Emerging Technologies for Water and Wastewater Treatment: Advances, Challenges, and Future Perspectives

Afshin Maleki*

Environmental Health Research Center, Research Institute for Health Development, Kurdistan University of Medical Sciences, Sanandaj, Iran

Abstract: Emerging approaches to water and wastewater treatment can complement established processes, but high removal in laboratory tests rarely indicates how well a technology will perform in practice. This targeted critical review examines advanced oxidation, membranes, electrochemical and bioelectrochemical systems, functional adsorbents, biological innovations, hybrid trains and digital tools. Rather than comparing removal percentages in isolation, it considers contaminant fate, matrix effects, operating demands, residual management, environmental burdens and the maturity of supporting evidence. Each technology has conditional strengths: oxidation can transform persistent organics but may create toxic intermediates; membrane separation and adsorption generate concentrates or spent materials; biological and resource-recovery processes depend on stable operation and suitable feed characteristics. The proposed application-specific framework links the treatment objective and wastewater matrix to process limitations, evidence scale and system-level trade-offs. Across the literature, the most persistent gaps concern sustained real-wastewater trials, material durability, secondary residues and comparable energy, cost and life-cycle reporting. Decisions therefore require evidence from complete treatment trains, not laboratory performance alone.

Keywords: Advanced oxidation, Biochar, Hydrochar, Membrane technology, Resource recovery, Technology readiness, Wastewater treatment, Water treatment.

1. INTRODUCTION

Water security is shaped not only by freshwater availability but also by treatment capacity, pollution pressures and the ability to reuse water safely. Expanding urbanization, industrial activity and climate-related stresses increase pressure on water infrastructure, while wastewater remains an underused resource in many settings [1]. At a broader environmental scale, evidence of transgressed planetary boundaries, including freshwater change, underscores the need to assess water management as part of Earth-system sustainability [2]. Treatment priorities have broadened from conventional organic matter, nutrient and pathogen control to include persistent organic micropollutants, complex industrial mixtures and increasingly stringent reuse objectives [3, 4].

Clarification, biological treatment, filtration and disinfection remain essential, yet no treatment train works equally well for every contaminant or wastewater matrix. Sorption and membrane rejection transfer pollutants into residual streams; oxidation changes their chemical identity and may leave harmful intermediates. Comparing processes by the disappearance of a target compound alone therefore overlooks both effluent quality and the burden of managing what remains [3, 5, 6].

Recent developments include photocatalytic materials, new membrane configurations, electrochemical reactors, biomass-derived sorbents, biological systems and digital control. The evidence supporting them varies substantially: some conventional membrane reuse trains and biological configurations have operating-plant records, whereas many novel materials have been tested only under controlled laboratory conditions. This review therefore considers treatment performance alongside the realism of tested water matrices, operational durability, residual management and evidence of deployment. Studies coauthored by Maleki on photocatalysis, sorbents and prediction models are assessed against the same criteria as independent studies [7-11].

Growing concern about trace organic pollutants also requires distinguishing contaminant detection from demonstrated treatment risk. Pharmaceuticals, pesticides, persistent fluorinated substances and disinfection-sensitive precursors have different removal pathways, and the suitability of a technology depends on source-water characteristics and intended reuse standards. For example, a process that achieves high dye decolorization under laboratory conditions may provide limited evidence for removal of mixtures of low-concentration pharmaceuticals or PFAS. This distinction motivates a treatment-objective-based synthesis rather than a generalized ranking of advanced technologies [12, 13].

Bulk indicators can also misrepresent risk: lower chemical oxygen demand does not necessarily imply the removal of biologically active micropollutants. Relevant endpoints depend on exposure, persistence,

*Address correspondence to this author at the Environmental Health Research Center, Research Institute for Health Development, Kurdistan University of Medical Sciences, Pasdaran Blvd., Sanandaj, Kurdistan Province 6616613391, Iran; Tel: +98 87 33661817; E-mail: maleki@muk.ac.ir

Received on 04-09-2026 Accepted on 23-10-2026 Published on 02-11-2026

E-ISSN: 2311-8741/26

detection limits and receiving-water or reuse requirements. For separation processes, the contaminant mass retained in a concentrate or spent solid remains part of the assessment; for oxidation, transformation products and post-treatment toxicity matter as well [3-5, 12].

Previous reviews provide detailed accounts of individual technologies, including advanced oxidation, photocatalysis, potable-reuse membranes and conventional versus emerging treatment options [4-6, 12]. What is less consistently addressed across these separate literatures is how to compare different processes against the same treatment objective without confusing degradation with separation, laboratory promise with field reliability, or nominal removal with net environmental benefit. The present review brings these distinctions into one qualitative framework. Its contribution is not a new technology ranking, but a transparent way to identify which evidence and operating conditions are needed before a process can be recommended for a particular wastewater.

2. REVIEW METHODOLOGY

This work is a targeted structured critical review, not a systematic review or a PRISMA-based evidence synthesis. Candidate literature was identified through targeted scholarly discovery, examination of publisher-hosted and bibliographic article records, and backward checking of reference lists from relevant studies and reviews. The topics used to guide discovery combined water or wastewater treatment and reuse with specific process families: advanced oxidation, photocatalysis, membranes, electrocoagulation and other electrochemical methods, biochar and hydrochar, aerobic granular sludge, anammox, microalgae, hybrid treatment, resource recovery, and digital twins. These terms describe the conceptual search blocks, not archived, reproducible database-specific search strings. Publications from 2018–2026 received emphasis, while earlier foundational studies were retained where they were needed to frame a treatment mechanism or established application. The precise databases, dates, Boolean strings and numbers screened were not prospectively logged and cannot now be reconstructed reliably; no claim of exhaustive retrieval is made.

The purposive selection favored directly relevant water-treatment studies reporting interpretable evidence on pollutant removal or transformation, operational conditions, matrix effects, reactor configuration, stability, residuals, demonstration scale or environmental and economic consequences. Studies confined to material synthesis without demonstrated water-treatment relevance were not used as primary operational evidence. Experimental papers were used for their reported test configurations and results; published critical reviews were used to frame mechanisms and research trends; institutional reports were used for broader water-management context. Exclusion from the narrative should not be understood as a formal quality-based rejection of every unselected paper. Records were compared by treated-water objective, pollutant type and concentration, real versus synthetic matrix, batch or continuous operation, test duration, energy and reagent inputs, residual management, and evidence for regeneration or replacement.

Critical appraisal was qualitative and domain-specific, rather than a numerical quality score or meta-analysis. The evidence was differentiated into: (i) mechanistic and batch laboratory demonstrations, often with model solutions; (ii) continuous-flow testing, with explicit attention to whether the influent was real wastewater; (iii) pilot operation at relevant loads and durations; and (iv) documented full-scale operation. These are descriptors of the evidence associated with a specific configuration, not readiness labels automatically transferable to an entire technology family. Reported removal, degradation or recovery was interpreted with its corresponding matrix, treated volume, operating period, system boundary and measured endpoint. Studies with dissimilar functional units or water-quality targets were not pooled or assigned comparative numerical performance ranks [3, 5, 6, 14, 15].

The analysis first considered the strengths and limitations within each technology family and then applied the common criteria to alternative treatment objectives (Section 7; Table **1**). Particular attention was paid to whether a process destroys a contaminant, transfers it to a separate residual stream, or recovers a usable product; possible unintended impacts were tracked alongside the stated treatment benefit. The included 73 references form a purposive, non-exhaustive selection, not an auditable count of all eligible studies. Unrecorded search dates, platform-specific strings, inclusion-flow counts and any missed publications limit reproducibility and introduce possible selection bias. Studies coauthored by Maleki were assessed against the same relevance and evidence-scale criteria as other publications; no formal risk-of-bias instrument or quantitative synthesis was applied.

