Decentralized Systems

Centralized treatment plants benefit from economies of scale, particularly for AD and CHP production. However, transporting recovered heat over long distances is difficult, and direct reuse of water, heat, and nutrients may be limited. Decentralized systems at the city-block scale can connect recovered resources more easily with nearby users. Recovered water, heat, and nutrients may support applications such as vertical farming, while local photovoltaic systems may provide part of the required electricity. These links can improve resource efficiency and increase system resilience. Modeling studies suggest that block-scale source separation combined with anaerobic co-digestion can produce more energy than it consumes when sufficient local demand is available. Nevertheless, decentralized systems require stronger microbial risk control and greater coordination among property owners, operators, and other stakeholders than centralized plants [33]. Hybrid systems offer a more realistic alternative. Sludge treatment can remain at a central facility, while heat and nutrient recovery are placed close to local users. However, new regulatory and financial arrangements are required to fairly distribute costs and benefits across different areas and stakeholders [28]. The most appropriate configuration, therefore, depends on population density, infrastructure quality, local demand for recovered resources, and policy support [34].

3.5. Regulatory, Infrastructural, and Governance Barriers

Existing discharge permits, energy-pricing systems, and carbon-accounting methods often do not assign sufficient value to recovered resources. As a result, utilities may have little economic motivation to integrate energy, nutrient, and water recovery at the plant-wide level. Life cycle assessment (LCA) has reported environmental co-benefits from energy recovery in combined industrial and municipal wastewater systems. However, regional financial and regulatory frameworks rarely provide direct rewards for these benefits [35,36]. For recovered materials, practical deployment also depends on appropriate product-quality criteria, contaminant limits, end-use requirements, and regulatory approval. Without adequate quality assurance and demonstrated environmental safety, wastewater-derived products may fail to achieve their intended substitution benefits, even when the recovery processes are technically effective.

Governance barriers are particularly important for decentralized systems. Several organizations or property owners may need to jointly manage source separation, infrastructure operation, and resource distribution. Earlier reviews suggest that incentives for carbon reduction and resource recovery can encourage the adoption of technologies. These incentives, however, should be combined with updated standards that account for both energy savings and greenhouse gas reductions [37]. Without policies that recognize broader environmental benefits and simplify approval procedures for hybrid projects, the development of energy-efficient, low-carbon wastewater treatment systems is likely to remain slow and limited.

4. Prospects and Future Pathways

Moving municipal wastewater treatment toward energy-efficient, low-carbon operation requires more than incremental improvements to individual technologies. Integrated system configurations are needed to achieve measurable benefits under real operating conditions. This section discusses suitable technology combinations, improved benchmarking approaches, the roles of life-cycle and economic assessments, policy requirements, major research priorities for the next 5–10 years, and possible strategies for applying net-zero systems in different urban settings.

4.1. Context-Specific Technology Combinations and System Designs

No single technology portfolio is optimal across all municipal wastewater systems. Promising configurations typically combine upstream organic-matter capture with anaerobic conversion, wastewater heat recovery, and energy-efficient nitrogen removal, but the preferred combination depends on climate, influent characteristics, existing infrastructure, and local demand for recovered resources [7,15,19]. Enhanced magnetic separation and high-rate contact stabilization can increase the fraction of influent COD available for subsequent methane production, while heat may be recovered from warm wastewater before discharge. However, upstream heat extraction should not reduce wastewater temperature to levels that compromise downstream biological treatment [19,29].

At the plant scale, processes need to be coordinated rather than optimized independently. Co-digestion can increase methane production, while wastewater-source heat pumps can reduce external thermal-energy demand, although the electricity required for heat-pump operation must remain part of the overall energy balance [15]. Mainstream partial denitrification-anammox can further reduce aeration and external-carbon demand for the remaining nitrogen load, but its benefits depend on stable nitrite supply, temperature, and process control [5,14]. Plant-wide modeling studies suggest that such integration can improve overall energy and carbon performance relative to isolated process optimization, provided that interactions among carbon capture, nitrogen removal, heat recovery, and greenhouse-gas emissions are explicitly considered [9,20]. Hybrid centralized-decentralized configurations may further improve resource use by locating heat or nutrient recovery close to end users, such as district-heating networks or urban agriculture.

