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Review Article

Emerging nutrient removal technologies in wastewater treatment: Advancements in nitrogen and phosphorus management

Micheal Abimbola Oladosu[1*], **Moses Adondua Abah[2]**, **Olaide Ayokunmi Oladosu[3]**, **Sandra Chiamaka Okoye[4]**, **Omokhudu Great Igiekhumhe[5]**, **Rhoda Oluwatoyosi Oniyele[6]** and **Angel Ojimaojo Ekele[2]**

1. Department of Biochemistry, Faculty of Basic Medical Sciences, University of Lagos, Idi-Araba, Lagos, Nigeria.
2. Department of Biochemistry, Faculty of Pure and Applied Sciences, Federal University of Wukari, Wukari, Taraba State, Nigeria.
3. Department of Computer Science, Faculty of Science and Technology, Babcock University, Ilishan, Nigeria.
4. Department of Biological Sciences, College of Liberal Arts and Sciences, Eastern Illinois University, Charleston, USA.
5. Department of Marine Science and Technology, School of Earth and Mineral Sciences, Federal University of Technology, Akure, Ondo State, Nigeria.
6. Department of Environmental Health Sciences, Faculty of Public Health, University of Ibadan. Ibadan, Oyo State, Nigeria.

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Corresponding Author
Prof. Dr. Micheal Abimbola Oladosu
E-mail: mikeoladosu@gmail.com
Tel: +2348035264566

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Abstract

The growing concerns over eutrophication, along with increasingly rigorous environmental policies, have intensified the demand for advanced nutrient removal technologies in wastewater treatment. This review examines recent advances in nitrogen and phosphorus removal, analysing both conventional and emerging methods. Technologies evaluated include enhanced biological nutrient removal (EBNR), membrane bioreactors (MBRs), advanced oxidation processes (AOPs), bio-electrochemical systems, and novel adsorbent materials. Through a systematic review of the literature from 2019 to 2025, this study assessed technological advancements, performance indicators, and implementation challenges. The results demonstrate that hybrid systems integrating biological and physicochemical processes achieve removal efficiencies exceeding 95% for nitrogen and 98% for phosphorus, surpassing conventional methods. Anammox-based processes and engineered wetlands show promise for sustainable nutrient management. The integration of artificial intelligence with process optimisation has enhanced treatment efficiency while reducing operational costs. This review provides critical insights for researchers, engineers, and policymakers in developing environmentally sustainable wastewater treatment solutions.

1. Introduction

Nutrient pollution from nitrogen and phosphorus contamination represents one of the most critical environmental challenges of the 21st century [1]. Excessive nutrient discharge from wastewater

Table 1. Comparative performance metrics of conventional biological nutrient removal process configurations.

Process configuration	Nitrogen removal efficiency (%)	Phosphorus removal efficiency (%)	Energy consumption (kWh/m^3)	Key operational challenges
Conventional Activated Sludge	15-30	10-25	0.6-1.0	Limited nutrient removal capacity
Modified Bardenpho	75-85	80-90	1.0-1.4	Complex operation, high HRT
UCT Process	70-82	85-92	0.9-1.3	RAS distribution challenges
Modified UCT	78-88	88-95	1.1-1.5	Multiple recycle streams
A^2O Process	70-85	80-90	0.8-1.2	pH and alkalinity management
SBR (BNR mode)	80-90	85-95	0.7-1.1	Precise timing control required

Source: Compiled from Metcalf & Eddy [6], Tchobanoglous et al. [18], and Henze et al. [19].

treatment plants, agricultural runoff, and industrial effluents has caused eutrophication, harmful algal blooms, and deterioration of water quality worldwide [2, 3]. This challenge aligns with the United Nations Sustainable Development Goal 6, which emphasizes the urgent need for improved nutrient pollution management [4].

Conventional municipal wastewater treatment operations, primarily designed for organic matter and pathogen removal, are inadequate for nutrient elimination under increasingly stringent standards [5]. Traditional biological nutrient removal (BNR) processes achieve 70-85% nitrogen and 80-90% phosphorus removal, which is often insufficient to meet current regulatory requirements [6, 7]. Current regulations limit total nitrogen concentrations to 3-8 mg/L and total phosphorus to 0.1-1.0 mg/L in treated effluent [8]. The economic and environmental impacts are significant. The European Environment Agency estimates that eutrophication costs the European Union approximately €2.3 billion annually in lost ecosystem services [9], while harmful algal blooms cause economic losses of $4.6 billion yearly in the United States alone [10].

Technological innovations have introduced novel nutrient management approaches, including improved biological operations, membrane-based processes, advanced oxidation methods, and hybrid systems [11,12]. Digital transformation in engineering, process optimization algorithms, and sustainable technologies create new opportunities for energy-efficient and economically viable nutrient removal [13,14]. Early treatment systems from the mid-20th century focused on organic matter removal through conventional activated sludge processes [15]. Environmental awareness of nutrient pollution in 1960s and 1970s led to development of the biological nutrient removal processes [16]. Conventional BNR systems operate under sequential anaerobic, anoxic, and aerobic conditions, enabling phosphorus release and uptake, nitrification, and denitrification [17]. The Bardenpho, University of Cape Town (UCT), and modified UCT configurations have become standard methods for simultaneous nitrogen and phosphorus removal [18,19]. However, these systems face limitations, including high energy requirements, sensitivity to changes in operating conditions, and incomplete nutrient removal under variable loads [20]. Table 1 summarises the major categories of emerging nutrient removal technologies and their underlying mechanisms discussed in this review.

2.2. *Enhanced biological nutrient removal (EBNR) technologies*

Recent developments in enhanced biological nutrient removal have focused on refining microbial communities and optimising process design to improve system stability [21, 22]. The major configurations of enhanced biological nutrient removal are illustrated in Fig. 1.