3. DEFINING AND EVALUATING EMERGING TECHNOLOGIES

An emerging technology may introduce a different mechanism, a new material or reactor design, or a

Table 1: Qualitative Application-Specific Comparison of Treatment Objectives, Relative Advantages, Residual Burdens and Evidence Maturity. The Entries are Conditional and do not Represent Universal Rankings

Technology platform	Suitable objectives / wastewater context	Comparative advantage	Principal limitation, secondary burden and evidence caution
AOP / photocatalysis	Polishing refractory dissolved organics after adequate pretreatment; matrix chemistry must be considered	Potential transformation of target compounds	Oxidant/electricity demand, transformation products and toxicity; many novel catalysts have short bench-scale evidence [5, 6, 16–23]
Membranes	Specified dissolved-solute rejection and fit-for-purpose reuse; process depends on salinity and product standard	Selective barriers; established RO reuse trains have operational experience	Fouling, cleaning, heat/power and concentrate; novel FO/MD materials cannot inherit RO maturity [4, 24–33]
Electrochemical	Appropriate conductive industrial, colloidal, metal-bearing or oily streams; selectivity depends on water chemistry	In situ coagulation, targeted oxidation or ion separation	Electrode consumption/passivation, sludge or by-products and electrical demand; full-scale claims are process-specific [34–39]
Bioelectrochemical	Selected streams compatible with microbial electron transfer and recoverable products	Possible coupling of biological conversion and electrical functions	Auxiliary energy, electron-transfer rates and electrode stability; net-positive scale-up is not established generically [40]
Functional adsorbents	Targeted polishing where competing solutes and regeneration can be managed	Flexible selective uptake; potentially modular operation	Spent sorbent/regenerant, material manufacture and breakthrough; modified biochars often supported by batch evidence [9–11, 41–48]
Biological innovations	Biodegradable wastewater and nutrient control; AGS, PN/A and algae fit different conditions	Potential efficient removal or nutrient assimilation in suitable regimes	Biomass stability, temperature, nitrite control and harvesting; full-scale AGS evidence not transferable to PN/A or algae [49–59]
Hybrid trains	Multi-pollutant wastewaters needing complementary treatment functions	Can pair separation, oxidation and biological pathways	Additional units, by-products, operator and capital burdens; synergy requires matched benchmark [40, 60–63]
Digital tools	Monitoring/control of instrumented treatment systems with representative operating data	Prediction, anomaly detection and optimization support	Sensor drift, external validation and human safeguards; model accuracy does not prove facility savings [11, 71, 72]

substantial modification of an established process. Novelty, however, says little about whether the change improves treatment. The comparison here uses four related dimensions: effectiveness against a defined effluent target; operational feasibility; environmental implications; and maturity of evidence. Removal, selectivity and possible mineralization must be interpreted against influent concentration, matrix complexity, contact time and analytical detection. Adsorption and membranes generally retain contaminants in another stream, whereas oxidation may form products that require further characterization.

Operational feasibility covers power and reagent requirements, fouling, cleaning, regeneration and the stability of catalysts, electrodes or biomass under variable loading. Environmental evaluation extends beyond the reactor to material production, emissions, spent media and other residuals. Techno-economic and life-cycle comparisons are meaningful only when the functional unit, water-quality endpoint and system boundary are sufficiently aligned.

Evidence maturity belongs to a particular configuration, not to an entire technology category. A synthetic-water batch experiment can establish a plausible mechanism; it cannot demonstrate steady performance under variable influent quality or predict long-term maintenance. Continuous-flow tests with real wastewater, pilot campaigns and documented operating plants answer progressively different practical questions. Accordingly, Table **1** reports conditional strengths and remaining uncertainties rather than a universal readiness score [14, 15].

For cross-study interpretation, the denominator in reported metrics is as important as the numerator. Percent removal, adsorption capacity per gram, apparent degradation rate constants, energy per treated volume and energy per order of pollutant reduction quantify different aspects of performance. They cannot be collapsed into a single score without normalizing the influent matrix, treatment endpoint, recoveries and uncertainty. Likewise, a technology readiness label requires evidence of operating duration and scale, not simply a high removal percentage. The review therefore favors transparent trade-off descriptions over unsubstantiated numerical scoring [5, 14, 16].

4. EMERGING TREATMENT TECHNOLOGY PLATFORMS

4.1. Advanced Oxidation and Photocatalytic Processes

Advanced oxidation processes (AOPs)—including ozone-, UV-, Fenton-, persulfate- and electrochemically driven treatments—can degrade recalcitrant organic pollutants through reactive chemical species. Applicability depends on water chemistry, oxidant utilization, competing reactions and electrical demand. Cross-process energy comparisons demonstrate why removal efficiency cannot be treated as the sole optimization objective [5]. Heterogeneous photocatalysis may broaden light-driven treatment options, but photon delivery, catalyst recovery, deactivation and real-matrix interference remain substantial engineering obstacles [6].

Two studies involving Maleki show the value—and limits—of pairing treatment experiments with additional endpoints. Kohzadi *et al*. examined Rhodamine B photocatalysis with neodymium-doped TiO_2, incorporating predictive modelling and toxicity assessment [7]. Salehzadeh *et al*. studied magnetic Mo–ZnO/Fe_3O_4 composites for phenol treatment in hydrothermal-carbonization wastewater [8]. These examples move beyond parent-compound removal, but do not establish reactor durability or performance at treatment-plant scale.

Recent reviews address oxidant activation, mineralization, catalyst stability and competition from background water constituents. Together they show why favorable reaction chemistry does not by itself make an oxidation process suitable for a treatment plant [16-21].

The mechanism of oxidation requires careful definition because hydroxyl radical production is not the sole pathway in all advanced oxidation systems. Selective oxidants, matrix scavengers and reactive halogen species can alter kinetics as well as product distributions. Sulfate-radical and photo-Fenton systems may perform differently from UV/H_2O_2 under identical nominal oxidant doses, and comparisons are meaningful only when pH, background inorganic ions, dissolved organic matter and irradiation conditions are sufficiently characterized. Mechanistic confirmation should rely on multiple complementary analytical approaches rather than an isolated radical-quenching experiment [22].

Photocatalysis must be evaluated at reactor scale as well as material scale. Catalyst immobilization, photon distribution, mass transfer and solids recovery may determine feasibility even when suspended particles achieve rapid degradation in a batch test. Where the treatment objective warrants it, parent-compound measurements should be accompanied by mineralization indicators, transformation-product analysis and toxicity testing [23].

Dissolved organic carbon and bicarbonate may consume reactive species; chloride can alter oxidant pathways and the distribution of by-products. Faster disappearance of an analyte may therefore coexist with incomplete hazard reduction. For the wastewater of interest, energy demand, residual oxidant, plausible transformation products and post-treatment toxicity are more informative than a single removal value [5, 16, 18, 21].

Photocatalytic studies also differ in lamp intensity, optical path, irradiated area, catalyst loading and photon flux. These differences affect measured rates and make extrapolation from suspended nanoparticles under intense illumination to immobilized flow reactors unreliable. Reports on promising catalysts should document leaching, recovery losses, deactivation, repeated use and electricity consumption. The Maleki-associated studies [7, 8] contribute to the discussion of photocatalysis and ecotoxicology, but not to proof of full-scale feasibility.

4.2. Advanced Membrane-Based Technologies

Advanced membrane development seeks greater selectivity, fouling resistance and integration into reuse trains. Established nanofiltration and reverse osmosis can contribute to high-quality reclaimed water in multiple-barrier systems, but concentrate disposal, membrane integrity, cleaning and electricity demand must be considered together [4]. Forward osmosis and membrane distillation offer specialized operating advantages, although draw-solution regeneration, wetting, scaling and heat demand constrain their competitiveness. Membrane bioreactors combine biomass retention with separation but require robust fouling control. In contrast to oxidative treatment, membrane rejection ordinarily relocates contaminants rather than destroying them. Membrane-based treatment has also been reviewed in the context of sustainable development and circular water management [24].