Additionally, algae-based systems offer an emerging option for coupling nutrient uptake with photosynthetic oxygen supply and biomass valorization, potentially reducing reliance on mechanical aeration [27]. In a demonstration-scale membrane-coupled high-rate algal pond treating urban wastewater, Robles et al. [26] reported an operational energy demand of approximately 0.29 kWh/m^3 and a total operation and maintenance (O&M) cost of €0.04 per m^3 (including electricity costs), with nitrogen and phosphorus removal rates reaching 11 and 1.6 g/m^3·d, respectively. Broader deployment, however, remains sensitive to seasonal light and temperature variation, land or reactor footprint, biomass harvesting and downstream processing, and the market value of recovered biomass [26,27]. In addition to nutrient removal, the potential value of algal biomass as a recovered resource depends on its composition, contaminant content, processing requirements, and suitability for downstream applications. Biomass production alone is therefore insufficient to demonstrate environmental benefits unless product quality and the feasibility of subsequent use are also considered. Long-term full-scale municipal evidence remains comparatively limited, suggesting that algae-based systems are more likely to complement than replace compact conventional treatment where climate, land availability, and local biomass-use opportunities are favorable.

4.2. Consistent Benchmarking and Standardized Indicators

Future wastewater systems should be evaluated using common plant-wide indicators rather than reporting only the efficiency of individual technologies. Suitable indicators include specific energy use or recovery, expressed as kWh/m^3 of treated wastewater; carbon footprint, expressed as kg CO_2-eq/m^3; and multifunctional life-cycle performance scores [20,34,36]. Reports of energy neutrality should also include both direct and indirect greenhouse gas emissions. Electricity production, thermal-energy recovery, and chemical-energy recovery should be calculated and presented separately [9,20]. Nutrient-recovery assessments should consider recovery efficiency together with agricultural bioavailability, product quality, and microbial risks specific to each recovered material [24,25]. Benchmarking methods should also account for seasonal temperature changes, variations in influent composition, and operational disturbances. Steady-state models often exclude these factors and may therefore overestimate performance. Wider adoption of standardized and uncertainty-aware indicators would improve comparisons among treatment plants and support the selection of more sustainable designs.

4.3. Role of LCA, TEA, Digital Twins, and Policy Design

LCA and techno-economic analysis (TEA) can help identify technologies that are suitable for specific local conditions. For a pilot-scale nutrient-recovery system producing ammonium nitrate and struvite, Mayor et al. [23] reported a negative net present value for the baseline nutrient-recovery scheme, with chemical consumption accounting for 30% of the gross cost. Sensitivity analysis indicated that the scheme could become economically favorable if the market values of ammonium nitrate and struvite increased to €0.68 and €0.58 per kg, respectively. This example illustrates that reagent consumption, product value, energy prices, and plant scale can be as important as recovery efficiency in determining deployment feasibility.

Using real-time operating data, digital twins can simulate changes in water, energy, carbon, and nutrient flows. These tools assist operators in selecting suitable control strategies when influent characteristics, loading conditions, or climate factors vary. In this way, digital twins may reduce the difference between model predictions and actual full-scale performance. Uncertainty-based LCA indicates that small variations in operating parameters may shift the estimated plant carbon balance from positive to negative [36,38]. Therefore, reported results should include parameter ranges and sensitivity analyses rather than only average values. Policy instruments should recognize the combined environmental benefits of resource recovery. Energy tariffs, carbon-credit systems, and discharge permits could be modified to reward whole-system performance instead of pollutant removal alone [37]. Recovered nutrients and heat should receive an appropriate economic value alongside electricity generation. Such incentives may reduce financial risks for integrated and hybrid projects. Without supportive policies, technically effective systems may remain economically unattractive in many regions.

