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Article

Integrative Sustainability Assessment of Advanced Wastewater Treatment Technologies: Environmental Impact, Geochemical Insights, and Techno-Economic Evaluation for Circular Water Management

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ABSTRACT

Rapid advancements in wastewater treatment technologies are essential for achieving sustainability goals related to circular water use, carbon neutrality, and resource efficiency. This review provides an integrative assessment of key advanced treatment systems including membrane filtration, advanced oxidation processes, and anaerobic digestion by examining their environmental performance, geochemical implications, and techno-economic feasibility. Findings from life cycle assessment (LCA), carbon footprint evaluations, and cost–benefit analyses identify technologies with high eco-efficiency and reduced greenhouse gas emissions, particularly those enabling energy recovery and enhanced water reuse. The synthesis demonstrates that combining environmental indicators with geochemical insights supports the development of sustainable treatment pathways. Overall, the review highlights the need for integrated evaluation frameworks that link technological function with environmental and economic outcomes, guiding future wastewater treatment under circularity and climate-resilient frameworks.

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Research Highlights

- Provides an integrated sustainability assessment of advanced wastewater treatment technologies using life cycle, geochemical, and techno-economic perspectives.
- Identifies energy-recovery and water-reuse-oriented systems as the most eco-efficient options with reduced greenhouse gas emissions.
- Emphasizes the need for quantitative, circular-economy-based evaluation frameworks to guide climate-resilient wastewater management strategies.

1. Introduction

Rapid urbanization, industrial expansion, and population growth in the 21st century have placed unprecedented pressure on global freshwater resources, with water demand projected to increase by 20–30% by 2050, intensifying challenges related to pollutant loading, groundwater depletion, and the energy–water nexus [1, 2]. As a result, the treatment of wastewater has transitioned from being a sanitation-focused necessity to a core aspect of environmental management, and it plays an important role in the attainment of the United Nations Sustainable Development Goals (SDGs), particularly those pertaining to clean water (SDG 6), sustainable settlements (SDG 11) and climate action (SDG 13) [3–5]. Conventional wastewater treatment methods, though capable of effective removal of contaminants, have received increased scrutiny related to sustainability. Conventional treatment methods have relatively high energy demands, produce high volumes of sludge, have high chemical requirements, and are contributors to greenhouse gas emissions [6–8]. Additionally, many traditional treatment systems were not designed for energy efficiency, carbon neutrality, or to comply with contemporary environmental standards focused on resource recovery and circularity.

As a result of these challenges, the use of new technologies and methods for wastewater treatment has gained momentum, especially regarding sustainability and the circular economy. Some of these new technologies include advanced oxidation processes (AOPs), membrane filtration systems, electrochemical treatment technologies, anaerobic digestion, and hybrid systems. These technologies represent a growing area of innovation with favourable prospects regarding energy efficiency, environmental impacts, and the likelihood of recovering valuable resources from wastewater (water, nutrients, biogas) [9–11]. However, assessing the sustainability of these 'green' technologies requires far more than evaluating contaminant removal alone. A comprehensive framework incorporating environmental and economic indicators such as Life Cycle Assessment (LCA), carbon footprint analysis, and techno-economic evaluation is needed to determine their long-term sustainability and environmental compatibility [12, 13]. LCA is particularly important as it captures the cradle-to-grave impacts of treatment systems, including resource use, emissions, sludge management, and end-of-life processes.

This article critically reviews the assessment of established and emergent technologies for treating wastewater in terms of sustainability. To articulate performance, viability and global sustainability targets, it draws on life cycle-based frameworks that quantify resource use and emissions over treatment regimes, carbon footprint assessments that address trade-offs for climate risk, and techno-economic evaluations detailing economic viability and sustainability over time. This review synthesizes multiple dimensions in order to propose a systematic framework that facilitates evidence-based decision-making in the implementation of clean, efficient and environmentally sound wastewater treatment systems for a circular- and sustainable-water future.

Although numerous studies have investigated individual wastewater treatment technologies, there is a deficiency of comprehensive evaluations that concurrently consider their environmental efficacy, geochemical consequences, and techno-economic feasibility. Most current reviews concentrate on discrete technological efficiencies or contaminant removal metrics, failing to connect these results to more comprehensive sustainability indicators, including carbon neutrality, energy recovery potential, and circular resource flows. This review addresses this deficiency by offering a thorough, interdisciplinary assessment of advanced wastewater treatment technologies through integrated methodologies including life cycle assessment (LCA), carbon footprint analysis, and techno-economic evaluation. The originality of this study resides in the integration of these three dimensions to discern genuinely sustainable treatment pathways and to suggest a comprehensive framework that facilitates evidence-based decision-making for circular and climate-resilient water management.

A key novel contribution of this review is the integration of geochemical analysis into sustainability assessment of wastewater treatment technologies. Unlike conventional reviews that emphasize treatment efficiency or economic performance in isolation, the geochemical perspective enables evaluation of contaminant speciation, transformation pathways, by-product formation, and the long-term environmental behavior of effluents and residuals. By linking geochemical processes with life cycle assessment and techno-economic evaluation, this review provides a more comprehensive framework for assessing environmental compatibility and circularity in wastewater treatment systems.