Implementation evidence is strongest for membrane-based potable reuse trains rather than for every novel membrane concept. Tang *et al*. [4] describe applications in California and Singapore where reverse osmosis functions as part of a multi-barrier approach. This practical experience supports the feasibility of membrane-enabled reuse,

but does not establish that newer forward-osmosis or membrane-distillation configurations have equivalent maturity. Their evaluation should distinguish the energy required for primary separation from draw-solute recovery or heat supply, and should account for concentrate disposal, pretreatment, membrane replacement, and monitoring. Comparisons expressed only as membrane flux or contaminant rejection can obscure these treatment-train costs.

The literature also describes distinct membrane challenges. Reviews address electrodialysis, forward osmosis and membrane distillation for metal-bearing wastewater [25]; membrane-distillation wetting associated with mineral scaling [26]; nanofibrous designs intended to reduce fouling [27]; and conductive membranes proposed for localized Joule heating and fouling or wetting monitoring [28]. They concern different operating problems and provide different levels of validation.

Water-quality targets govern the selection of membrane barriers. Reverse osmosis may be appropriate where extensive dissolved-solute rejection is required; nanofiltration can be sufficient for some less demanding applications. The viability of forward osmosis depends partly on draw-solute recovery, while membrane distillation depends on heat availability, thermal gradients, scaling and wetting. Permeability or flux alone cannot resolve their relative performance [4, 29].

Fouling control is a central example of the distinction between material-level improvement and system-level benefit. Hydrophilic surface modification, modified feed channels, cleaning protocols and advanced monitoring can reduce particular fouling mechanisms, but performance can differ across organic, colloidal, biological and inorganic foulants. For reverse-osmosis systems, site-specific biofouling can increase operating pressure and cleaning frequency [30]. Pilot validation should report transmembrane pressure, normalized permeability, chemical-cleaning frequency, irreversible fouling and membrane lifetime. Concentrate disposal is especially consequential for reuse systems: successful contaminant rejection into a smaller stream does not eliminate the contaminant burden [29, 31-33].

A potable-reuse barrier requires more stringent verification than an industrial process-water train with lower quality requirements. Suspended solids and organic loading may make pretreatment decisive; saline concentrates may determine disposal feasibility. Novel forward-osmosis, membrane-distillation or conductive designs therefore need their own evidence of water quality, auxiliary demands and sustained operation, rather than inheriting the maturity of reverse-osmosis reuse systems [4, 24-29].

Durability evidence remains especially uneven for novel coatings and conductive membranes. A study showing improved flux recovery after one cleaning cycle does not establish resistance to months of mixed-foulant exposure. Long-term reporting should include normalized permeability, selectivity drift, cleaning chemical and water use, membrane replacement, loss of functional coating and concentrate characteristics. Operational comparisons should therefore use equivalent product-water specifications and include pretreatment and post-treatment, not only intrinsic membrane material properties [26–33].

4.3. Electrochemical and Bioelectrochemical Technologies

Electrooxidation, electrocoagulation and capacitive deionization offer electrically driven routes for contaminant transformation, in situ coagulation and ion separation. Performance depends on electrode selection, current density, conductivity and wastewater chemistry. Electrode passivation, by-product formation, concentrate or sludge handling and electricity intensity can offset apparent process advantages. Bioelectrochemical configurations connect microbial metabolism with electron transfer and may enable coupled removal and resource recovery, but electrode costs, low-rate performance and scale-up remain critical questions. Evidence should be judged under matched water-quality targets rather than by comparing isolated laboratory efficiencies. Reviews of electrocoagulation further emphasize its application-specific mechanisms, operating conditions, and sludge-related trade-offs [34].

The applications reported for electrochemical treatment differ appreciably. Reviews cover contaminant-rich effluents and oxidation pathways [35, 36], as well as the particular salinity and oil-related problems of produced water [37]. A continuous-flow electrocoagulation–flotation study in municipal wastewater examined variations in current density and weather-related influent conditions [38]; a separate review addresses mine-water chemistry and metal removal [39]. None of these sources provides a universal energy or removal benchmark for all electrochemical processes.

Capacitive deionization and other selective electrochemical separations address a different task from the destruction of refractory organics. Their application is sensitive to ionic strength, target-ion selectivity, regeneration cycles and scaling. In systems targeting resource recovery, the value of concentrated

product streams should be assessed against electricity demand and product purification costs. Bench experiments using simplified salts are useful for studying electrode properties but cannot alone substantiate selective recovery in real municipal or industrial effluents.

Electrical processes introduce a distinctive accounting challenge: the reactor may reduce purchased reagents while increasing power demand or sacrificial electrode consumption. For electrocoagulation, the mass of metal released from the electrodes, sludge production and downstream solids handling should be reported; for electrooxidation, current efficiency and energy normalized to useful treatment must accompany pollutant transformation data. In saline waters, chloride-derived oxidants can improve apparent removal while increasing the importance of by-product characterization. Pilot comparisons must also document conductivity control, electrode cleaning and replacement schedules [34–39].

Bioelectrochemical reactors may link microbial conversion with electrical recovery, but a favorable electrode-level energy balance need not imply a plant-wide benefit. Pumping, mixing, separation, electrode replacement and other auxiliary requirements must also be included. The literature on electrochemical–biological integration [40] supports investigation of combined treatment, not general claims that microbial fuel cells or microbial electrolysis cells are energy-positive or ready for full-scale operation. These remain questions for configuration-specific testing.

4.4. Advanced Adsorption and Functional Materials

Adsorption is operationally flexible and can be integrated as a selective polishing stage. Functional biochar and hydrochar, magnetic materials and other engineered sorbents provide opportunities to tune surface chemistry and binding sites. However, surface area alone does not determine uptake: pollutant structure, pore accessibility, pH, ionic strength and competition from dissolved constituents also matter. Biomass-derived sorbents are attractive when feedstock availability and production impacts are favorable, but chemical activation and regeneration can raise costs and environmental burdens. General biochar and hydrochar reviews discuss how feedstock, processing conditions, oxygen-containing surface groups, pore accessibility, and sorbate chemistry jointly affect adsorption behavior [41-44].

In relevant studies, Kohzadi and colleagues evaluated modified hydrochar for methylene blue adsorption [9], iron-modified hydrochar and biochar for Rhodamine B removal [10], and machine-learning prediction of malachite green uptake on wheat-straw-derived hydrochar [11]. Together these examples show how surface engineering and data analysis can improve laboratory understanding. They also expose a key translation gap: single-solute batch performance and model fit do not establish breakthrough behavior, sorbent regeneration, competing-solute effects or practical cost. Future studies should prioritize real matrices and repeated fixed-bed adsorption–desorption cycles.

Recent reviews distinguish the performance of biomass-derived sorbents according to feedstock, thermal processing, modification chemistry and contaminant class. General biochar assessments discuss separation mechanisms, performance variability and cost implications [41, 42]; hydrochar reviews address surface functionality, metal binding, regeneration and reuse [43, 44]. Phosphorus-rich biochar/hydrochar has additional metal-binding mechanisms, but its environmental risks require separate appraisal [45]. Industrial-waste-derived biochar has been specifically reviewed for dyes and heavy metals [46], while broader heavy-metal-focused assessments discuss biochar adsorption pathways and constraints [47, 48]. These sources complement, rather than independently validate the real-wastewater scalability of, the Maleki-coauthored batch adsorption studies [9-11].

For engineered sorbents, the key question is often sustained working capacity rather than equilibrium uptake. Natural organic matter and competing solutes may change breakthrough, while regeneration is useful only if the material retains capacity and the spent regenerant can be managed. Reviews identify stability, leaching and repeated use as material-specific concerns [41, 44, 47].

A low-cost feedstock does not necessarily produce a low-cost adsorbent. Washing, drying, thermal or hydrothermal treatment, chemical activation, shaping, transport and spent-material handling can outweigh the value of the raw material. Batch capacities obtained at high contaminant concentrations may also say little about polishing trace pollutants. Fixed-bed breakthrough, competitive sorption, regeneration over repeated cycles, fines release and disposal must therefore be assessed before a cost advantage is claimed [9-11, 41-48].