4.4. Main Research Priorities

Several research issues should receive greater attention during the next 5–10 years. First, more long-term full-scale studies are required to determine whether mainstream anammox can remain stable in cold climates. Pilot systems have confirmed their technical possibility, but plant-wide energy savings remain uncertain or relatively limited [14]. Second, recovered products differ substantially in pathogen, trace-contaminant, and regulatory risk profiles, so that biosolids, crystallized mineral fertilizers, source-separated urine products and other recovered materials should not be evaluated under a common safety assumption. Integrated risk assessment can support safe agricultural use while avoiding unnecessary treatment expenses [32]. Third, thermal- and chemical-energy recovery should be compared using equal system boundaries, LCA assumptions, operating periods, and economic conditions. Such consistent plant-wide comparisons are still uncommon but are important for choosing appropriate recovery pathways [16]. Fourth, suitable financial and governance models for decentralized and hybrid systems remain insufficient [39]. Quantitative case studies should examine how capital costs, operating expenses, environmental benefits, and revenues from recovered products can be shared among municipalities, utilities, building owners, operators, and final users [33]. Finally, open-source digital-twin platforms should be developed using real-time sensor data and uncertainty-based modeling. These tools need to be practical for routine plant operation rather than limited to research demonstrations.

4.5. Application and Scaling in Real Cities

The wider adoption of net-zero wastewater treatment will depend on whether system designs are adapted to local climate, infrastructure, population density, governance capacity, and resource demand. Hybrid centralized-decentralized systems may help expand net-zero treatment from individual demonstration projects to broader urban applications [6]. In densely populated cities, source separation at the building or city-block level can be connected with centralized sludge treatment. This configuration may support vertical farming, local reuse of treated water, nutrient recycling, and electricity supply from photovoltaic systems. It can also help control microbial risks at appropriate treatment locations [33]. In low-density areas or cities with aging infrastructure, replacing the entire treatment system may not be economically feasible. A more practical initial strategy may involve retrofitting existing plants with organic-matter up-concentration, improved AD, and heat-recovery systems selected based on local demand [37]. Successful large-scale adoption depends on three key conditions: standardized performance metrics for fair comparison, policy frameworks that reward co-benefits, and digital tools for continuous optimization. When these conditions are met, municipal wastewater treatment can shift from a major energy consumer to a resilient, resource-positive part of sustainable cities.

5. Conclusions

Municipal wastewater treatment is moving from energy-intensive pollution control toward integrated resource recovery, but the gap between theoretical potential and practical performance remains substantial. AD and related chemical-energy recovery pathways currently have the strongest record of full-scale deployment, while emerging options require longer-term validation under variable operating conditions. Progress toward net-zero operation depends on plant-wide optimization that jointly considers energy demand and recovery, direct greenhouse-gas emissions, nutrient recovery, economics, and infrastructure constraints. For utilities and plant operators, near-term priorities should include plant-wide energy and greenhouse-gas auditing, direct CH_4 and N_2O monitoring, and staged retrofits of technologies with demonstrated operational reliability. Technology developers and researchers should emphasize long-term field validation, failure modes, and uncertainty-aware LCA and TEA rather than reporting peak process performance alone. Municipalities and regulators should align energy tariffs, carbon accounting, recovered-product standards, and incentives with verified life-cycle benefits. With these measures, WWTPs can increasingly function as low-carbon resource-recovery hubs within the urban circular economy. For wastewater-derived materials, future assessments should consider not only recovery yield but also product quality, environmental safety, downstream processing burdens, and demonstrated end-use value. Integrating these material-related criteria with plant-wide energy and greenhouse-gas assessment is essential for identifying recovery pathways that deliver measurable environmental benefits.

Author Contributions

X.C.: Methodology, writing—original draft preparation, data curation, visualization, investigation; D.-J.L.: Conceptualization, writing—reviewing and editing, supervision, funding acquisition, project administration. All authors have read and agreed to the published version of the manuscript.

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Use of AI and AI-Assisted Technologies

During the preparation of this work, the authors used ChatGPT (OpenAI) to assist with language polishing and improving the clarity of the manuscript. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

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