2. Review of Current Technologies to Treat Wastewater

Contemporary wastewater treatment has shifted beyond conventional pollutant removal toward integrated systems that balance treatment efficiency with energy demand, environmental impact, and resource recovery potential. Rather than evaluating technologies in isolation, recent research emphasizes comparative performance across multiple sustainability indicators, including contaminant removal efficiency, energy intensity, greenhouse gas emissions, and by-product management [14, 15]. Within this context, five treatment technologies have emerged as particularly significant due to their widespread global implementation, technological maturity, and demonstrated capacity to support circular water management. These technologies advanced oxidation processes, membrane filtration systems, electrochemical treatments, anaerobic digestion, and hybrid configurations exhibit distinct advantages and limitations that must be critically assessed based on site-specific conditions, regulatory requirements, and long-term sustainability objectives. This section synthesizes current evidence to compare these technologies, highlighting trade-offs, operational challenges, and opportunities for optimization rather than presenting a purely descriptive overview (Figure 1).

Figure 1. Modern wastewater treatment technologies.

2.1. Advanced Oxidation Process (AOP)

Advanced oxidation processes (AOPs) are chemical treatment technologies designed to remove organic and inorganic contaminants through the in situ generation of highly reactive hydroxyl radicals (OH) [16]. These radicals possess a high oxidation potential and react non-selectively with a wide range of pollutants via hydrogen abstraction, electron transfer, and radical addition mechanisms. Through these reactions, complex and persistent contaminants are transformed into simpler intermediates and, in favourable conditions, mineralized into harmless end products such as carbon dioxide (CO_2) and water (H_2O).

Hydroxyl radicals in AOPs are generated through various chemical, photochemical, and catalytic pathways. Commonly applied AOPs include ozonation, Fenton and Photo-Fenton reactions, UV/H_2O_2 systems, and TiO_2-based heterogeneous photocatalysis [17]. The efficiency of radical generation and subsequent contaminant degradation is strongly influenced by operational parameters such as oxidant dosage, pH, irradiation intensity, catalyst availability, and the presence of radical scavengers in the wastewater matrix.

From a performance perspective, AOPs demonstrate high treatment efficiency, with reported removal rates of emerging contaminants frequently exceeding 90% [18]. These processes are particularly effective for degrading pharmaceuticals, endocrine-disrupting compounds, and per- and polyfluoroalkyl substances (PFAS), which are often resistant to conventional biological treatment methods [19]. However, this high treatment performance is accompanied by notable energy demands, especially in UV-based AOP systems, where energy consumption can exceed 1 kWh m^{-3} of treated wastewater. Moreover, under non-optimal operating conditions, incomplete oxidation may result in the formation of toxic transformation by-products, underscoring the need for careful system design, monitoring, and process optimization to ensure environmental safety and sustainability [20].

In practical applications, AOPs have been successfully implemented for the treatment of hospital and pharmaceutical wastewater, achieving effective removal of compounds such as diclofenac and carbamazepine. They are also widely applied in potable water reuse schemes, notably in tertiary treatment systems such as the UV/H_2O_2 process employed by the Orange County Water District in California. Additionally, AOPs are increasingly used for industrial wastewaters characterized by high loads of recalcitrant organic contaminants, where conventional treatment approaches are insufficient (Figure 2).

2.2. Membrane Filtration Systems

In membrane technologies a semi-permeable barrier is used to separate contaminants based on size and charge. Microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO) are some types of membrane technologies. Membrane bioreactor (MBR) is a combined system that combines biological treatment and membrane filtration to improve the quality of effluents [21].

2.2.1. Performance Indicators

- High separation efficiency (RO removes $>$95% of dissolved solids),
- MBRs remove $>$99% of suspended solids and BOD,
- Energy use of MBRs is typically 0.8–1.5 kWh/m^3,
- Membrane fouling is a significant operational difficulty that requires periodic cleaning and replacements.

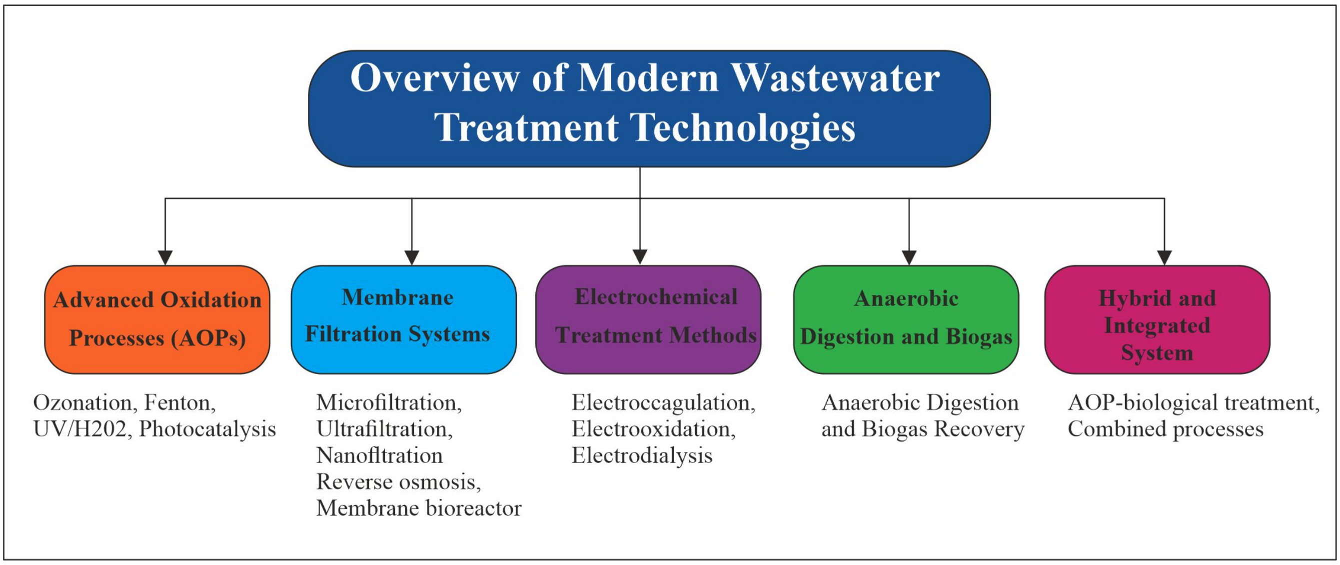

Figure 2. Overview of modern wastewater treatment technologies.