Hydrochar and pyrolytic biochar differ in surface oxygen functionality, carbon structure and pore development, with considerable variation by feedstock and processing conditions [41-44]. Chemical

modification can improve affinity for a selected compound while increasing activation burden or possible leaching. The Maleki-coauthored dye-adsorption and prediction studies [9-11] demonstrate laboratory-level opportunities; column performance and multi-cycle regeneration remain necessary to support application claims.

4.5. Advanced Biological and Biotechnological Processes

Full-scale aerobic granular sludge (AGS) operation offers firmer implementation evidence than short experiments with emerging biological configurations [49]. Nevertheless, treatment stability remains dependent on wastewater temperature, hydraulic loading and nutrient composition. Comparisons with activated sludge are more informative when they report start-up duration, biomass retention, variable effluent quality and operator interventions alongside average removal.

Aerobic granular sludge, partial nitritation–anammox and microalgal treatment provide distinct routes to improved nutrient management. A comparison of microbial communities in full-scale aerobic granular-sludge and flocculent-sludge plants supplies field-based evidence for AGS, but does not establish universal performance under all influent conditions [49]. For mainstream partial nitritation–anammox, consistent nitrite provision and reactor configuration are central technical questions, rather than only short-term nitrogen removal efficiency [50]. Microalgae-based treatment can assimilate nutrients and yield biomass, but the costs and feasibility of harvesting remain an important barrier to scale-up [51]. Other reviews on granule formation, biomass stability and integrated bioprocesses provide additional context; their specific findings should not be generalized beyond the configurations evaluated [52-58].

Evidence on granular systems addresses different questions. AGS studies describe granulation, storage and restart limitations [52, 54], while work on anammox granulation concerns microbial organization rather than proof of stable mainstream operation [53]. AGS–membrane bioreactor reviews discuss possible fouling interactions [55]; other investigations examine rapid granulation and cationic contaminants [56], microalgal remediation [57] and algae–bacterial granulation [58]. These findings should remain attached to the configurations actually studied.

Aerobic granular sludge is distinguished by microbial spatial organization and excellent settling potential rather than by a fundamentally new pollutant chemistry. Gradients within granules can support different redox niches, but granule morphology, filamentous growth and disintegration depend on loading, feeding regime and hydrodynamic selection. Evidence from operating plants is therefore valuable, yet plant-specific granulation success should not be extrapolated automatically to different industrial wastewater compositions or climates. Reporting stable nitrogen and phosphorus removal over extended operation is more meaningful than reporting granule size alone [52, 54].

The central bottleneck for mainstream partial nitritation–anammox is stable ecological control at comparatively dilute nitrogen loadings and variable temperatures. Suppressing nitrite-oxidizing bacteria while sustaining ammonia-oxidizing and anammox activities is difficult; process-wide environmental evaluation should also examine any associated nitrogen-oxide emissions rather than assuming an automatic climate benefit [50, 53]. Microalgal cultivation can assimilate nutrients and generate potentially recoverable biomass, but harvesting, dewatering, light availability, seasonal variability and safe biomass end use require separate assessment [51, 57-59].

AGS, mainstream partial nitritation–anammox and algae-based processes impose different operating burdens: maintaining granule retention, controlling nitrite oxidizers, and providing light and biomass harvesting, respectively. Their maturity is equally uneven. Evidence from a full-scale AGS application [49] should not be equated with a short laboratory test of anammox or microalgae, even when the reported nutrient removal appears similar [50, 51, 53, 57].

Meaningful comparisons across these biological systems require data on seasonal temperature, hydraulic load, influent variability and sustained compliance. Mechanistic laboratory results are valuable, but they cannot establish the staffing requirements or reliability of a utility-scale installation [49-51, 53, 57].

4.6. Hybrid and Process-Intensified Systems

Hybrid trains are useful when their components address different limitations of a wastewater stream. Combining an advanced oxidation process with a membrane bioreactor, for instance, may improve the treatment of less biodegradable pollutants or certain fouling conditions [60]. Yet each added stage brings costs, operating demands and possible residuals. The proper comparison is with a simpler train that meets the same effluent target, using equivalent boundaries [61].

The hybrid evidence is not uniform: the AOP–MBR literature focuses on oxidation-mediated polishing and

process integration [60], whereas the membrane-fouling review distinguishes direct foulant removal from changes in mixed-liquor characteristics [61]. Electrochemical–biological integrations offer complementary redox and biodegradation mechanisms [40]; pharmaceutical-wastewater reviews support their investigation but not universal cost-effectiveness [62]. A low-voltage electrocoagulation–submerged MBR study supplies configuration-specific evidence for greywater treatment and fouling mitigation, with aluminum management remaining an operational consideration [63].

Hybrid processes should be evaluated according to the problem each unit solves. Oxidation before biological treatment may increase biodegradability but can also consume energy and generate compounds inhibitory to downstream biomass; oxidation after biological treatment targets residual trace organics but may still require quenching or by-product monitoring. Similarly, coupling adsorption to membrane filtration can buffer certain foulants, yet introduces the need to replace or regenerate the adsorbent. Synergy therefore must be demonstrated against a common effluent-quality target using the same influent, rather than inferred merely from a high combined percentage removal [61].

A hybrid configuration should not be called synergistic solely because it achieves high overall removal. The combined process needs comparison with a suitable non-hybrid treatment train under matched influent and effluent conditions; energy, maintenance and all secondary streams belong in that comparison [40, 60-63].

5. WATER REUSE, RESOURCE RECOVERY, AND CIRCULAR TREATMENT SYSTEMS

Wastewater offers opportunities to recover water, nutrients, energy and useful materials. Struvite precipitation, ammonia separation and biogas generation serve different purposes and require different downstream handling. Their environmental value depends on product quality, chemical and energy demand, methane losses, transport and viable markets. Soo *et al*. review these choices for different wastewater streams [64]. A recovery percentage alone does not establish a circular benefit.

Resource recovery should be measured against a realistic counterfactual. Nutrient products require mass recovery, purity and suitable end use; gross biogas generation must be distinguished from net savings after upgrading and methane losses. Accounting rules, local substitution benefits and markets determine whether a recovery process has an environmental advantage [64].

Recent resource-recovery and algal-valorization studies likewise identify product quality, material balances, energy use and market access as constraints on practical recovery [59, 65-67].

Nutrient recovery illustrates why measured removal and useful recovery must be reported separately. Struvite precipitation may simultaneously capture ammonium and phosphate in a reusable mineral, but its yield depends on pH, magnesium supply, competing calcium species and reactor mixing [68]. Product purity and fertilizer acceptance determine whether the recovered solids have a viable market. Electrochemical recovery may reduce certain reagent additions or enable targeted extraction; nevertheless, its electricity, electrode and downstream product-separation requirements must be included when comparing it with conventional precipitation [69].

Biogas can offset a plant's heat or electricity use, provided that gas cleaning, digestate management and fugitive methane are accounted for [65, 66]. Recovery of phosphorus from sewage-sludge incineration ash has different feedstock and contamination constraints from struvite precipitation in a liquid sidestream [70]. The mass and quality of recovered products, not merely diversion of a waste stream, determine the practical result.

Water reuse priorities should be differentiated by purpose. Irrigation, cooling, industrial process water, aquifer recharge and potable reuse impose different microbiological and chemical requirements, so an unnecessarily intensive train may waste energy without proportional risk reduction. Conversely, assuming that a single barrier is adequate can understate residual hazards. Fit-for-purpose decision-making requires explicit reuse standards, failure safeguards and contaminant monitoring, together with public health and environmental oversight [4, 64-66].

Recovered struvite or other nutrient products may contain impurities and depend on local fertilizer acceptance. Biomass and biogas schemes additionally face separation energy, safe end use, gas cleaning and methane containment. These factors should be included in the same system boundary used to claim circular benefits [59, 65-70].