Enhanced biological phosphorus removal (EBPR) systems that utilize polyphosphate-accumulating organisms (PAOs) and glycogen-accumulating organisms (GAOs) show marked improvements in phosphorus uptake capacity and process stability under variable loading conditions [23]. Anaerobic ammonium oxidation (anammox) represents a paradigm shift in nitrogen removal, with bacteria converting ammonium and nitrite directly to nitrogen

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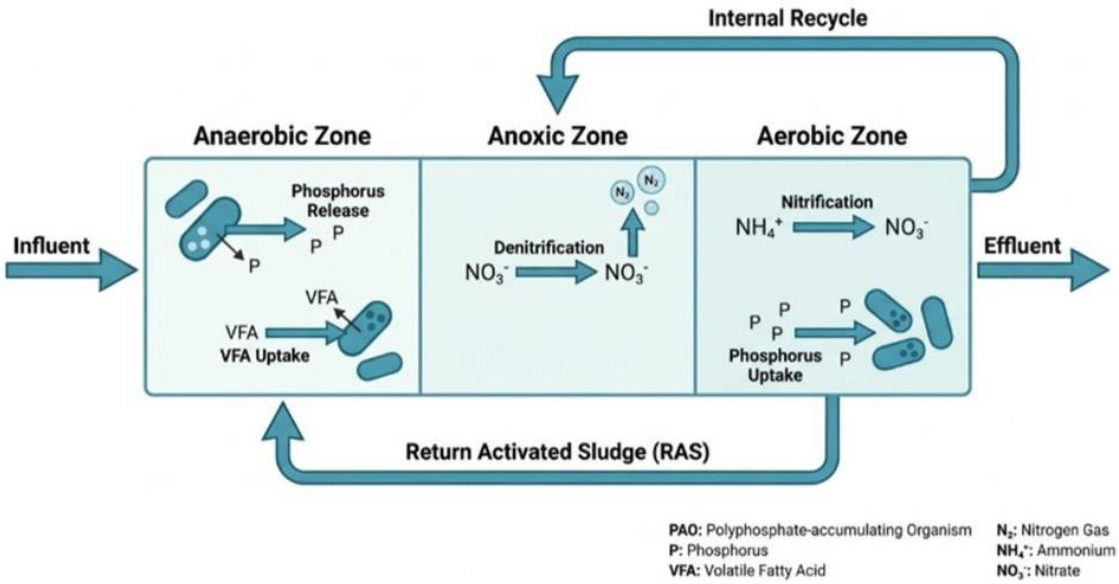

Figure 1. Schematic of enhanced biological nutrient removal processes.
Source: Adapted from Chen et al. [21].

gas under anaerobic conditions [24, 25]. This process reduces oxygen demand by 62.5%, eliminates external carbon source requirements, and achieves operational cost savings of 25-60% [26]. Developments include partial nitritation-anammox (PNA) processes for mainstream treatment, granular anammox systems with enhanced biomass retention, integrated fixed-film activated sludge configurations, and temperature-adapted cultures for cold climates [27, 28]. Simultaneous nitrification, denitrification, and phosphorus removal (SNDPR) systems achieve comprehensive nutrient removal through precise control of dissolved oxygen, pH, and hydraulic retention time [29], with advanced control strategies utilizing artificial intelligence significantly improving performance [30, 31].

Membrane bioreactors (MBRs) have emerged as the leading technology for advanced wastewater treatment, offering superior effluent quality and a compact footprint compared to conventional systems [32, 33]. Recent innovations include anaerobic-anoxic-oxic (A2O) MBR systems, moving bed biofilm reactor (MBBR)-MBR hybrid systems, osmotic membrane bioreactors for simultaneous treatment and water recovery, and electrochemically assisted MBRs for improved fouling control [34, 35]. Forward osmosis and membrane distillation technologies achieve near-complete nutrient rejection while producing high-quality permeate for reuse [36, 37].

Advanced oxidation processes that utilize hydroxyl radicals show significant potential for nutrient removal, particularly for recalcitrant nitrogen compounds [38]. Developments include electrocoagulation for phosphorus removal, electrochemical ammonia oxidation, and electro-Fenton processes for organic nitrogen degradation [39, 40]. Photocatalytic processes include UV/TiO2 photocatalysis, visible light-driven photocatalysts, and solar-powered systems for decentralised applications [41, 42].

Novel adsorbent materials demonstrate exceptional nutrient removal capabilities [43], including modified biochar with enhanced phosphorus affinity, magnetic nanoparticles for selective nutrient recovery, metal-organic frameworks for high-capacity adsorption, and layered double hydroxides for anion removal [44, 45]. Algae-based biosorbents, microbial fuel cell systems with simultaneous treatment and energy generation, and constructed wetlands with engineered substrates are promising [46, 47].