2.2.2. Real-World Applications

- Municipal wastewater recycling and industrial effluent polishing,
- Water reuse for arid climates (e.g. NEWater program in Singapore),
- Food and beverage industries, pharmaceuticals, textiles.

2.3. Electrochemical Treatment Technologies

Electrochemical technologies can be characterized as technologies that oxidize contaminants directly or indirectly through the application of an electric current. These technologies include electrocoagulation (EC), electrooxidation (EO), and electrodialysis. They are becoming more popular for their capacity for modularization and the absence of chemicals [22].

2.3.1. Performance Metrics

- Effective for removal of COD, heavy metals, pathogens, and dyes.
- EC alone can remove COD by 80–95%, depending on the electrode material.
- Energy consumption is reported to be in the range of 0.5–2.0 kWh/m^3.
- Efficiency is dependent on pH, conductivity, and electrode design.

2.3.2. Application Examples

- Treatment of textile dye wastewater (e.g., industrial areas in India and Bangladesh).
- Small-scale decentralized systems in rural or peri-urban communities.
- Pre-treatment of landfill leachate and brine from industrial processes.

2.4. Anaerobic Digestion and Biogas Production

Anaerobic digestion (AD) is a process in which microorganisms decompose organic material in the absence of oxygen producing biogas (methane and CO_2) and digestate [23]. This technology is especially effective for treatment of high-strength organic wastewater and sewage sludge.

Performance Metrics

- COD removal efficiency: 70–90%
- Methane production: ~0.25–0.35 m^3 CH_4/kg of COD removed
- Energy neutral or positive when biogas is collected and used
- His process is very sensitive to temperature changes and shock loading.

2.5. Integrated and Hybrid Systems

Hybrid systems consist of two or more treatment processes, utilized to use the synergistic effects and avoid the limitations of one technology on its own [24, 25]. Integrated/hybrid systems would include biological/AOP treatments, MBR/RO trains, constructed wetlands with electrochemical cells, or photocatalytic membranes, etc. Metrics for performance include:

- High removal rates of conventional pollutants and emerging pollutants
- Advantageous for system resilience and flexibility in processes
- Degree of energy and cost savings will be variable to system configuration
- Advanced control will also be challenged with the additional complexity of integration.

Examples of Real-World Applications Would Include

- Industrial parks and eco-industrial zones that are using zero-liquid-discharge (ZLD) models
- Water reuse systems, decentralized and urban
- Hybrid constructed wetlands with solar-powered electrochemical oxidation in rural Asia and Africa.

A robust sustainability assessment of wastewater treatment technologies must consider energy consumption, economic feasibility, and environmental footprint. Energy demand is often the main limiting factor, making it essential to evaluate specific energy use and opportunities for optimization or energy recovery [26]. Economic feasibility should account for both CAPEX and OPEX, including costs related to chemicals, maintenance, sludge handling, and potential savings from resource recovery. The environmental footprint must be quantified through life cycle indicators such as greenhouse gas emissions, sludge generation, and secondary pollution risks [27]. Incorporating these parameters within a circular economy framework provides a more realistic basis for sustainability claims and supports evidence-based technology selection.

3. Environmental Impact Assessment

Evaluation of the environmental sustainability of wastewater treatment technologies must be done through a comprehensive approach that is not limited to treatment efficacy [28, 29]. It requires the quantification of important indicators such as resource use, emissions, and global environmental burdens across the full life cycle of the system. Life Cycle Assessment (LCA) offers a methodologically standardized scientific basis for evaluating these assessments, and it is progressively being used as a study tool for the evaluation of both contemporary and emerging wastewater treatment technologies [30].

3.1. Life Cycle Assessment (LCA) Methodologies

Life Cycle Assessment (LCA) is a standardized, cradle-to-grave analytical framework used to quantify the environmental impacts of products and processes across their entire lifecycle, encompassing raw material extraction, construction, operation, maintenance, and end-of-life management. When applied to wastewater treatment systems, LCA provides a comprehensive evaluation of how different technologies influence key sustainability indicators, including energy consumption, greenhouse gas emissions, eutrophication potential, acidification, and resource depletion [31, 32].

Importantly, LCA outcomes extend beyond environmental accounting and play a critical role in guiding technology design and optimization. By identifying environmental "hotspots" within treatment systems such as energy-intensive units, chemical consumption, or sludge handling stages LCA supports informed design decisions, including process selection, operational optimization, and integration of renewable energy or resource recovery components. Comparative LCA further enables evaluation of alternative treatment configurations and emerging technologies against conventional systems, allowing stakeholders to balance environmental performance with operational and economic considerations. Consequently, LCA serves as a decision-support tool that strengthens the development and implementation of sustainable and circular wastewater treatment technologies.