6. DIGITALIZATION AND INTELLIGENT WATER TREATMENT

Sensors, machine learning and digital twins can improve monitoring and support treatment control; they do not themselves remove pollutants. Laboratory adsorption models associated with Maleki show predictive potential under the conditions studied [11], but plant use requires representative inputs,

independent validation and attention to uncertainty as influent quality changes. Digital twins additionally depend on calibrated instruments and regular maintenance. Their operational value should ultimately be judged by measured improvements in reliability, energy demand or chemical use [71].

Dynamic modelling and wastewater-monitoring reviews similarly emphasize well-defined control objectives, calibrated sensors and validation under actual process conditions [72].

For predictive models, we recommend clear separation of model development and testing, reporting of measurement uncertainty and validation on genuinely independent operating periods. Randomly splitting highly correlated laboratory observations may exaggerate performance outside the training conditions. Documentation of data provenance, data-leakage safeguards and recalibration is proposed here as good validation practice, not presented as a finding demonstrated by every cited wastewater-control study [7, 11, 71, 72].

Sensor drift, equipment replacement and unanticipated disturbances can weaken the connection between a digital twin and the plant it represents [71, 72]. Operator override and fail-safe procedures are therefore recommended as implementation safeguards. These are proposals of the present review, not outcomes directly established by the cited digital-twin studies.

7. DISCUSSION: CROSS-TECHNOLOGY COMPARATIVE ASSESSMENT

The comparison in this review addresses a practical choice: which treatment function is required for a defined wastewater, and what evidence supports achieving that function without unacceptable secondary burdens? Table **1** applies the four dimensions set out in Section 3 to each platform: relevant treatment objective and matrix, relative strength, principal operational and environmental trade-offs, and demonstration-scale caution. The comparison is qualitative because the cited studies do not share common influents, functional units or operating boundaries. It does not imply that a technology family has one uniform level of maturity [4-6, 14, 15, 49].

7.1. Suitability for Wastewater Characteristics and Treatment Objectives

For relatively biodegradable municipal wastewater, biological treatment often provides a practical primary treatment function, while membrane barriers may be added when the specified reuse quality demands further separation [4, 49]. For a treated effluent containing recalcitrant organic micropollutants, AOPs can be considered as polishing steps if radical scavenging, transformation products and energy demand are controlled [5, 16]. These are conditional treatment-train choices, not claims that either family will outperform others at every site. High suspended solids or organic loading can make membrane fouling and oxidation demand more consequential; efficient pretreatment may therefore change the preferred option [5, 24, 30].

Industrial effluents require a different analysis. Conductivity, salinity and the identity of metals, colloids or oily constituents influence the feasibility of electrocoagulation and related processes, as do sludge and electrode requirements [34-39]. Engineered sorbents may serve as polishing media where competition and regeneration are manageable, but single-dye batch data cannot establish performance in mixed effluents [9-11, 41-44]. Heat availability and concentrate disposal may also determine whether a membrane or electrochemical route is preferable for saline streams [25, 26, 37].

A fair comparison begins with the same product-water requirement and a transparent functional unit. Percent removal, energy per cubic meter, adsorption capacity and energy per order address different endpoints and cannot be compared directly without contextual denominators. Where available, a continuous-flow real-water experiment is more informative about operating sensitivity than a short synthetic batch test; full-scale RO reuse experience and an examined full-scale AGS plant provide configuration-specific evidence, not transferable validation for all novel membranes or biological variants [4, 49]. Environmental and economic comparisons likewise require equivalent boundaries that include pretreatment, auxiliaries, replacement and residual treatment. Published assessments of MBRs, nanotechnology-based treatment and integrated wastewater–sludge systems illustrate why outcomes can change with configuration and assumptions [14, 15, 73].

7.2. Cross-Technology Environmental Burdens and Residual Management

The fate of the contaminant is central to environmental comparison. Membrane rejection and adsorption transfer pollutants into concentrate, spent media or regenerant, so removal from the product water is not necessarily removal from the overall system [4, 9, 10, 24, 41]. Electrocoagulation can generate metal-rich solids, and electrooxidation in chloride-containing water may require assessment of

reactive by-products; electrode use and electricity supply also contribute burdens [34-39]. AOPs can transform persistent organics, but loss of the parent compound neither establishes mineralization nor excludes intermediates with residual toxicity [5, 6, 16-18]. Biological treatment can mineralize biodegradable organics or convert nutrients, yet sludge production, process stability and possible nitrogen-related emissions must be accounted for according to the actual configuration [49, 50, 53]. These pathways should be presented as distinct management obligations, not collapsed into a single removal metric.

A second comparison concerns what sits outside the nominal treatment reactor. Oxidants, cleaning reagents, sorbent activation and regeneration, membrane replacement, electricity and concentrate treatment can shift impacts upstream or downstream. Resource recovery may offset burdens only when product purity, avoided production, market uptake and methane or other process emissions are included in a coherent balance [14, 15, 64-70, 73]. Consequently, a sustainability claim should specify treated-water quality, system boundary, electricity mix and residual end point, and where possible report both life-cycle impacts and toxicity-related endpoints. Because many available studies are short-term or use inconsistent inventories, this review does not assign universal carbon, energy or cost rankings to the treatment categories.

7.3. Evidence Maturity and Comparative Decision Boundaries

Before a technology is called cost-effective or implementation-ready, the supporting evidence should be classified at the configuration level. Synthetic-water batch studies primarily support mechanistic or screening claims; continuous-flow real-wastewater tests probe matrix sensitivity; sustained pilot and operational plant records supply stronger evidence about reliability and maintenance. Even at comparable scale, reported costs can depend on chemical supply, analytical monitoring, staffing, replacement intervals, residual liability and electricity prices. Sensitivity analysis and transparent uncertainty are therefore essential, and missing cost data should be called an evidence gap rather than evidence of low cost [14, 15, 64, 73]. The contribution of the framework is to make these qualifications explicit when comparing options for a defined influent and discharge or reuse standard.

8. CHALLENGES TO SCALE-UP AND FULL-SCALE IMPLEMENTATION

Scale-up is a test of stable effluent quality under changing loads, not merely of a larger reactor. The likely failure modes differ: uncontrolled oxidant dose, loss of membrane integrity, early adsorbent breakthrough, electrode passivation or biological instability. Pilot protocols should specify acceptable variability, monitoring endpoints, consumables, maintenance and conditions that trigger intervention. A short laboratory trial cannot establish these operating requirements.

Utility adoption also depends on infrastructure, staffing, permits and financing. Integration with pipework, power and solids-handling systems may be decisive even when the treatment mechanism is promising. Procurement decisions should therefore be based on documented operating duration, resource use and realistic residual-disposal plans, with techno-economic and life-cycle assessments updated as field evidence improves [14, 15, 73].

Regulatory readiness depends on demonstrated control of failure modes as well as average effluent quality. Monitoring plans should identify the consequences of oxidant overdosing, loss of membrane integrity, adsorbent breakthrough, microbial upset or digital sensor failure, and specify where redundant barriers are needed. Procurement and operator skills can determine whether an otherwise technically attractive installation remains functional over its service life. These institutional and operational factors are rarely captured in short laboratory comparisons but materially affect technology choice [4, 14, 30, 71].

9. FUTURE PERSPECTIVES AND RESEARCH PRIORITIES

Several research priorities follow. Reporting should distinguish parent-compound loss from mineralization or phase transfer and include matrix composition, initial concentrations and relevant toxicity endpoints. Promising technologies need sustained real-wastewater flow tests, not only single-solute batches. Hybrid trains should face matched conventional benchmarks; digital tools require independent validation and operational safeguards. Finally, treatment experiments should be designed from the outset to capture residuals, material life, energy, costs and life-cycle consequences.