The integration of multiple treatment technologies has emerged as a key strategy for achieving ultra-low nutrient concentrations while optimizing operational efficiency [48]. Successful hybrid configurations

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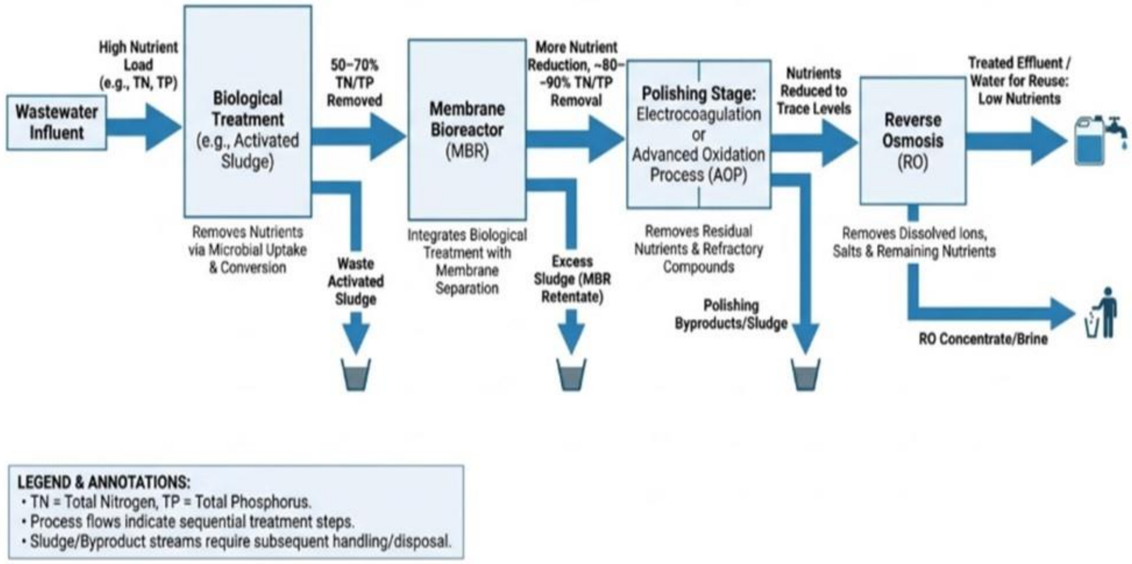

Figure 2. Process flow diagram of integrated nutrient removal systems.
Source: McManus et al. [49].

include MBR-reverse osmosis systems for water reuse, biological treatment followed by electrocoagulation, constructed wetlands integrated with advanced oxidation, and algae-based systems combined with membrane separation [49, 50]. A representative process flow for integrated/hybrid nutrient removal systems is shown in Fig. 2.

This review aimed to assess the status of emerging nutrient removal technologies, examine their performance characteristics and implementation challenges, summarise promising technological trends, and provide recommendations for future research priorities. This review considers technologies developed or significantly advanced over the past five years, emphasising their practical applications and scaling potential.

2. Materials and methods

2.1. Literature search strategy

A comprehensive literature review covering January 2019 to July 2025 was conducted. Multiple academic databases were systematically searched, including Web of Science, Scopus, PubMed, and Google Scholar. The search strategy employed Boolean operators with the following key terms: "nutrient removal" AND "wastewater treatment"; "nitrogen removal" OR "phosphorus removal"; "enhanced biological nutrient removal" OR "EBNR"; "membrane bioreactor" AND "nutrient removal"; "advanced oxidation processes" AND "nutrients"; "anammox" OR "partial nitritation"; "bioelectrochemical systems" AND "nutrient removal". While the systematic search focused on literature from 2019-2025, seminal works predating this period were included where necessary to provide a foundational context for technological developments.

2.2. Inclusion and exclusion criteria

The inclusion criteria comprised peer-reviewed journal articles and conference proceedings, studies published in English, research focusing on municipal or industrial wastewater treatment, technologies with demonstrated nutrient removal capabilities, and studies reporting quantitative performance data. The exclusion criteria included review articles without original data, studies focusing solely on agricultural runoff treatment, technologies in the early conceptual stages without experimental validation, publications lacking sufficient technical detail, and studies with inadequate quality control or methodology.

2.3. Data extraction and analysis

From each selected publication, information was systematically extracted, including technology type and configuration, operating conditions and parameters, influent and effluent nutrient concentrations, removal efficiency percentages, energy consumption and operational costs, system

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Table 2. Performance comparison of advanced oxidation processes.

AOP technology	Target compound	Removal efficiency (%)	Energy consumption (kWh/m³)	Operational costs ($/m³)	Key advantages	Limitations
Electrocoagulation (Al)	Total Phosphorus	85-98	2.5-4.2	0.18-0.35	Simple operation, no chemicals	Electrode consumption
Electrocoagulation (Fe)	Total Phosphorus	88-96	2.8-4.5	0.22-0.38	Effective coagulation	Sludge production
Electrochemical Oxidation	Ammonia-N	70-90	4.5-8.0	0.45-0.80	Direct oxidation	High energy demand
UV/TiO_2 Photocatalysis	Organic-N	80-95	3.2-6.5	0.32-0.65	Complete mineralization	UV lamp maintenance
Solar Photocatalysis	Organic-N	75-88	0.5-1.2	0.08-0.18	Renewable energy	Weather dependent
Electro-Fenton	Mixed N-compounds	85-92	5.5-9.2	0.55-0.92	Broad applicability	Complex chemistry

Source: Compiled from Oller et al. [38], Ahmed et al. [42], and Malato et al. [41].

Table 3. Summary of literature review methodology.

Database	Search period	Initial results	After screening	Final inclusion	Quality score range
Web of Science	2019-2025	1,247	342	68	6.8-9.2
Scopus	2019-2025	1,156	289	54	6.5-9.0
PubMed	2019-2025	434	98	23	7.1-8.9
Google Scholar	2019-2025	2,890	156	42	6.2-8.8
Total Unique	*2019-2025*	*3,678*	*521*	*187*	*6.2-9.2*

Source: Authors' compilation based on systematic literature review methodology.

Note: Quality scores assessed on a 10-point scale based on experimental design rigor, data quality, reproducibility, industrial relevance, and publication quality.

advantages and limitations, and scalability potential and commercial applications.

2.4. Quality assessment

Study quality was evaluated using established criteria including experimental design rigor, data quality and statistical analysis, reproducibility of results, industrial relevance and applicability peer review status and journal impact factor. Table 2 summarises the literature search strategy, inclusion/exclusion criteria, and data extraction parameters used in this review.

