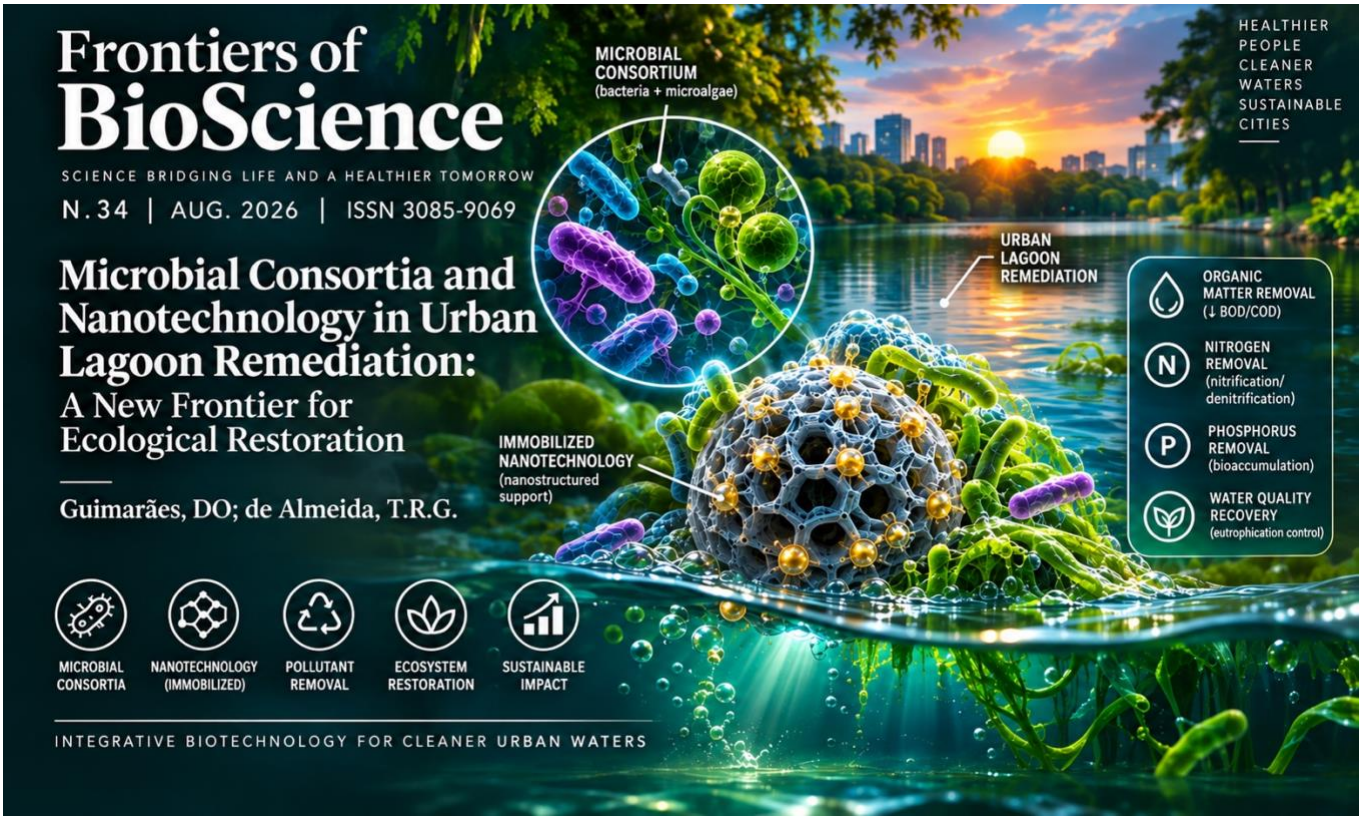


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ABSTRACT

Urban lagoons receiving domestic sewage are affected by organic loading, nitrogen and phosphorus enrichment, hypoxia, microbial hazards, and sediment nutrient recycling. This critical narrative review distinguishes pollutant removal measured in wastewater reactors from sustained recovery of an open aquatic ecosystem. Published experimental evidence demonstrates ammonium-nitrogen and orthophosphate-phosphorus removal rates of 9.05 ± 1.24 and 0.79 ± 0.06 mg L−1 d−1, respectively, in an indigenous microalgal–bacterial treatment system; a separate continuous-flow consortium operated for 120 days, achieving complete phosphorus removal under specified conditions at hydraulic retention times exceeding 6 h. Field observations are less uniform: a floating-wetland pilot improved mean total-nitrogen mass removal by 13% relative to an uncovered control, whereas storm-event monitoring of two full-scale wetlands found median total-nitrogen load changes of −2% and +3%. We propose a falsifiable translation framework combining screened indigenous consortia, modular recirculation, net nutrient mass balances, immobilised nano-enabled polishing tested against conventional comparators, and independent ecological monitoring. This is a conceptual research proposal, not a report of newly collected environmental data or established nano-specific efficacy. Source control, biosafety, retention and recovery of materials, and ecological outcomes are prerequisites for responsible application.

KEYWORDS: urban lagoon; sewage; indigenous microbial consortia; microalgae–bacteria; biofilm; nutrient mass balance; floating treatment wetland; contained nanotechnology; ecological recovery; One Health.

SCIENTIFIC HIGHLIGHTS

• Directly measured wastewater removal, pilot-lagoon performance and whole-ecosystem recovery are not equivalent endpoints.

• Published quantitative observations reveal both strong reactor-scale results and highly variable full-scale wetland outcomes.

• Indigenous-consortium selection and nano-specific polishing must be assessed in independent, adequately replicated comparisons.

• The proposed innovation is a safety-gated, mass-balanced path from biological function to verifiable ecological restoration.

1. INTRODUCTION

Domestic sewage introduces organic matter, ammonium, phosphorus, faecal organisms and emerging contaminants into shallow urban waters. Oxygen depletion, turbidity, eutrophication and harmful cyanobacterial blooms reflect interacting biological and physicochemical processes rather than a single pollutant [1, 2].