3.1.1. LCA Analyses can Fall under Two Broad System Boundaries

- Cradle-to-Grave: Comprises all life cycle stages-from raw material extraction through operational life and final disposal.
- Cradle-to-Gate: Includes the system stages from raw material procurement through to when the treated effluent passes out of the facility and excludes downstream impacts, such as reuse or distribution.

Life Cycle Assessment is carried out following ISO 14040 and ISO 14044 protocols, and generally consists of (i) Goal and scope definition, where system boundaries, functional units (for example, per m^3 of treated wastewater), and environmental impact categories, are defined, (ii) Life Cycle Inventory (LCI), where data on energy and material inputs and emissions are collected for each stage within the treatment system (iii) Life Cycle Impact Assessment (LCIA), where the LCI data are converted into potential environmental impacts using characterization models, and finally, (iv) Interpretation, where results are evaluated to identify hotspots, trade-offs, and strategies for improvement. There are several available commercial and open-source software platforms that can be used for LCA modelling, with life cycle inventory (LCI) databases:

- SimaPro (PRé Sustainability), which is one of the most commonly used LCA platforms in both academia and industry and provides access to databases such as Ecoinvent and ILCD
- GaBi (Sphera), which maintains process modelling on water, energy, and emissions from wastewater systems, with strong industrial applications
- OpenLCA, which is free and an open-source software that is being increasingly used in academic research
- Umberto NXT LCA, which combines process flow diagrams of wastewater treatment systems and material flow analysis for complex models of wastewater treatment processes.

3.1.2. Application of LCA in Wastewater Treatment

LCA has compared various technologies:

- MBRs vs. CAS (Conventional Activated Sludge): MBRs may consume more energy compared to CAS but produce higher quality effluent and less sludge [33].
- AOPs: seem to have a greater overall environmental impact due to electricity use when not powered by renewables [34].
- Anaerobic Digestion: Supports favourable LCA findings if the energy from the biogas generated can offset energy, labor, and feedstock drawn from habitated operational inputs [35].

3.1.3. Challenges and Considerations

- Data quality and insulation representativeness (site-specific vs average datasets)
- System boundary definitions and functional unit
- Allocation of the environmental burden in multi-output systems (biogas + treated effluent).

3.2. Carbon Footprint and Greenhouse Gas Emissions

3.2.1. Carbon Footprint Comparison Across Technologies

Carbon footprint, which is part of a life cycle assessment (LCA), focuses on quantifying greenhouse gas (GHG) emissions, typically in terms of CO_2-equivalent (CO_2-eq), and occurs across the life cycle of wastewater treatment technologies [36, 37]. Sources of CO_2-eq emissions can be both direct (e.g., biological processes releasing CH_4 and N_2O) and indirect (e.g., caused by the use of electricity for aeration or membranes).

Research has shown that conventional activated sludge (CAS) treatment systems are responsible for carbon footprints from 0.3 to 0.7 kg CO_2-eq m^3 of treated wastewater, primarily due to the dependence on energy-intensive aeration along with nitrous oxide emissions during nitrogen removal processes [38]. Membrane bioreactors (MBRs) also produce high-quality effluent, but generally consume considerably more energy and have carbon footprints greater than approximately 0.8 kg CO_2-eq m^3 [39].

In favourable circumstances, systems based on anaerobic digestion (AD) can result in less GHG emissions, especially when sufficiently capturing methane gas for use in generating electricity or heat, offsetting an external energy footprint. However, depending on the efficiency of the process and the boundaries set, some AD systems will be close to net-zero or negative footprints [40]. Advanced oxidation processes (AOPs) and electrochemical systems also produce higher carbon footprints as a result of electricity use, but more sustainable or lower energy use can help benefit the carbon footprints for infrastructures utilizing them [41].

3.2.2. Integration of Renewable Energy

The integration of renewable energy technologies such as solar PV, biogas produced from AD or wind turbines into wastewater treatment facilities could greatly reduce their carbon footprint. For example, modular solar-assisted electrochemical systems and electromagnetic UV reactors powered by PV for AOPs have been shown to achieve CO_2 emissions as much as 70% lower than grid connection for conventionally operated systems [42, 43]. Energy neutral or positive operations capable of heat and power generation have also been shown to work at full-scale WWTPs employing anaerobic sludge digestion with CHP units. Furthermore, hybrid systems that apply local renewable energy are increasingly being investigated, not only to mitigate climate change but also to reduce costs under time-of-use pricing and trading schemes [44–46].

3.3. Environmental Trade-Offs and Hotspots

3.3.1. Eutrophication Potential

While the removal of nitrogen and phosphorus is a critical action to prevent eutrophication of receiving water bodies, the energy and chemical inputs necessary to achieve nutrient removal (alum, ferric salts) results in significant environmental impact burdens. While biological nutrient removal processes work, they may also be a source of nitrous oxide emissions, a GHG that is nearly 300 times as potent as CO_2 [47].

3.3.2. Chemical Use

AOPs and coagulation processes generally require considerable amounts of reagents, including H_2O_2, ozone, and ferric chloride. If these materials of concern are not dosed or managed efficiently, toxic residue could occur in treated residuals, along with toxic by-products (e.g., bromate from ozonation, or chlorinated organics from electrochemical processes) [48, 49].

3.3.3. Sludge Generation

The generation and disposal of sludge is a significant environmental hotspot. Conventional systems will produce a lot of secondary sludge that will need to be dewatered, stabilized, and land-applied or incinerated, each of which carries a carbon and/or pollution burden. Anaerobic digestion reduces sludge volume and energy recovery, while membrane systems typically produce less volume of sludge, but it is more concentrated, which makes it harder to manage overall [50].