2.5. Performance metrics and evaluation framework

The technology performance was evaluated based on technical performance (nitrogen and phosphorus removal efficiency, effluent quality consistency, process stability and reliability, and operational complexity), economic factors (capital expenditure, operational expenditure, energy consumption, chemical consumption, and maintenance requirements), and environmental impact (carbon footprint, chemical usage and environmental fate, sludge production and disposal, resource recovery potential, and overall sustainability assessment). Table 3 compares nitrogen and phosphorus removal efficiencies reported for the major technology classes.

3. Results and discussion

3.1. Technology performance analysis

The comprehensive literature review identified 187 relevant studies that examined emerging nutrient removal technologies. Fig. 3 compares the nitrogen and phosphorus removal efficiencies and energy

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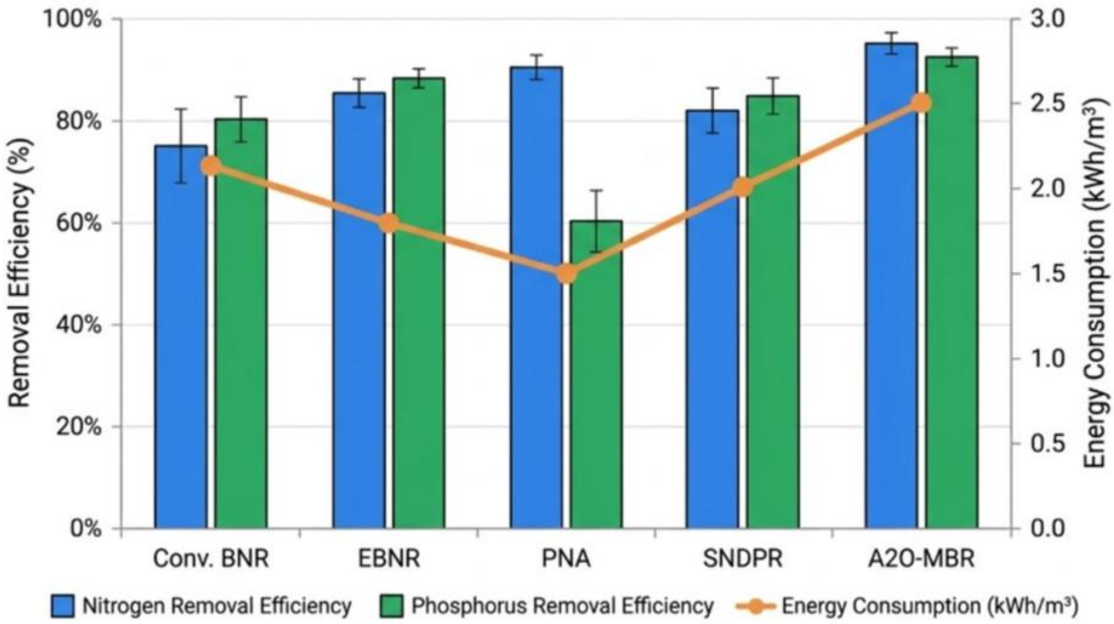

Figure 3. Performance comparison of enhanced biological processes.

Note: X-axis represents Technology Type (Conv. BNR = Conventional BNR; EBNR = Enhanced BNR; PNA = Partial Nitritation-Anammox; SNDPR = Simultaneous Nitrification-Denitrification-Phosphorus Removal; A2O-MBR = Anaerobic-Anoxic-Oxic Membrane Bioreactor). Left Y-axis represents Removal Efficiency (%) for nitrogen (blue bars) and phosphorus (green bars).
Right Y-axis represents Energy Consumption (kWh/m³, orange line). Error bars indicate standard deviation from reviewed studies (n=187).
Source: Authors' compilation based on systematic literature review methodology.

demands of the major biological technology categories identified in this review. Analyses revealed significant, advancements in treatment efficiency with many technologies achieving nitrogen removal rates exceeding 95% and phosphorus removal rate above 98% under optimized conditions.

Anammox-based processes have demonstrated exceptional nitrogen removal performance. Partial nitritation-anammox systems achieved total nitrogen removal efficiencies of 85-95% while reducing energy consumption by 35-60% compared to conventional nitrification-denitrification [51, 52]. Granular anammox systems have shown particular promise, with biomass retention exceeding 99% and nitrogen loading rates up to 45 kg N/m³·d [53]. SNDPR systems equipped with advanced process control achieved simultaneous nitrogen and phosphorus removal efficiencies of 92-96% and 88-94% respectively [54, 55]. The integration of machine learning algorithms integration improved process stability by 25-40% while reducing chemical consumption by 15-30% [54, 55].

Advanced MBR configurations have demonstrated superior nutrient removal, with total nitrogen concentrations consistently below 3 mg/L and total phosphorus below 0.5 mg/L in the treated effluent [56]. A2O-MBR systems achieved the highest performance, with nitrogen and phosphorus removal efficiencies of 96-99% and 97-99.5% respectively [57]. Forward osmosis systems have shown exceptional promise for simultaneous nutrient removal and water recovery, achieving nutrient rejection rates above 99% while producing high-quality permeate suitable for direct potable reuse [58]. However, membrane fouling and energy-intensive draw solution recovery remain significant challenges for large-scale implementation [59].

Electrochemical AOPs demonstrate variable performance depending on the operating conditions. Electrocoagulation achieved phosphorus removal efficiencies of 85-98% with aluminum or iron electrodes, while electrochemical ammonia oxidation achieved 70-90% nitrogen removal under optimized conditions [60, 61]. Photocatalytic processes have shown significant improvements with the development of visible-light-active catalysts

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Table 4. Detailed performance data for advanced oxidation processes.