Improving the effluent of a treatment reactor does not automatically restore the receiving lagoon. Continued sewage and stormwater inputs, groundwater exchange, internal sediment loading and ecological feedbacks may delay recovery even after external nutrient reductions [3, 4].

2. SCOPE AND CRITICAL APPROACH

This critical narrative review synthesises mechanistic, experimental and field evidence available through 31 August 2026; it is neither a systematic review nor a meta-analysis. Studies were selected for relevance to indigenous consortia, biofilms, floating wetlands, nanomaterial containment, treatment performance and environmental risk. Heterogeneous water matrices, retention times and endpoints preclude a pooled removal percentage.

We distinguish established mechanisms, controlled treatment performance, observed ecological responses and prospective hypotheses. Concentration changes, net contaminant export and whole-lagoon restoration have different evidentiary requirements.

3. BIOGEOCHEMICAL BASIS OF MICROBIAL TREATMENT

3.1 Organic carbon oxidation and oxygen demand

Aerobic heterotrophs oxidise biodegradable organic carbon to carbon dioxide and biomass, lowering biochemical and chemical oxygen demand (BOD/COD). Yet degradation consumes oxygen; uncontrolled stimulation may aggravate hypoxia. Design therefore requires measured aeration, hydraulic loading and biomass retention. Concentration decreases may also reflect settling or assimilation rather than mineralisation.

Anaerobic and fermentative pathways may generate reduced metabolites; their activity does not necessarily signify improved habitat conditions. Carbon removal and subsequent nutrient conversion should be engineered as defined stages.

3.2 Nitrogen cycling: conversion is not necessarily removal

Nitrogen cycling includes ammonia and nitrite oxidation, complete nitrification, denitrification, anammox and assimilation, regulated by oxygen, carbon, pH, temperature and biofilm conditions [5]. Complete ammonia oxidation by certain Nitrospira organisms illustrates the need to measure function rather than infer it from genus labels [6].

Nitrification converts nitrogen species but does not reduce total nitrogen (TN). Denitrification can remove nitrogen as gas, with potential nitrous oxide by-products; assimilation becomes net removal only after biomass harvest. TN, nitrogen speciation and, where feasible, gas fluxes should be quantified.