These priorities differ by function. Oxidative systems need evidence on transformation products and toxicity; separation technologies need credible routes for concentrates, regenerants and spent solids. Recovery studies should report product purity and net material and energy balances rather than relying on recovery fractions alone [4, 5, 12, 64–70]. Prediction

tools remain valuable only when tested independently of model development [71, 72].

A staged evidence pathway is therefore preferable to a universal technology ranking: confirm the mechanism and fate of pollutants; establish robust continuous operation in a relevant matrix; quantify performance variation, maintenance and residuals at pilot scale; and compare an integrated option with a credible incumbent under common product-water specifications and system boundaries. Failure to pass one stage should redirect research rather than be obscured by favorable short-term removal results. This sequence is proposed as a decision aid, not as a validated scoring tool or a substitute for site-specific engineering judgment [5, 14, 15, 60, 73].

10. CONCLUSIONS

Selection of an emerging treatment process should begin with the wastewater matrix, contaminant fate and required effluent quality, not with the highest removal percentage reported in the literature. Oxidation may be appropriate for persistent dissolved organics if transformation products and toxicity can be managed; membranes and adsorbents provide separation or polishing but leave concentrates and spent materials. Electrochemical processes address selected industrial applications, whereas biological treatment and resource recovery depend on stable operating conditions and a viable product or nutrient pathway. The comparative framework developed here makes these trade-offs explicit by considering operational demands, secondary burdens and the strength of evidence alongside treatment performance. Established reuse trains and full-scale biological applications provide stronger implementation evidence than short laboratory demonstrations of novel materials. The next step for less mature approaches is sustained real-wastewater operation with documented durability, residual management and transparent techno-economic and life-cycle accounts. No technology family can be ranked as universally preferable without comparable water-quality targets and system boundaries.

DECLARATIONS

Author Contributions

Afshin Maleki: Conceptualization, methodology, literature review, critical analysis, writing—original draft, and writing—review and editing.

Declaration of Conflicting Interest

The author declares that there are no relevant financial or non-financial competing interests to report.

Funding

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Ethics Approval

Not applicable; this article is a literature review and reports no new research involving human participants or animals.

Data Availability

No new experimental datasets were generated for this review.

Declaration of AI-Assisted Manuscript Preparation

During preparation and revision of this manuscript, the author used ChatGPT (OpenAI) to assist with language editing and manuscript organization.

REFERENCES

[1] UNESCO. The United Nations World Water Development Report 2024: Water for Prosperity and Peace. Paris: UNESCO; 2024. https: //www.unesco.org/en/reports/wwdr/2024

[2] Richardson K, Steffen W, Lucht W, *et al*. Earth beyond six of nine planetary boundaries. Sci Adv. 2023; 9: eadh2458. https://doi.org/10.1126/sciadv.adh2458

[3] Shannon MA, Bohn PW, Elimelech M, Georgiadis JG, Marinas BJ, Mayes AM. Science and technology for water purification in the coming decades. Nature. 2008; 452: 301-310. https://doi.org/10.1038/nature06599

[4] Tang CY, Yang Z, Guo H, Wen JJ, Nghiem LD, Cornelissen E. Potable water reuse through advanced membrane technology. Environ Sci Technol. 2018; 52: 10215-10223. https://doi.org/10.1021/acs.est.8b00562

[5] Miklos DB, Remy C, Jekel M, Linden KG, Drewes JE, Hübner U. Evaluation of advanced oxidation processes for water and wastewater treatment - A critical review. Water Res. 2018; 139: 118-131.

[6] Rengifo-Herrera JA, Pulgarin C. Why five decades of massive research on heterogeneous photocatalysis, especially on TiO2, has not yet driven to water disinfection and detoxification applications? Critical review of drawbacks and challenges. Chem Eng J. 2023; 477: 146875. https://doi.org/10.1016/j.cej.2023.146875

[7] Kohzadi S, Bundschuh M, Rezaee R, Marzban N, Vahabzadeh Z, Johari SA, *et al*. Integrating machine learning with experimental investigation for optimizing photocatalytic degradation of Rhodamine B using neodymium-doped titanium dioxide: a comprehensive approach with toxicity assessment. Environ Sci Pollut Res Int. 2024; 31(43): 55301-55316. https://doi.org/10.1007/s11356-024-34843-0

[8] Salehzadeh H, Kohzadi S, Vahabzadeh Z, *et al*. Integrated photocatalytic and ecotoxicological evaluation of magnetic Mo-ZnO/Fe3O4 nanocomposites for phenol removal from hydrothermal carbonization wastewater. J Water Process Eng. 2026; 92: 110638. https://doi.org/10.1016/j.jwpe.2026.110638

[9] Kohzadi S, Marzban N, Godini K, Amini N, Maleki A. Effect of hydrochar modification on the adsorption of methylene blue from aqueous solution: an experimental study followed by intelligent modeling. Water. 2023; 15: 3220. https://doi.org/10.3390/w15183220

[10] Kohzadi S, Marzban N, Libra JA, Bundschuh M, Maleki A. Removal of RhB from water by Fe-modified hydrochar and biochar - an experimental evaluation supported by genetic programming. J Mol Liq. 2023; 369: 120971. https://doi.org/10.1016/j.molliq.2022.120971

[11] Kohzadi S, Marzban N, Zandsalimi Y, *et al*. Machine learning-based modeling of malachite green adsorption on hydrochar derived from hydrothermal fulvification of wheat straw. Heliyon. 2023; 9: e21258. https://doi.org/10.1016/j.heliyon.2023.e21258

[12] Shamshad J, Ur Rehman R. Innovative approaches to sustainable wastewater treatment: a comprehensive exploration of conventional and emerging technologies. Environmental Science: Advances. 2025; 4: 189-222. https://doi.org/10.1039/D4VA00136B

[13] Fu K, Huang J, Luo F, Fang Z, Yu D, Zhang X, *et al*. Understanding the selective removal of perfluoroalkyl and polyfluoroalkyl substances via fluorine-fluorine interactions: A critical review. Environmental Science & Technology. 2024; 58(38): 16669-16689. https://doi.org/10.1021/acs.est.4c06519

[14] Gao T, Jin Y, Xiao K. Techno-Economic and Environmental Impact Assessment of Membrane Bioreactors for Wastewater Treatment: A Review. Engineering. 2026; 59: 297-311. https://doi.org/10.1016/j.eng.2025.05.001

[15] Pandit S, Yadav N, Sharma P, Prakash A, Kuila A. Life cycle assessment and techno-economic analysis of nanotechnology-based wastewater treatment: Status, challenges and future prospectives. J Taiwan Inst Chem Eng. 2025; 166: 105567. https://doi.org/10.1016/j.jtice.2024.105567

[16] Hübner U, Spahr S, Lutze H, Wieland A, Rüting S, Gernjak W, *et al*. Advanced oxidation processes for water and wastewater treatment - Guidance for systematic future research. Heliyon. 2024; 10(9): e30402. https://doi.org/10.1016/j.heliyon.2024.e30402

[17] Mukherjee J, *et al*. Advanced oxidation process for the treatment of industrial wastewater: A review on strategies, mechanisms, bottlenecks and prospects. Chemosphere. 2023; 345: 140473. https://doi.org/10.1016/j.chemosphere.2023.140473

[18] Su R, Zhu Y, Gao B, Li Q. Progress on mechanism and efficacy of heterogeneous photocatalysis coupled oxidant activation as an advanced oxidation process for water decontamination. Water Res. 2024; 251: 121119. https://doi.org/10.1016/j.watres.2024.121119

[19] Iqbal MA, *et al*. Advanced photocatalysis as a viable and sustainable wastewater treatment process: A comprehensive review. Environ Res. 2024; 253: 118947. https://doi.org/10.1016/j.envres.2024.118947

[20] Tanos F, *et al*. A comprehensive review on modification of titanium dioxide-based catalysts in advanced oxidation processes for water treatment. ChemSusChem. 2024; 17: e202301139. https://doi.org/10.1002/cssc.202301139