Process type	**Reactor configuration**	**HRT (h)**	**Influent N (mg/L)**	**Effluent N (mg/L)**	**Influent P (mg/L)**	**Effluent P (mg/L)**	**Power density (W/L)**	**Chemical dosage**	**Ref.**
EC-Aluminum	Batch reactor	0.5-2.0	45-120	38-98	8.5-25	0.2-1.8	250-450	None	[60]
EC-Iron	Continuous flow	1.0-3.0	38-95	32-78	12-35	0.4-2.1	280-520	None	[40]
EO-Ti/IrO_2	Fixed bed	2.0-4.0	85-150	8-38	N/A	N/A	400-800	0.5-2.0 g NaCl/L	[61]
UV/TiO_2	Slurry reactor	1.5-6.0	25-75	2-18	N/A	N/A	15-35 (UV)	0.5-2.0 g/L TiO_2	[62]
Solar/$BiVO_4$	Compound parabolic	3.0-8.0	30-85	4-22	N/A	N/A	Solar irradiance	1.0-3.0 g/L catalyst	[63]
Electro-Fenton	Stirred reactor	2.0-5.0	55-125	8-28	15-40	1.2-4.5	350-650	Fe^{2+}: 20-100 mg/L	Multiple sources

Note: EC = Electrocoagulation; EO = Electrochemical Oxidation; N/A = Not Applicable.
Source: Compiled from multiple peer-reviewed studies [38, 40, 60-63].

development. UV/TiO2 processes achieved nitrogen compound degradation rates of 80-95%, while novel bismuth-based photocatalysts demonstrated 85-92% ammonia removal under visible light irradiation [62, 63]. Detailed performance data for the various AOP configurations are presented in Table 4.

Engineered adsorbents have demonstrated exceptional nutrient removal with rapid kinetics and high capacity. Modified biochar materials have achieved phosphorus adsorption capacities of 15-45 mg P/g, while magnetic nanoparticles have enabled selective nutrient recovery with regeneration efficiencies exceeding 90% [64, 65]. Metal-organic frameworks showed particularly promising phosphorus removal results with adsorption capacities reaching 100-250 mg P/g and selective removal in the presence of competing ions [66], however, material costs and long-term stability remain challenges.

Hybrid treatment configurations consistently achieved superior performance compared to individual technologies. MBR-electrocoagulation systems demonstrated total nitrogen and phosphorus removal efficiencies of 97-99% and 98-99.8% respectively, while maintaining stable operation under varying load conditions [67, 68]. Constructed wetlands integrated with advanced materials have achieved impressive results for decentralized applications, with removal efficiencies of 88-95% for nitrogen and 92-98% for phosphorus, while providing additional ecosystem benefits [69, 70].

3.2. Economic and energy analysis

Cost analysis revealed significant variations among technologies. Fig. 4 presents a comparative summary of capital and operational costs across the reviewed technology classes. Conventional BNR systems require capital investments of \$800-1,500 per m^3/d capacity, while advanced MBR systems ranged from \$1,200-2,500 per m^3/d [71]. Anammox-based processes showed lower capital requirements (\$600-1,200 per m^3/d) due to reduced reactor volumes and equipment complexity [72]. The operational costs vary substantially based on energy consumption, chemical requirements, and maintenance needs. Anammox systems demonstrated the lowest operational costs (\$0.15-0.35 per m^3), followed by optimized EBNR systems (\$0.25-0.45 per m^3) and advanced MBR configurations (\$0.40-0.80 per m^3) [73, 74].

Energy analysis revealed significant differences among treatment approaches. Conventional BNR

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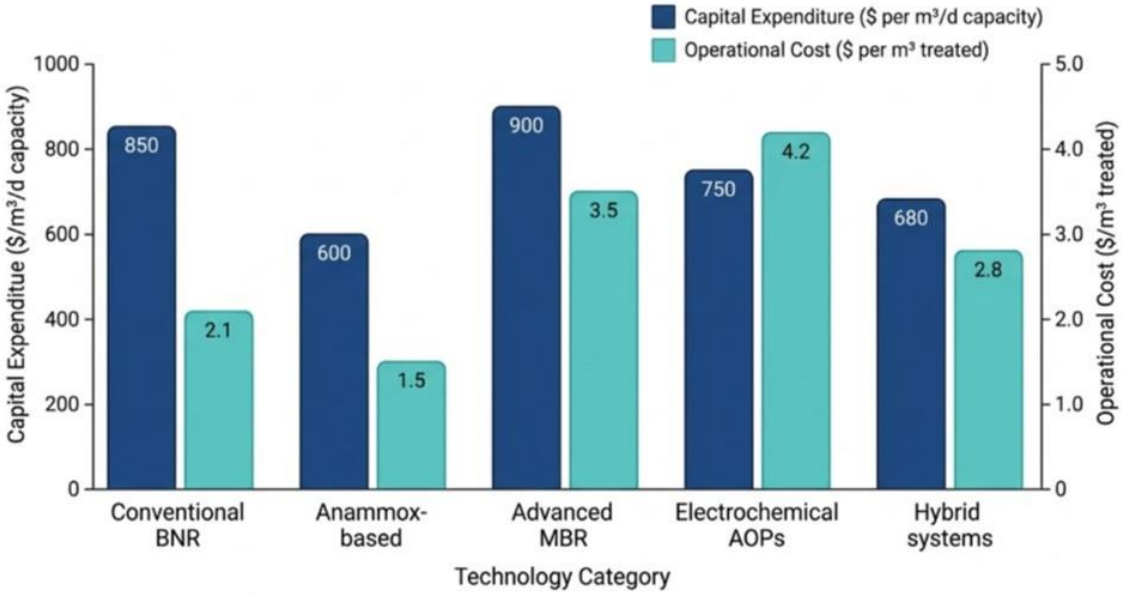

Figure 4. Economic comparison of nutrient removal technologies.
Source: Authors' compilation based on systematic literature review methodology.

systems typically consumed 0.8-1.5 kWh/m³, whereas advanced biological processes reduce energy requirements to 0.4-0.8 kWh/m³ through process optimization [75]. MBR systems showed higher energy consumption (1.2-2.5 kWh/m³) primarily due to membrane aeration requirements [76]. AOPs demonstrated high energy intensities (2-8 kWh/m³) but offered rapid treatment and high removal efficiencies [77, 78].