3.3.4. Hotspot Integration

LCA-based hotspot identification can show the stages that have the highest environment burdens on the treatment train. For example, as demonstrated in literature, a substantial proportion of the total energy use and emissions (over 60%) is contributed by aeration and membrane cleaning in MBR systems, and the generation of oxidants and UV lamps in AOP systems are also hotspots [51]. A treatment train must find balance between the efficiency of treatment and environmental impacts (e.g. centralized versus decentralized or reuse) [52].

4. Techno-Economic Evaluation

The applicability of large-scale wastewater treatment technologies is strongly influenced by their economic viability and long-term sustainability. While environmental performance is essential, treatment systems must also be economically feasible over their entire lifecycle, including capital investment, operational and maintenance costs, and end-of-life management [53]. Techno-economic analysis (TEA) therefore plays a central role in sustainability assessment by evaluating cost-performance trade-offs, energy expenditures, and potential revenue streams from resource recovery, such as energy generation, nutrient recovery, and water reuse. In this section, modern wastewater treatment technologies are assessed using TEA to determine their financial feasibility, scalability, and capacity to deliver environmental benefits in a manner that supports sustainable implementation across diverse economic and regional contexts (Figure 3).

4.1. Capital and Operational Costs

Capital expenditure (CapEx) covers expenditures related to infrastructure development, reactor and site-specific equipment, whereas operational expenditure (OpEx) covers expenditures on energy, labor, routine maintenance, chemicals and disposal of sludge.

Membrane bioreactors (MBRs) and advanced oxidation processes (AOPs) are associated with higher capital expenditure (CapEx) and operational expenditure (OpEx) due to the use of specialized components such as membranes, UV lamps, and ozonators. In many cases, the CapEx of these systems can be 20–50% higher than that of conventional wastewater treatment technologies [54].

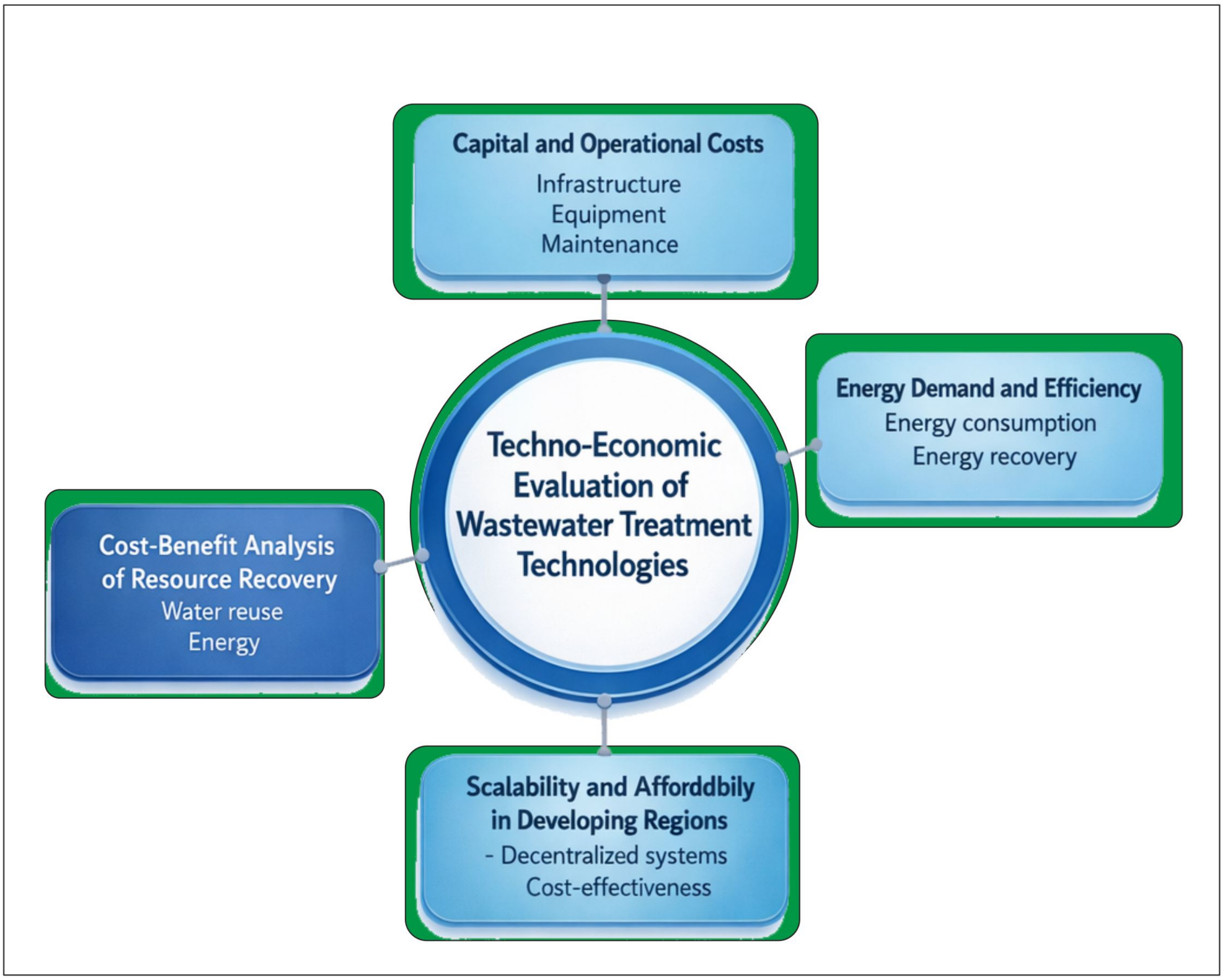

Figure 3. Techno-economic evaluation of modern wastewater treatment technologies.