3.3 Phosphorus accumulation, capture, and sediment recycling

Phosphorus-accumulating organisms retain intracellular polyphosphate under appropriate metabolic conditions [7]. In lagoons, sediment release can replenish dissolved phosphorus. Uptake or adsorption becomes durable removal only when phosphorus-rich biomass, solids or media are recovered and safely managed.

4. FUNCTIONAL MICROBIAL CONSORTIA

4.1 Beyond single-strain bioaugmentation

Consortia may combine complementary metabolism, cross-feeding and microenvironment formation, but greater diversity does not guarantee efficacy. Competition, grazing and community instability can counteract benefits. Selection should therefore rely on measured function and safety, not lists of presumed beneficial genera.

A 2024 synthesis documented both facilitative and antagonistic microalgal–bacterial interactions [8]. Light, turbidity and diel oxygen variation complicate extrapolation from wastewater cultures to open lagoons.

4.2 Indigenous microalgal–bacterial associations

Microalgae assimilate nutrients and can supply photosynthetic oxygen to heterotrophs; bacterial respiration may supply carbon dioxide. This exchange is affected by light attenuation, self-shading and night-time respiration, requiring day–night oxygen monitoring.

Sousa et al. measured ammonium-nitrogen removal of 9.05 ± 1.24 mg L−1 d−1 and orthophosphate-phosphorus removal of 0.79 ± 0.06 mg L−1 d−1 using a native consortium in urban wastewater [9]. Faecal indicators and selected resistance markers declined, but the findings neither establish potability nor predict open-lagoon efficacy.

A continuous-flow indigenous microalgal–bacterial system operated for 120 days, and phosphorus removal was complete at retention times exceeding 6 h under the studied conditions [10]. These reactor results are not equivalent to measured lagoon restoration.

4.3 Biofilm retention and persistence

Biofilms retain slow-growing organisms and create oxygen gradients needed for coupled nutrient transformations. Moving-bed systems depend on carrier surface, shear, extracellular polymers and diffusion; thick or unstable biofilms can limit performance [11].

Bioaugmentation may fail because of inoculum washout or ecological competition [12]. Recent research highlights aggregation and co-immobilisation as potential determinants of persistence [13], supporting contained enrichment of indigenous communities rather than indiscriminate inoculation into public waters.

5. WHAT NANOTECHNOLOGY CAN REALISTICALLY CONTRIBUTE

5.1 Mechanistic opportunities and the problem of attribution

Nanostructured materials may supply high surface area, surface charge, selective adsorption, catalytic activity and functional membranes [14]. A claimed “nano-enhancement” is meaningful only if it surpasses a matched conventional material under the same operating conditions.

Adsorption transfers contaminants into a solid phase; membranes concentrate them in a retentate; photocatalysis may form transformation products. Each route requires contaminant-fate analysis and management of spent materials or by-products.

5.2 Nanoengineered supports and membranes

Nanocomposite membranes can alter permeability, fouling and selectivity [15], but antimicrobial surfaces may inhibit biofilms. Treatment objectives should not be conflated: microbial immobilisation and oxidative or antimicrobial polishing may require separate compartments.

A safer design retains microorganisms in biological reactors and immobilised nanomaterials in monitored polishing modules. Test modified surfaces against equivalent conventional supports, documenting leaching, durability, recovery and residuals.

5.3 Adsorption, photocatalysis, and safe containment

Iron-oxide and carbon-based adsorbents, recoverable magnetic composites and photocatalytic coatings are plausible polishing options, contingent on contaminant chemistry, regeneration and cost. Oxidants generated by photocatalysis may also harm beneficial microorganisms.

Environmental nanotechnology requires assessment of material manufacture, transformation, exposure and downstream releases [16]. Containment and recovery reduce but do not eliminate risk; laboratory removal efficiency does not justify direct nanoparticle dispersal into a lagoon.

6. FROM REACTOR PERFORMANCE TO LAGOON RESTORATION

6.1 Why recirculation is not equivalent to removal

External modular treatment permits controlled retention, aeration and waste handling, but its lagoon-scale impact depends on treated flow relative to lagoon volume, incoming loads, sediment release and short-circuiting. High reactor removal percentages can coexist with small changes in the receiving water.