3.3. Environmental impact assessment

Life cycle assessment studies revealed enhanced biological processes generally produced lower carbon footprints compared to physicochemical alternatives. Anammox-based systems demonstrated carbon footprints 30-50% lower than those of conventional BNR processes due to reduced energy consumption and eliminated methanol requirements [79, 80]. MBR systems showed mixed results, with lower carbon emissions from reduced land use, offset by higher energy consumption. Advanced MBR configurations with energy recovery systems have achieved carbon footprints comparable to those of conventional treatments [81].

Several emerging technologies have demonstrated significant nutrient recovery and reuse potential. Adsorption-based systems enabled phosphorus recovery as fertilizer-grade materials [82, 83], while anammox processes reduced overall nitrogen loads requiring disposal. Algae-based treatment systems showed particular promise for simultaneous nutrient removal and biomass production for bioenergy applications [84]. Table 5 compares the carbon footprint, resource recovery potential, and sustainability metrics of the reviewed technologies.

3.4. Implementation challenges and barriers

Despite impressive laboratory and pilot-scale results, several technical challenges limit the full-scale implementation. Process stability under varying load conditions remains a significant concern for biological processes, particularly for anammox systems operating at low temperatures [85]. Membrane fouling continues to limit MBR performance and increase operational costs [86]. Control system complexity represents another barrier, with advanced process control requiring specialized expertise and sophisticated monitoring equipment [87, 88].

High capital costs for advanced technologies create adoption barriers, particularly in developing regions with limited treatment infrastructures. Regulatory frameworks often lag behind technological developments, creating uncertainty regarding technology adoption and investment [89]. Long payback periods for advanced systems may discourage their adoption despite superior

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Table 5. Environmental impact comparison of nutrient removal technologies.

Technology category	Carbon footprint (kg CO_2-eq/m^3)	Energy recovery potential	Chemical consumption	Sludge production (kg DS/m^3)	Resource recovery	Overall sustainability score*
Conventional BNR	0.65-0.95	Low	Moderate	0.35-0.55	Minimal	6.2/10
Enhanced BNR	0.45-0.75	Moderate	Low-Moderate	0.28-0.48	Low-Moderate	7.8/10
Anammox-based	0.25-0.45	High	Minimal	0.15-0.25	Moderate	8.9/10
MBR Systems	0.85-1.25	Moderate	Moderate	0.25-0.35	High (water reuse)	7.5/10
AOP Systems	1.2-2.8	Low	High	0.45-0.85	Low	5.5/10
Hybrid Systems	0.55-0.85	High	Moderate	0.30-0.50	High	8.2/10
Constructed Wetlands	0.15-0.35	Very High	Minimal	0.20-0.35	Very High	9.3/10

*Sustainability Scoring Criteria (10-point scale): Carbon footprint (25%); Resource recovery (25%); Chemical consumption (20%); Energy efficiency (20%); Ecosystem impact (10%).
Source: Compiled from LCA studies by Hospido et al. [79], Foley et al. [80], and multiple sources [81-84].

performance [90, 91]. Risk aversion in the water treatment industry further slows technology transfer from research to commercial applications.

3.5. Technological trends and innovations

The analysis revealed key trends in emerging nutrient removal technologies. The shift toward biological processes optimized through advanced control systems represents a fundamental change from traditional physicochemical approaches [92, 93]. Anammox-based processes have the potential for sustainable nitrogen removal with reduced energy and chemical inputs. The integration of digital technologies and artificial intelligence transforms process optimization capabilities [94]. Machine learning algorithms enable real-time operating parameter adjustments, thereby improving efficiency and stability while reducing operational complexity. These advances suggest that future wastewater treatment plants will operate as intelligent, self-optimizing systems. Membrane technologies continue to evolve toward higher flux, and lower fouling configurations [95, 96]. The development of novel materials and surface modifications promises to address long-standing challenges while maintaining superior effluent quality.

3.6. Performance optimization strategies

Most successful emerging technologies employ multifaceted optimization strategies to address technical and operational challenges. Process intensification through advanced reactor designs enables higher loading rates and reduced footprints while maintaining the treatment efficiency [97]. Engineered microbial communities and bioaugmentation strategies enhance the stability and performance of biological processes [98,99]. Energy optimization through process integration and energy recovery systems significantly improves the economic viability of advanced treatment technologies [100,101]. Heat recovery, biogas capture, and renewable energy integration create opportunities for net-positive energy treatment plants.