In comparison to conventional systems, the OpEx of membrane systems is greater because it is not only because of fouling and regular cleaning, but also because of the energy used to aerate the tanks, and the expensive replacement of the fouled membranes. Actually, OpEx might constitute up to 60 per cent of the lifecycle expenses.

The other one, namely, anaerobic digestion (AD) has relatively moderate CapEx and, possibly, lower OpEx because of its energy-independent nature and lower volume of sludge, however, some complexity is introduced with process controls and gas management.

The local labor, the material availability and the treatment volume have a very potent impact on cost variability. Thus, it is necessary to conduct economic analysis of the site.

4.2. Energy Demand and Efficiency

One of the leading operational costs drivers and environmental burden in the systems of the wastewater treatment is energy consumption.

Conventional activated sludge (CAS) systems usually require between 0.3 and 0.6 kWh/m^3, which is predominantly used as aeration.

- MBRs use a higher amount of energy, typically 0.8–1.5 kWh/m^3 according to membrane design and influent strength [55].
- Electrochemical systems and AOPs often require $>$2.0 kWh m^{-3}, leading to high operating costs unless offset by low-cost renewable energy or incentives.
- Anaerobic systems can be energy-neutral or net-positive when biogas is efficiently recovered and used in combined heat and power (CHP) units [56].

Recovery of energy (through AD or heat exchangers) and gains to energy efficiency (e.g. low-energy blowers, state-of-the-art process controls) are becoming more important to minimize OpEx and carbon footprint.

4.3. Cost-benefit Analysis of Resource Recovery

Resource recovery has been added as a co-benefit in many of the new treatment systems, to convert waste to useful products, i.e.:

- Biogas produced from anaerobic digestion can provide electricity or heat and has significant energy value
- Nutrient recovery e.g. struvite precipitation of nitrogen and phosphorus,
- Treated water re-used for irrigation, industry, or potable water supply.

Even though resource recovery may lead to higher up-front capital costs, it can alleviate operational costs and provide revenue generation opportunities after some time. For example:

- Research by Lessmann et al. [57] found that nutrient recovery decreased the demand for fertilizers by 20%, resulting in cost savings for agro-industrial systems.
- In Singapore's NEWater system, the revenue from water reuse paid for 25–30% of the operational cost of using industrial-grade reclaimed water.

Cost-benefit analyses must assess the need for capital investment in relationship to market dynamics, purity of products generated, and incentives regulations provide in assisting with integration into a circular economy.

4.4. Scalability and Affordability in Developing Regions

Scalability and affordability are necessary for broader uptake, especially in low- and middle-income countries (LMICs), as stakeholders navigate budget concerns or infrastructure deficit issues.

- Decentralized treatment units, to include modular MBRs and constructed wetlands with low-energy AOPs, are being packaged in urban and peri-urban areas in a variety of configurations.
- Electrochemical systems and solar-assisted advanced oxidation processes may provide options for off-grid treatment needs, but many of these cases require technological support and/or durable maintenance capabilities.
- Many capital-light anaerobic baffled reactors (ABRs) or Upflow Anaerobic Sludge Blanket (UASB) systems are adopted for use in domestic and institutional wastewater in South Asia; here the costs are minimal for energy input, maintenance, and operational training needs.

Cost models for affordability should include lifecycle cost per m^3 treated, burden of maintenance, and the local capacity to implement and own technology.

5. Integration with Circular Economy and Environmental Policy

The process for advancing to sustainable wastewater treatment is increasingly necessitated by the circular economy (CE) and global environmental policy. Modern wastewater treatment technologies are evaluated not solely on contaminant removal efficiency, but also on their capacity for resource recovery, waste reduction, and compliance with social and environmental sustainability goals (Figure 4) [58, 59].

5.1. UN Sustainable Development Goals (SDGs) Compliance

Wastewater treatment systems contribute directly to multiple United Nations Sustainable Development Goals (SDGs) by improving water quality, enhancing resource efficiency, and reducing environmental impacts. SDG 6 (Clean Water and Sanitation) is supported through advanced treatment technologies such as membrane filtration and advanced oxidation processes (AOPs), which enable high-quality effluent suitable for reuse and effective removal of emerging contaminants using efficient and cost-effective approaches [60].

SDG 12 (Responsible Consumption and Production) is addressed through technologies that promote circular resource use, including anaerobic digestion and nutrient recovery systems that reduce waste generation while enabling the recovery of water, energy, and nutrients within wastewater treatment processes [61]. SDG 13 (Climate Action) is advanced by low-carbon treatment configurations, energy-efficient systems, and the integration of renewable energy sources, which collectively contribute to reducing greenhouse gas emissions and improving the climate resilience of wastewater infrastructure [62]. The successful implementation of these technologies requires not only technical innovation but also supportive policy frameworks and strong community buy-in to ensure long-term operational success and alignment with sustainability objectives.

5.2. Policy Implications and Regulatory Drivers

Regulatory structures are influential in determining how wastewater innovations will develop. In many industrialized countries, discharge limits on nutrients and micropollutants, has primarily stimulated uptake of advanced oxidation technologies (AOPs) and membrane-based technologies [63]. However, developing economies are increasingly beginning to use policy instruments i.e. pollution taxes, effluent trading, and/or green procurement programs [64].