[21] Zhang H, *et al*. A critical review of ozone-based electrochemical advanced oxidation processes for water treatment: Fundamentals, stability evaluation, and application. Chemosphere. 2024; 365: 143330. https://doi.org/10.1016/j.chemosphere.2024.143330

[22] Satyam S, Patra S. The evolving landscape of advanced oxidation processes in wastewater treatment: Challenges and recent innovations. Processes. 2025; 13(4): 987. https://doi.org/10.3390/pr13040987

[23] Jari Y, Najid N, Necibi MC, Gourich B, Vial C, Elhalil A, *et al*. A comprehensive review on TiO2-based heterogeneous photocatalytic technologies for emerging pollutants removal from water and wastewater: From engineering aspects to modeling approaches. J Environ Manage. 2025; 373: 123703. https://doi.org/10.1016/j.jenvman.2024.123703

[24] Shehata N, Egirani D, Olabi AG, Inayat A, Abdelkareem MA, Chae KJ, Sayed ET. Membrane-based water and wastewater treatment technologies: Issues, current trends, challenges, and role in achieving sustainable development goals, and circular economy. Chemosphere. 2023; 320: 137993. https://doi.org/10.1016/j.chemosphere.2023.137993

[25] Carmona B, Abejón R. Innovative membrane technologies for the treatment of wastewater polluted with heavy metals: Perspective of the potential of electrodialysis, membrane distillation, and forward osmosis from a bibliometric analysis. Membranes. 2023; 13: 385. https://doi.org/10.3390/membranes13040385

[26] Chang H, Zhu Y, Huang L, Yan Z, Qu F, Liang H. Mineral scaling induced membrane wetting in membrane distillation for water treatment: Fundamental mechanism and mitigation strategies. Water Res. 2023; 247: 120807. https://doi.org/10.1016/j.watres.2023.120807

[27] Tan YZ, Alias NH, Abd Aziz MH, Jaafar J, Che Othman FE, Chew JW. Progress on improved fouling resistance-nanofibrous membrane for membrane distillation: A mini-review. Membranes. 2023; 13: 727. https://doi.org/10.3390/membranes13080727

[28] Liao X, Lim YJ, Khayet M, Liao Y, Yao L, Zhao Y, Razaqpur AG. Applications of electrically conductive membranes in water treatment via membrane distillation: Joule heating, membrane fouling/scaling/wetting mitigation and monitoring. Water Res. 2023; 244: 120511. https://doi.org/10.1016/j.watres.2023.120511

[29] Zhu L, Ding C, Zhu T, Wang Y. A review on the forward osmosis applications and fouling control strategies for wastewater treatment. Frontiers of Chemical Science and Engineering. 2022; 16: 661-680. https://doi.org/10.1007/s11705-021-2084-4

[30] Hoek EMV, Weigand TM, Edalat A. Reverse osmosis membrane biofouling: causes, consequences and countermeasures. npj Clean Water. 2022; 5: 45. https://doi.org/10.1038/s41545-022-00183-0

[31] Tarun SS, Dakshesh SK, Arthanareeswaran G. Tuning of polymeric membranes to mitigate fouling and removal of dissolved compounds for wastewater treatment: a review. Frontiers in Membrane Science and Technology. 2024; 3: 1389239. https://doi.org/10.3389/frmst.2024.1389239

[32] Mallah NB, Shah AA, Pirzada AM, *et al*. Advanced Control Strategies of Membrane Fouling in Wastewater Treatment: A Review. Processes. 2024; 12: 2681. https://doi.org/10.3390/pr12122681

[33] Du S, Zhao P, Wang L, He G, Jiang X. Progresses of advanced anti-fouling membrane and membrane processes for high salinity wastewater treatment. Results Eng. 2023; 17: 100995. https://doi.org/10.1016/j.rineng.2023.100995

[34] Krishnamurthy BD, Puttaraju LM, Veeregowda P, Guruprasad RP, Balakrishna LS. Electrocoagulation in Wastewater Treatment: A Comprehensive Review of Heavy Metal and Pollutant Removal. Asian Journal of Chemical Sciences. 2024; 14: 114-136. https://doi.org/10.9734/ajocs/2024/v14i6339

[35] Brião GV, da Costa TB, Antonelli R, Costa JM. Electrochemical processes for the treatment of contaminant-rich wastewater: A comprehensive review. Chemosphere. 2024; 355: 141884. https://doi.org/10.1016/j.chemosphere.2024.141884

[36] Najafinejad MS, Chianese S, Fenti A, Iovino P, Musmarra D. Application of electrochemical oxidation for water and wastewater treatment: An overview. Molecules. 2023; 28: 4208. https://doi.org/10.3390/molecules28104208

[37] Ghaffarian Khorram A, Fallah N, Nasernejad B, Afsham N, Esmaelzadeh M, Vatanpour V. Electrochemical-based processes for produced water and oily wastewater treatment: A review. Chemosphere. 2023; 338: 139565. https://doi.org/10.1016/j.chemosphere.2023.139565

[38] Hassan N, Lezy J, Parmentier D, Van Hulle SWH. Electrocoagulation flotation as a municipal wastewater (pre-)treatment technology: Effect of weather conditions

and current density. J Environ Manage. 2023; 345: 118906. https://doi.org/10.1016/j.jenvman.2023.118906

[39] Shahedi A, Darban AK, Jamshidi-Zanjani A, Homaee M. An overview of the application of electrocoagulation for mine wastewater treatment. Environ Monit Assess. 2023; 195: 522. https://doi.org/10.1007/s10661-023-11044-9

[40] Yakamercan E, Bhatt P, Aygun A, Adesope AW, Simsek H. Comprehensive understanding of electrochemical treatment systems combined with biological processes for wastewater remediation. Environ Pollut. 2023; 330: 121680. https://doi.org/10.1016/j.envpol.2023.121680

[41] Trivedi Y, Sharma M, Mishra RK, Sharma A, Joshi J, Gupta AB, *et al*. Biochar potential for pollutant removal during wastewater treatment: A comprehensive review of separation mechanisms, technological integration, and process analysis. Desalination. 2025; 600: 118509. https://doi.org/10.1016/j.desal.2024.118509

[42] Wang Y, Chen L, Zhu Y, *et al*. Research status, trends, and mechanisms of biochar adsorption for wastewater treatment: A scientometric review. Environ Sci Eur. 2024; 36: 25. https://doi.org/10.1186/s12302-024-00859-z

[43] Jalilian M, Bissessur R, Ahmed M, Hsiao A, He QS, Hu Y. A review: Hydrochar as potential adsorbents for wastewater treatment and CO2 adsorption. Sci Total Environ. 2024; 914: 169823. https://doi.org/10.1016/j.scitotenv.2023.169823

[44] Khanzada AK, Al-Hazmi HE, Kurniawan TA, Majtacz J, Piechota G, Kumar G, *et al*. Hydrochar as a bio-based adsorbent for heavy metals removal: A review of production processes, adsorption mechanisms, kinetic models, regeneration and reusability. Sci Total Environ. 2024; 945: 173972. https://doi.org/10.1016/j.scitotenv.2024.173972

[45] Ge Q, Dong C, Wang G, Zhang J, Hou R. Production, characterization and environmental remediation application of emerging phosphorus-rich biochar/hydrochar: A comprehensive review. RSC Adv. 2024; 14: 33649-33665. https://doi.org/10.1039/D4RA03333G

[46] Okoro HK, Emenike EC, Iwuozor KO, Egbemhenghe A, Bello-Hassan MT, Adu AO, *et al*. Industrial waste biochar for heavy metal and dye remediation in wastewater: an overview. Water Practice & Technology. 2025; 20(3): 595-616. https://doi.org/10.2166/wpt.2025.037

[47] Zhang XS, Chen YG, Wang QY, Sun YL. Advances in heavy metal wastewater treatment with biochar adsorption. Biofuels, Bioproducts and Biorefining. 2025; 19: 2399-2417. https://doi.org/10.1002/bbb.2751