For a constituent with a verified sink, apparent treatment removal is R = Q(Cin − Cout)/1000 (kg d−1), where Q is flow (m3 d−1) and C is concentration (mg L−1). This calculation alone does not establish destruction or permanent export if the contaminant merely changes phase or chemical form.

A lagoon inventory follows dM/dt = Lin + Linternal − Lout − R − E, including external

inputs, internal loading, hydrologic export, engineered removal and other quantified sinks. All terms require the same constituent and mass boundary; bathymetry, flows and seasonal measurements are essential.

6.2 Ecological interventions in parallel

Floating wetlands supply plant roots, habitat and biofilm surfaces, but benefits vary with coverage, hydraulics and harvest. Field syntheses warn against scaling mesocosm percentages to whole lakes [17] and emphasise baseline measurements and controls [18]. They complement, rather than replace, sewage interception.

7. A COMPARATIVE TRANSLATIONAL RESEARCH FRAMEWORK

Research should begin with seasonal lagoon diagnosis: hydrology, BOD/COD, nitrogen, phosphorus, sediments, pathogen indicators and ecological status. Indigenous microbial communities should then undergo laboratory functional screening and biosafety assessment before contained pilot testing.

Parallel treatment trains with identical hydraulics and stages but different consortia are valuable for screening. One reactor per arm, however, risks pseudoreplication; replicated units or a predefined crossover design are required for causal inference. Nano-enabled polishing should subsequently be tested against a matched conventional material, isolating differences in geometry, contact time and hydraulic resistance.

Primary endpoints should include paired influent/effluent BOD/COD, TN and nitrogen species, TP and orthophosphate, suspended solids, flow and independently confirmed mass export. Report concentrations and loads (kg d−1), hydraulic retention and uncertainty. Secondary outcomes include energy, greenhouse gases, microbial persistence, carrier leaching, waste streams, costs, oxygen profiles, chlorophyll-a and faecal indicators.

Progression gates should comprise source diagnosis, indigenous-consortium safety, replicated biological comparisons, nano-specific attribution and monitored field demonstration. Stop conditions include hypoxia, toxicity, pathogen enrichment, antimicrobial-resistance concerns and material leakage. Before–after–control–impact (BACI) monitoring improves inference; success thresholds must reflect site-specific baselines, uncertainty and legal standards.

Evidence synthesis — intervention classes

1. Retained bacterial biofilms. Organic carbon conversion; nitrification and coupled nitrogen processes. Evidence: Established wastewater reactor practice [11]. Limitation: Requires oxygen control, biofilm retention, and load balancing.

2. Indigenous microalgal–bacterial consortia. Nutrient uptake; metabolic cooperation; biomass generation. Evidence: Laboratory and continuous-flow wastewater studies [8, 9, 10]. Limitation: Light dependence and biomass harvesting; variable field transfer.

3. Immobilised nanomaterials and membranes. Selective adsorption, separation, or catalytic polishing. Evidence: Materials and wastewater studies/reviews [14, 15, 16]. Limitation: Leaching, residuals, fouling, cost, uncertain lagoon-scale benefit.

4. Constructed floating wetlands. Root-associated uptake and ecological habitat support. Evidence: Field syntheses with heterogeneous effects [17, 18]. Limitation: Area and hydraulics constraints; harvesting and source control needed.

8. BIOSAFETY, ONE HEALTH, AND REGULATORY RESPONSIBILITY

Sewage can contain pathogens and antimicrobial-resistance determinants; metagenomic sewage surveillance illustrates this concern [19]. Indigenous origin or genus identification does not guarantee inoculum safety. Community characterisation and relevant resistance screening should precede exposure to public-access waters.

Published reviews identify matrix compatibility, inoculum persistence and site-specific responses as limitations of bioaugmentation [20]. Contained enrichment is preferable to indiscriminate direct release. Reducing an indicator microorganism does not certify drinking-water safety.

Nano-enabled modules require exposure, leachate, ecotoxicity, recovery and waste-management assessment. Public-water pilots must also meet applicable environmental approvals and water-use standards.