In addition to regulatory frameworks, regional policies that fall under regional water management schemes for example, EU Water Framework Directive, U.S. Clean Water Act, and India's National Mission for Clean Ganga (NMCG), have identified water reuse, energy neutrality, and nutrient recovery, as policy goals. Effective implementation of these policies will require aligning financial incentives with environmental outcomes and enforcing assessments of sustainability based on lifecycle analysis [65].

Figure 4. Integration of modern wastewater treatment technologies with circular economy and environmental policy frameworks.

5.3. Barriers to Adoption and Scaling of Sustainable Technologies

Despite their potential, the broad-scale implementation of environmentally sustainable wastewater technologies faces a number of obstacles:

Upfront capital costs: Several technologies-including membrane bioreactors or electrochemical systems—require high amounts of supervision, leaving regions with fewer material resources unable to implement sustainable technologies [66].

Operational complexity and maintenance: Many advanced systems necessitate skilled operators, and a high frequency of maintenance which may not be available in rural or peri-urban contexts [67].

Regulatory fragmentation, including variations or outdated regulations across regions, can hinder adoption and limit incentives for implementing circular practices [68]. Addressing these barriers will take a multi-faceted approach. This requires institutional capacity building, incentivizing decentralized treatment contract models, facilitating public-private partnerships and adopting a circular economy lens to wastewater governance.

6. Case Studies and Comparative Analysis

An expanding body of real-world case studies demonstrates the technical feasibility and sustainability performance of advanced wastewater treatment technologies across diverse geographic and socio-economic settings. These applications enable comparative evaluation using standardized sustainability indicators, including life cycle environmental impacts, greenhouse gas (GHG) emissions, energy-use efficiency, land-use requirements, capital and operational costs, and resource recovery potential (Figure 5).

At the municipal scale, a membrane bioreactor (MBR) system implemented in Sweden was evaluated using Life Cycle Assessment (LCA), revealing improved effluent quality and reduced land-use requirements compared with conventional activated sludge systems. While the MBR configuration achieved lower GHG emissions due to higher treatment efficiency and compact design, it also exhibited increased energy consumption, highlighting a key trade-off between environmental performance indicators [69]. This case illustrates how LCA outcomes can inform technology selection by balancing effluent quality, spatial constraints, and energy demand.

In Singapore, the NEWater initiative represents a large-scale application of advanced oxidation and membrane filtration technologies to achieve high levels of potable water reuse. From a sustainability perspective, the system performs strongly against indicators related to water recovery efficiency, public health protection, and long-term water security. Although energy-intensive, its integration within a supportive policy framework and strong public acceptance demonstrates how governance and social indicators are critical alongside technical performance in enabling circular water infrastructure [70].

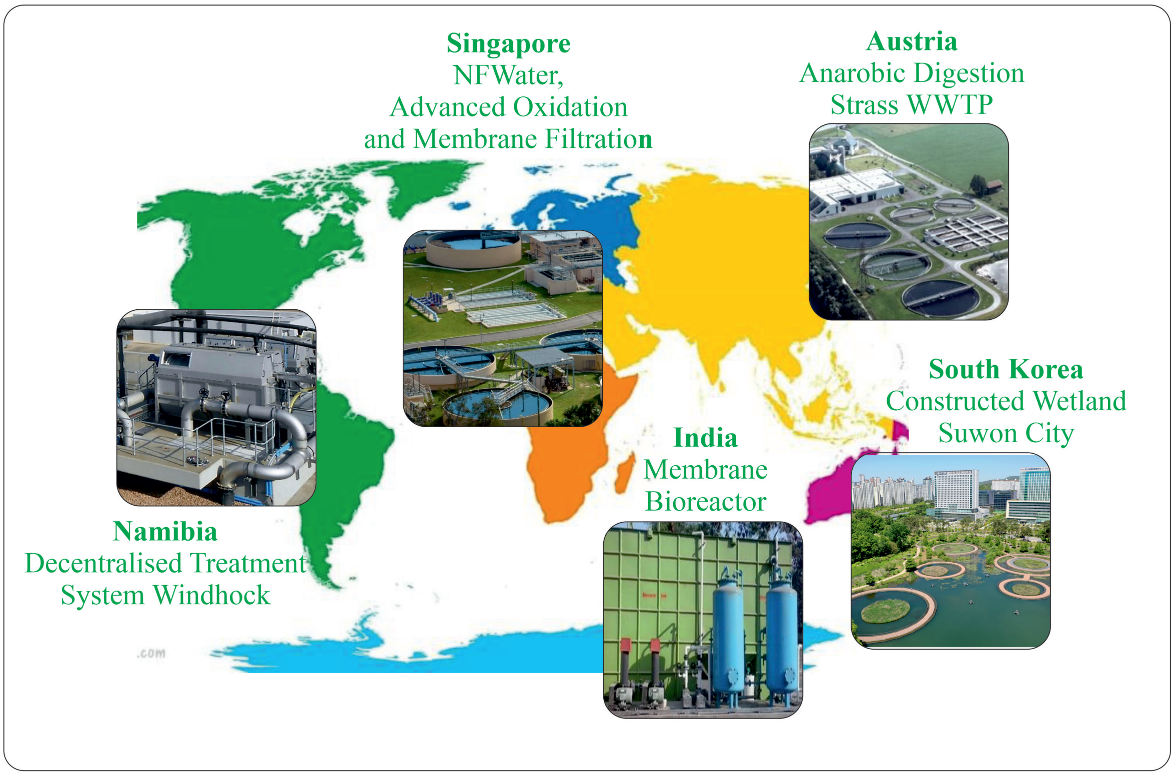

Figure 5. Global distribution of case studies and comparative sustainability assessments in wastewater treatment.