[48] Liu C, Bolan N, Rajapaksha AU, Wang H, Balasubramanian P, Zhang P, Nguyen XC, Li F. Critical review of biochar for the removal of emerging inorganic pollutants from wastewater. Chinese Chemical Letters. 2025; 36(2): 109960. https://doi.org/10.1016/j.cclet.2024.109960

[49] Pincam T, Liu YQ, Booth A, Wang Y, Lan G, Zeng P. A comprehensive comparison of microbial communities between aerobic granular sludge and flocculent sludge for nutrient removal in full-scale wastewater treatment plants. Chemosphere. 2024; 362: 142644. https://doi.org/10.1016/j.chemosphere.2024.142644

[50] Cao S, Koch K, Duan H, Wells GF, Ye L, Zhao Y, Du R. In a quest for high-efficiency mainstream partial nitritation-anammox (PN/A) implementation: One-stage or two-stage? Sci Total Environ. 2023; 883: 163540. https://doi.org/10.1016/j.scitotenv.2023.163540

[51] de Morais EG, Sampaio ICF, Gonzalez-Flo E, Ferrer I, Uggetti E, García J. Microalgae harvesting for wastewater treatment and resources recovery: A review. New Biotechnol. 2023; 78: 84-94. https://doi.org/10.1016/j.nbt.2023.10.002

[52] Liu S, Zhou M, Daigger GT, Huang J, Song G. Granule formation mechanism, key influencing factors, and resource recycling in aerobic granular sludge (AGS) wastewater treatment: A review. Journal of Environmental Management. 2023; 338: 117771. https://doi.org/10.1016/j.jenvman.2023.117771

[53] Xue Y, Ma H, Li YY. Anammox-based granulation cycle for sustainable granular sludge biotechnology from mechanisms to strategies: A critical review. Water Research. 2023; 228: 119353. https://doi.org/10.1016/j.watres.2022.119353

[54] Shameem KS, Sabumon PC. A Review on the Stability, Sustainability, Storage and Rejuvenation of Aerobic Granular Sludge for Wastewater Treatment. Water. 2023; 15: 950. https://doi.org/10.3390/w15050950

[55] Truong HTB, Bui HM. Potential of aerobic granular sludge membrane bioreactor (AGMBR) in wastewater treatment. Bioengineered. 2023; 14: 2260139. https://doi.org/10.1080/21655979.2023.2260139

[56] Guzmán-Fierro V, *et al*. Challenges of aerobic granular sludge utilization: Fast start-up strategies and cationic pollutant removal. Heliyon. 2023; 9: e13503. https://doi.org/10.1016/j.heliyon.2023.e13503

[57] Ali SS, Hassan LHS, El-Sheekh M. Microalgae-mediated bioremediation: Current trends and opportunities—a review. Arch Microbiol. 2024; 206: 343. https://doi.org/10.1007/s00203-024-04052-x

[58] Ahmad SFK, Kanadasan G, Lee KT, Vadivelu VM. Insight into recent advances in microalgae biogranulation in wastewater treatment. Crit Rev Biotechnol. 2024; 44: 1594-1609. https://doi.org/10.1080/07388551.2024.2317785

[59] Vatanpour V, Salimi Khaligh S, Sertgumec S, Ceylan-Perver G, Yuksekdag A, Yavuzturk Gul B, *et al*. A review on algal biomass dewatering and recovery of microalgal-based valuable products with different membrane technologies. J Environ Manage. 2024; 371: 123182. https://doi.org/10.1016/j.jenvman.2024.123182

[60] Vatanpour V, Shitreh S, Eryildiz-Yesir B, Ulucan-Altuntas K, Ozgun H, Ersahin ME, Koyuncu I. Integration of advanced oxidation processes (AOPs) and membrane bioreactors (MBRs) for wastewater treatment: A review. Sep Purif Technol. 2026; 394: 137411. https://doi.org/10.1016/j.seppur.2026.137411

[61] Ni L, Wang P, Westerhoff P, Luo J, Wang K, Wang Y. Mechanisms and strategies of advanced oxidation processes for membrane fouling control in MBRs: Membrane-foulant removal versus mixed-liquor improvement. Environ Sci Technol. 2024; 58(26): 11213-11235. https://doi.org/10.1021/acs.est.4c02659

[62] Adeoye JB, Tan YH, Lau SY, Tan YY, Chiong T, Mubarak NM, Khalid M. Advanced oxidation and biological integrated processes for pharmaceutical wastewater treatment: A review. J Environ Manage. 2024; 353: 120170. https://doi.org/10.1016/j.jenvman.2024.120170

[63] Bani-Melhem K, Elektorowicz M, Tawalbeh M, Al Bsoul A, El Gendy A, Kamyab H, Yusuf M. Integrating of electrocoagulation process with submerged membrane bioreactor for wastewater treatment under low voltage gradients. Chemosphere. 2023; 339: 139693. https://doi.org/10.1016/j.chemosphere.2023.139693

[64] Soo A, Kim J, Shon HK. Technologies for the wastewater circular economy—A review. Desalination and Water Treatment. 2024; 317: 100205. https://doi.org/10.1016/j.dwt.2024.100205

[65] Rachbauer L, Granda CB, Shrestha S, Fuchs W, Gabauer W, Singer SW, *et al*. Energy and nutrient recovery from municipal and industrial waste and wastewater—a perspective. J Ind Microbiol Biotechnol. 2024; 51: kuae040. https://doi.org/10.1093/jimb/kuae040

[66] Wada OZ, Ige AO, Egbewole BI, Olawade DB. Circular economy from wastewater resource recovery: A review of recent advances and global disparities. Sustainable Chemistry One World. 2026; 9: 100187. https://doi.org/10.1016/j.scowo.2026.100187

[67] Xu H, *et al*. Microalgae treatment of food processing wastewater for simultaneous biomass resource recycling and water reuse. J Environ Manage. 2024; 369: 122394. https://doi.org/10.1016/j.jenvman.2024.122394

[68] Santos AF, Mendes LS, Alvarenga P, Gando-Ferreira LM, Quina MJ. Nutrient Recovery via Struvite Precipitation from Wastewater Treatment Plants: Influence of Operating Parameters, Coexisting Ions, and Seeding. Water. 2024; 16: 1675. https://doi.org/10.3390/w16121675

[69] Natsi PD, Koutsoukos PG. Electrochemical recovery of N and P from municipal wastewater. Crystals. 2024; 14(8): 675. https://doi.org/10.3390/cryst14080675

[70] Park N, Kim M, Jung J, Ji S, Kim W. New Strategy to Maximize Phosphorus Utilization of Sewage Sludge Incineration Ash for Struvite Crystallization. Water. 2024; 16: 1682. https://doi.org/10.3390/w16121682

[71] Wang AJ, Li H, He Z, Tao Y, Wang H, Yang M, Savic D, Daigger GT, Ren N. Digital twins for wastewater treatment: a technical review. Engineering. 2024; 36: 21-35. https://doi.org/10.1016/j.eng.2024.04.012

[72] Parsa Z, Dhib R, Mehrvar M. Dynamic modelling, process control, and monitoring of selected biological and advanced oxidation processes for wastewater treatment: A review of recent developments. Bioengineering. 2024; 11: 189. https://doi.org/10.3390/bioengineering11020189

[73] Ahmad S, Daddi T, Novi A, Marrucci L. Evaluating environmental impacts and techno-economic feasibility of an integrated and novel wastewater and sludge treatment system for circular economy objectives. Computers & Industrial Engineering. 2025; 204: 111035. https://doi.org/10.1016/j.cie.2025.111035

https://doi.org/10.12974/2311-8741.2026.14.09

© 2026 Afshin Maleki
This is an open-access article licensed under the terms of the Creative Commons Attribution License (http://creativecommons.org/licenses/by/4.0/), which permits unrestriced use, distribution, and reproduction in any medium, provided the work is properly cited.