3.7. Sustainability and circular economy principles

Emerging nutrient removal technologies increasingly incorporate circular economy principles, emphasizing resource recovery and reuse over conventional disposal [102,103]. Phosphorus recovery as a fertilizer-grade struvite addresses both environmental protection and resource scarcity challenges. Nitrogen recovery through innovative biological processes reduces environmental impact while creating valuable products. The integration of treatment processes with urban infrastructure creates opportunities for decentralized, resource-positive systems [104,105]. Green infrastructure approaches that combine treatment, energy production, and urban amenities represent a paradigm shift toward sustainable urban water management. Fig. 5 illustrates the integration of circular economy

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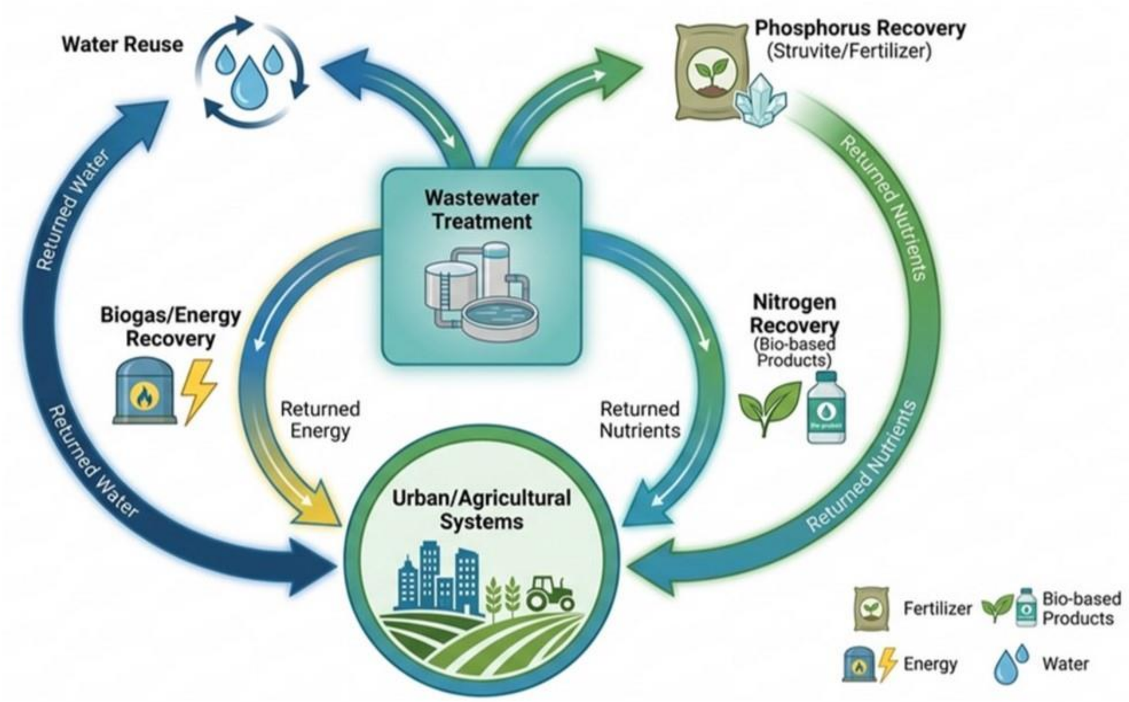

Figure 5. Circular economy integration in nutrient removal systems.
Source: Authors' compilation based on systematic literature review methodology.

principles into nutrient removal systems, highlighting key resource recovery pathways.

3.8. Regional and contextual considerations

Technology selection and optimisation must consider regional factors, including climate, infrastructure development, economic conditions, and regulatory frameworks [106,107]. Tropical regions may favour biological processes with higher temperature tolerance, whereas cold climates require specialised approaches to maintain biological activity. Developing regions often benefit from decentralised, low-maintenance technologies that operate with limited skilled personnel and infrastructure support [108,109]. Constructed wetlands, algae-based systems, and simple biological processes may provide more appropriate solutions than high-technology alternatives.

3.9. Future research directions and technology transfer

Several research priorities have emerged from this analysis. A fundamental understanding of microbial community dynamics in enhanced biological processes requires continued investigation to improve process stability and predictability [110]. Fig. 6 presents an assessment of the technology readiness levels (TRL) of the reviewed nutrient removal technologies, highlighting their proximity to full-scale commercial deployment.

Novel material research on membranes, adsorbents, and catalysts offers opportunities for breakthrough performance improvements [111, 112]. Process integration and optimisation represent promising research areas, particularly in the development of intelligent control systems and predictive maintenance strategies [113, 114]. The application of digital twin technologies and advanced modelling approaches could revolutionise treatment plant design and operation. Successful technology transfer from research to commercial applications requires addressing multiple barriers simultaneously [115]. Demonstration projects at appropriate scales provide crucial validation data while building operator confidence and regulatory approvals. Collaborative partnerships between research institutions, technology developers, and end users accelerate the deployment of proven technologies [116, 117]. Table 6 summarises key implementation strategies and