Decentralized treatment systems show distinct sustainability advantages in rural and peri-urban contexts, particularly in developing regions. A comparative study in India evaluated decentralized anaerobic baffled reactors against centralized activated sludge plants and found that decentralized systems exhibited lower GHG emissions, reduced capital costs, and improved overall sustainability when energy recovery and local water reuse were included within the system boundaries [71]. These findings emphasize the importance of defining appropriate LCA and TEA boundaries when assessing sustainability outcomes.

Comparative LCA studies further reinforce the role of resource recovery in improving environmental performance. Corominas et al. [72] assessed multiple wastewater treatment configurations and reported that systems incorporating energy recovery such as anaerobic digestion and microbial fuel cells performed better across several impact categories, including global warming potential, eutrophication, and human toxicity. However, these benefits were shown to be highly context-dependent, influenced by influent characteristics, electricity grid mix, and regulatory discharge standards.

Socio-economic and institutional factors also strongly influence sustainability outcomes. Case studies from sub-Saharan Africa and Latin America highlight the effectiveness of nature-based solutions, such as constructed wetlands, in contexts where low maintenance requirements, cost efficiency, and co-benefits (e.g., biodiversity enhancement and landscape aesthetics) are prioritized. In Kenya, such systems demonstrated favourable performance across economic and environmental indicators, whereas centralized mechanical systems often struggled due to limitations in funding, technical capacity, and maintenance infrastructure [73].

Overall, these case studies underscore the necessity of a systems-based approach to wastewater treatment selection. Sustainability performance cannot be generalized across technologies without considering local environmental targets, economic constraints, governance structures, and social acceptance. Consequently, aligning technology choice with context-specific sustainability indicators remains essential for achieving resilient and long-term wastewater management solutions.

7. Future Perspectives and Research Needs

Future wastewater treatment research must move toward quantifying sustainability indicators rather than relying solely on qualitative assessments. Emerging technologies should be evaluated using measurable metrics such as energy consumption, sludge generation rates, operational costs, greenhouse gas emissions, and resource recovery efficiency. Comparisons with conventional treatment systems are essential to demonstrate tangible improvements in environmental and economic performance.

Advancing Life Cycle Assessment (LCA) methodologies will be critical to capturing the full environmental footprint of treatment technologies, including upstream material use, operational emissions, and end-of-life impacts. Future LCAs should also integrate cost analysis and sludge management considerations to provide a more holistic evaluation of sustainability outcomes.

In resource-limited regions, research should prioritize decentralized, low-cost, and low-sludge technologies that maintain treatment efficiency while reducing environmental burden. Nature-based solutions and modular systems offer promising pathways for achieving lower sludge production and reduced operational complexity. Further, improved monitoring, data integration, and system modelling will enable quantitative assessment of sustainability benefits, supporting evidence-based decision-making. Interdisciplinary collaboration among engineers, environmental scientists, economists, and policy-makers will be essential for developing wastewater treatment solutions that are environmentally sound, economically feasible, and socially equitable.

8. Conclusions

This review underscores the growing importance of sustainable and advanced wastewater treatment technologies in addressing global freshwater scarcity and climate-related water challenges. While advanced systems such as AOPs, membrane processes, electrochemical treatments, anaerobic digestion, and hybrid configurations demonstrate strong contaminant removal and resource recovery potential, their practical application requires careful consideration of site-specific conditions, energy use, operational demands, and overall sustainability.

From a practical management perspective, techno-economic evaluations indicate that long-term sustainability improves significantly when treatment systems incorporate resource recovery pathways, including nutrient capture, energy generation, and water reuse. Embedding circular economy principles into regulatory and operational frameworks will be essential for enabling cost-effective and environmentally responsible treatment strategies aligned with global sustainability goals, particularly SDGs 6, 12, and 13.

Insights from global case studies highlight that both centralized and decentralized treatment models can be viable when supported by strong governance, stakeholder participation, and adaptive management. The increasing adoption of IoT-based monitoring and low-carbon technologies offers practical opportunities to enhance operational efficiency, improve system reliability, and expand access to sustainable treatment solutions in resource-limited settings.

Looking ahead, sustainable wastewater management will depend on interdisciplinary collaboration to ensure that technological innovation is matched with socioeconomic feasibility and policy alignment. Advancing Life Cycle Assessment (LCA) to incorporate regional, social, and economic dimensions will strengthen its role in guiding evidence-based decision-making. Ultimately, future wastewater systems must prioritize resilience, circularity, and equitable access, enabling communities to transition toward more sustainable and climate-adaptive water management practices.

Author Contributions

V.G.: Conceptualization, Visualization, Data curation, Writing original draft; R.K.: Data curation, Formal analysis, Methodology, Validation, Writing—reivew and editing; S.M.: Visualization, Validation, Supervision, Writing—review & editing. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this manuscript.

Use of AI and AI-Assisted Technologies

During the preparation of this manuscript, the authors used the Grammarly tool for English language editing and grammatical corrections. Following this assistance, the authors carefully reviewed and revised the content and take full responsibility for the accuracy, originality, and integrity of the manuscript.

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