9. QUANTITATIVE EVIDENCE: WHAT HAS ACTUALLY BEEN MEASURED?

9.1 Controlled biological treatment and the limits of direct extrapolation

Studies of indigenous microalgal–bacterial consortia and bacterial biofilm aggregation highlight complementary nutrient-removal pathways, but also expose limits from light availability, mass transfer, inoculum persistence and reactor-scale transfer [8, 11, 13]. These observations justify comparative biological testing rather than assuming a fixed lagoon-scale efficiency.

Quantitative evidence is strongest within controlled influent–effluent boundaries. Sousa et al. reported 9.05 ± 1.24 mg L−1 d−1 ammonium-nitrogen and 0.79 ± 0.06 mg L−1 d−1 orthophosphate-phosphorus removal [9]. Li et al. sustained a continuous-flow system for 120 days and observed complete phosphorus removal at hydraulic retention above 6 h [10]. Neither result measures an entire restored lagoon.

9.2 Field and pilot evidence: magnitude, heterogeneity, and confounding

A review of 335 field-scale constructed wetlands reported median removal efficiencies in hybrid wetland systems of approximately 76% organic matter, 63% TN and 72% TP [21]. These are synthesised treatment-system estimates, not predicted gains for sewage-polluted lagoons. In a 900 m2 floating wetland covering about 5% of a Florida pond, harvested plants exported 1,026 kg nitrogen and 262 kg phosphorus during 2016–2020 [22].

A 16-month study of four 6.5 m3 pilot lagoons using agri-food tertiary effluent found that 72% floating-wetland coverage increased TN mass removal by a mean 13% (maximum 55%) relative to control [23]. In contrast, two full-scale wetlands receiving construction runoff yielded median storm-event TN load reductions of −2% and +3% [24]. Distinct influent matrices and flow regimes limit comparison.

A 2026 Australian urban-lake study reported 70–95% suspended-solids, 59–93% TP and 14–45% TN reductions during event and pump testing [25], not general lagoon-wide performance. McCoy et al. found pond median nitrate-nitrogen decreased from 23 to 1.3 µg L−1 and phosphate-phosphorus from 42 to 19 µg L−1 (2020–2023), but floating wetlands, airlift pumps and phosphorus sorbents were combined [26].

Measured results — distinct experimental contexts

1. Sousa et al., 2024 [9]. System: Native microalgal–bacterial culture; urban wastewater. Observation: NH4+-N: 9.05 ± 1.24 mg L−1 d−1; PO4-P: 0.79 ± 0.06 mg L−1 d−1. Scope: Controlled wastewater treatment; not a lagoon-scale response..

2. Li et al., 2024 [10]. System: Continuous-flow microalgal–bacterial treatment of secondary effluent. Observation: 120-day operation; complete P removal at HRT >6 h, under reported conditions. Scope: Secondary effluent and specific HRT; biomass fate remains essential..

3. Wu et al., 2023 [21]. System: Review synthesis of 335 field-scale constructed wetlands. Observation: Hybrid wetlands: median ~76% organic matter, ~63% TN, ~72% TP removal. Scope: Pooled wetland systems; not primary observation of one urban lagoon..

4. White, 2021 [22]. System: 900 m2 floating wetland, ~5% pond surface coverage. Observation: 2016–2020 harvested biomass: 1,026 kg N and 262 kg P exported. Scope: Plant-tissue nutrient export, not comprehensive mass closure..

5. Abi Hanna et al., 2024 [23]. System: Four 6.5 m3 pilot lagoons; agri-food tertiary effluent; 16 months. Observation: 72% cover: mean +13% and up to +55% TN mass removal vs uncovered control. Scope: Relative improvement, not total absolute efficiency; non-domestic matrix..

6. Schwammberger et al., 2023 [24]. System: Two field-scale wetlands; construction stormwater; storm events. Observation: Median TN load changes: −2% and +3% in two systems. Scope: Demonstrates field-scale uncertainty and occasional net export..

7. Drapper et al., 2026 [25]. System: Urban lake with floating treatment wetland and recirculation. Observation: Test-reported TSS 70–95%, TP 59–93%, TN 14–45% reductions. Scope: Event/pump-test boundary; not universal lake-wide rate..