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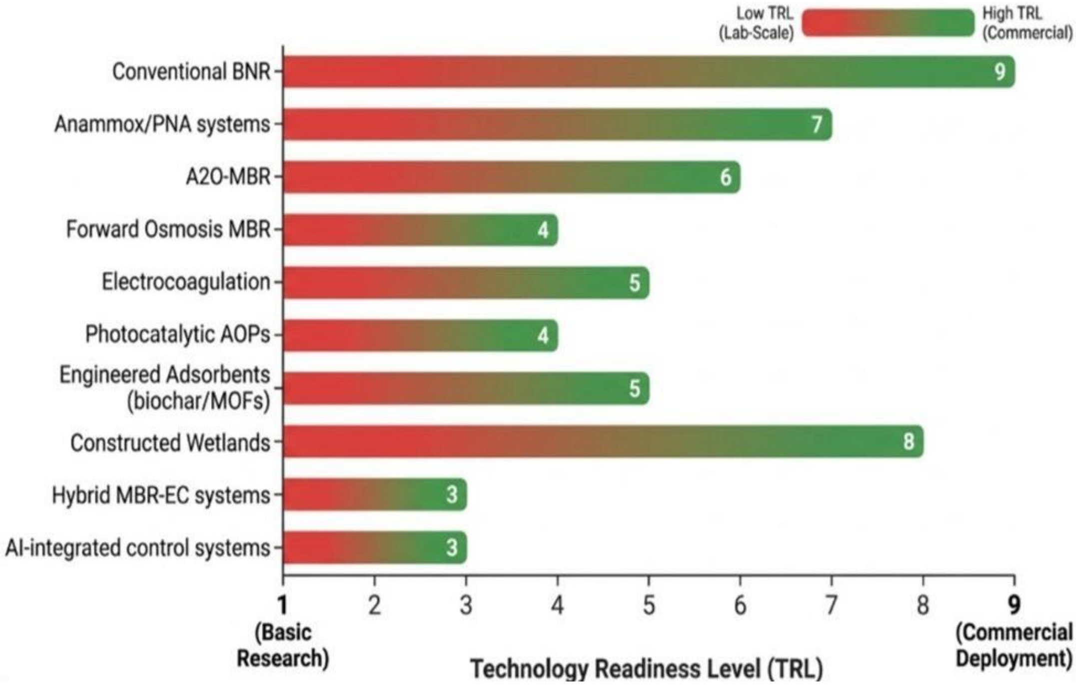

Figure 6. Technology readiness level assessment.
Source: Authors' compilation based on systematic literature review methodology.

Table 6. Technology implementation strategies and success factors.

Technology type	Commercial maturity level	Successful implementation examples	Key success factors	Primary barriers	Implementation timeline	Risk mitigation strategies
Enhanced BNR	Commercial (TRL 9)	>500 plants globally	Process control expertise, adequate infrastructure	Operational complexity	2-3 years	Phased implementation, operator training
Anammox Systems	Demonstration (TRL 7-8)	50+ full-scale plants	Proper inoculation, temperature control	Start-up challenges	3-5 years	Pilot testing, bioaugmentation
Advanced MBR	Commercial (TRL 9)	>1000 installations	Membrane selection, fouling control	High CAPEX/ OPEX	2-4 years	Performance guarantees, O&M contracts

Source: Compiled from Lackner et al. [115], Velenturf & Purnell [116], and industry implementation reports (2019-2024).
Financial mechanisms, including public-private partnerships, performance-based contracting, and green financing instruments, overcome economic barriers to technology adoption.

success factors for successful technology transfer and commercial deployment of emerging nutrient removal technologies.

4. Conclusions

This comprehensive review reveals significant advancements in emerging nutrient removal technologies regarding treatment efficiency, sustainability, and economic viability. Enhanced biological processes, particularly anammox-based systems, demonstrate exceptional promise for sustainable nitrogen removal with reduced energy

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consumption and operational costs. Advanced membrane technologies continue to achieve superior effluent quality while addressing traditional challenges through innovative materials and process configurations. The integration of digital technologies and artificial intelligence has transformed the process optimisation potential and autonomous operation capabilities. These developments suggest that future treatment plants will operate as intelligent, adaptive systems that respond responding to changing conditions while maintaining optimal performance.

Hybrid and integrated treatment approaches consistently demonstrate superior performance compared to individual technologies, achieving nitrogen and phosphorus removal efficiencies exceeding 95% and 98%, respectively. Successful commercial deployment requires coordinated research, demonstration, and policy programs to overcome the technical, economic, and regulatory barriers. The integration of circular economy concepts and resource recovery operations represents a paradigm shift in sustainable waste treatment. Advances in nutrient recovery technologies as valuable products address environmental protection and resource scarcity while enhancing economic viability.

Regional and contextual factors significantly influence technology selection and optimisation. Effective implementation must consider the local climate, logistics, economic development, and regulations. Nature-based and decentralised solutions particularly benefit developing countries with limited infrastructure. The potential of future nutrient removal technologies depends on the continued unification of biological, physical, and digital approaches. Successful technologies combine high performance with simple operation, cost-effectiveness, and environmental sustainability. Further research, demonstration, and favourable policy frameworks are needed to fully utilise these technological advancements. Recommendations include prioritising anammox process optimisation across diverse conditions, developing next-generation membrane materials with better fouling resistance, pursuing research on synergistic technology combinations with advanced control algorithms, and increasing nutrient recovery technology research to provide marketable products while attaining treatment targets. Implementation strategies should include full-scale demonstration projects, comprehensive operator training programs, gradual implementation with risk mitigation, and innovative financing mechanisms. Policy recommendations include updating discharge standards and regulations, implementing financial incentives for nutrient removal, developing standardised testing and certification methods, and increasing research funding for practical applications and technology transfer. International cooperation through technology transfer programs, collaborative global research, best practice sharing forums, and standardisation of international procedures will accelerate the advancement of sustainable nutrient removal solutions globally.

Disclaimer (artificial intelligence)

Author(s) hereby state that no generative AI tools such as Large Language Models (ChatGPT, Copilot, etc.) and text-to-image generators were utilized in the preparation or editing of this manuscript.

Authors' contributions

Conceptualization, M.A.O., M.A.A.; data curation, S.C.O., R.O.O.; formal analysis: O.G.I., A.O.E.; funding acquisition, M.A.O.; investigation, M.A.O., O.A.O.; methodology, S.C.O., R.O.O.; project adminis -tration: M.A.A.; resources: M.A.O.; software, A.O.E.; supervision, M.A.A., O.A.O.; validation, O.G.I.; visua -lization, R.O.O.; writing – original draft, M.A.O., S.C.O.; writing – review & editing, M.A.A., O.A.O.

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Availability of data and materials

All data resulting from this study have been included herein.

Conflicts of interest

The authors declare no conflict of interest.

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