8. McCoy et al., 2024 [26]. System: Urban retention pond; wetland + airlift + sorbent intervention. Observation: 2020–2023 nitrate-N median 23→1.3 µg L−1; PO4-P 42→19 µg L−1. Scope: Before–after, multicomponent intervention; cannot isolate causes..

Concentration, daily mass flux, harvested nutrient stock and ecological recovery are different endpoints; direct comparisons demand common accounting boundaries and uncertainty estimates.

10. A FALSIFIABLE, SAFETY-GATED TRANSLATIONAL FRAMEWORK

10.1 The central hypothesis: removal, attribution, and ecological benefit

We hypothesise that screened indigenous consortia in a contained recirculation train can increase verifiable nutrient export without elevating biological hazards, provided sewage inputs and internal loading are quantified. Nano-enabled polishing must demonstrate added benefit over matched conventional materials, followed by independent evaluation of receiving-water ecology. This hypothesis has not yet been experimentally tested in the proposed configuration.

10.2 Four preregistrable questions and decision gates

H1—Consortium selection. Under replicated matched hydraulics, do screened indigenous consortia differ in TN/TP mass removal after adjustment for load, temperature and retention? Estimate between-unit effects and confidence intervals.

H2—Nano-specific contribution. Does an immobilised nano-enabled material outperform conventional media with equivalent geometry and contact time on net removal or micropollutant capture, while meeting leaching, toxicity and residuals criteria?

H3—Ecological response. Does the lagoon demonstrate oxygen, chlorophyll-a, faecal-indicator, nutrient-inventory and sediment-flux improvements beyond seasonal variation and suitable reference sites? Evaluate with BACI design and mass-balance plausibility.

H4—Sustainability. Do incremental benefits justify energy, materials, labour, waste handling, replacement and life-cycle impacts? Safety or feasibility failures preclude field progression.

10.3 Accounting equations and measurement priorities

For each species, compute R = Q(Cin − Cout)/1000 in kg d−1, but label the result apparent removal until the terminal sink or recovered mass is verified. Reconcile dissolved, particulate, sorbed, biomass and gaseous fractions, distinguishing dilution, temporary accumulation and true export.

The staged sequence is diagnosis and source control → safe indigenous enrichment → replicated biological trials → nano-versus-conventional test → monitored receiving-water demonstration. Progress is halted by unacceptable toxicity, leakage or microbiological hazards; field monitoring should be independent of the operator.

10.4 Scientific novelty and the appropriate claim

Consortia, floating wetlands and nano-enabled treatment are established research themes [14, 15, 16, 21]. Our proposed contribution is a falsifiable framework that independently attributes biological and nano-specific effects, measures net mass export and ecological response, and incorporates material recovery and biosafety from the outset.

11. RESEARCH GAPS AND FUTURE DIRECTIONS

Five gaps require priority: incomplete nitrogen and phosphorus mass balances; lack of causal links between multi-omics and reaction rates; confounding by sewage inflows, seasonality and sediment release; nano-material comparisons without matched controls and leaching analysis; and sparse integrated ecological, biosafety and life-cycle endpoints. Replicated tests with open protocols are more informative than unvalidated inventories of candidate species.

12. CONCLUSION

Microbial communities can transform organic matter and nitrogen species and assimilate phosphorus, but their value depends on hydraulics, oxygen, biomass retention and managed nutrient export. Evidence is stronger for controlled treatment than for durable restoration of entire sewage-impacted lagoons.

Recoverable nanostructured adsorbents, membranes and catalysts may improve polishing, but their incremental benefits must exceed conventional controls and justify toxicity, leaching and life-cycle burdens. An evidence-led translational route therefore starts with sewage-source control and screened indigenous microbes, separates biological from nano-specific effects, and verifies outcomes in the receiving water. This framework offers testable hypotheses for responsible environmental engineering without claiming an unproven field technology.

DECLARATIONS

Article type: critical narrative review. Ethics: no original human, animal or environmental experiments were conducted for this review. Data availability: no new experimental dataset was generated; quantitative observations are attributed to their respective sources. Funding, institutional affiliations, author ORCID identifiers and competing-interest statements must be confirmed by the authors before editorial publication.

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