

Beyond Removal Efficiency: A Critical Review of the Long-Term Sustainability of Constructed Wetlands for Wastewater Treatment

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Abstract

Constructed wetlands (CWs) have become important nature-based systems for wastewater treatment because of their relatively low external energy requirements, operational simplicity, potential for decentralized application, and capacity to provide additional ecosystem services. However, portraying CWs as fundamentally sustainable may be misleading when treatment efficacy is assessed without accounting for the associated land requirements, hydraulic deterioration, greenhouse gas emissions, building materials, maintenance, and life-cycle costs. This review critically examines CW sustainability beyond conventional pollutant-removal efficiency, emphasising treatment performance, long-term hydraulic reliability, clogging, greenhouse gas emissions, land, energy, materials, economics, and resource recovery. Evidence from free-water-surface, horizontal subsurface-flow, vertical subsurface-flow, hybrid, and aerated systems indicates that CWs generally remove suspended solids and organic matter effectively, whereas nitrogen and phosphorus removal depend more strongly on hydraulic conditions, substrate characteristics, redox environment, carbon availability, and configuration. Long-term reliability is constrained principally by hydraulic deterioration and solids accumulation in subsurface systems, although pretreatment, modular design, and hydraulic management can extend service life. The sustainability advantage of CWs is further complicated by direct methane and nitrous oxide emissions and by environmental burdens associated with construction and, in intensified systems, aeration. Recent life-cycle research confirms that construction, energy use, system boundaries, and methodological assumptions can materially change environmental and economic conclusions. The review therefore argues that CW sustainability is a multidimensional, context-dependent property rather than a direct consequence of low electricity use or high removal efficiency. A practical framework is proposed that considers treatment performance, reliability, land, energy, greenhouse gases, materials, life-cycle cost, and resource recovery together. Priority needs are long-term full-scale monitoring, harmonized reporting and context-specific life-cycle evaluation, particularly in underrepresented tropical, arid and developing-country settings.

Keywords: Constructed Wetlands, Wastewater Treatment, Sustainability, Nature-Based Solutions, Long-Term Performance.

Introduction

The rapid growth of urban populations, industrial activity, and water demand has intensified wastewater management challenges. Poorly treated wastewater contributes to deteriorating receiving waters, eutrophication, public-health risks, and ecological degradation. At the same time, conventional treatment systems may require substantial energy, chemicals, infrastructure, and technical expertise. These pressures have spurred interest in treatment approaches that deliver adequate effluent quality while reducing resource consumption and environmental burdens.

Constructed wetlands are engineered systems that replicate selected physical, chemical, and biological processes found in natural wetlands. Depending on the configuration, wastewater may flow above the substrate or through porous media that support plants, microorganisms, and reactive surfaces. Treatment is consequently achieved through combinations of sedimentation, filtration, adsorption, precipitation, microbial transformation, and plant-associated processes. Major configurations include free-water-surface, horizontal subsurface-flow, vertical subsurface-flow, hybrid, and intensified or aerated systems (Vymazal, 2010; Langergraber, Dotro, Nivala, Rizzo, & Stein, 2020). These configurations can exhibit markedly different greenhouse-gas emission profiles because their hydraulic regimes, oxygen availability, organic-matter conditions, and operational requirements vary. Meaningful comparison, therefore, requires standardized reporting metrics, including emissions expressed as carbon dioxide equivalents over a defined time horizon such as the 100-year Global Warming Potential. Accordingly, sustainability should not be treated as a monolithic attribute of constructed wetlands but as a configuration- and context-dependent property.

The attraction of CWs extends beyond pollutant removal. Their low external energy requirements, potential for decentralized treatment, and capacity to provide landscape and ecological co-benefits have led to their characterization as sustainable alternatives to conventional wastewater treatment. Recent life-cycle literature generally reports favourable environmental performance for CWs relative to more energy-intensive conventional systems, while also emphasizing that construction materials, substrate production, aeration, greenhouse gas emissions, and system boundaries can materially affect results (Fuchs, Mihelcic, & Gierke, 2011; Garfi, Ziegler-Rodriguez, & Irene, 2026). However, the extent to which these assessments explicitly adhere to standardized life-cycle assessment protocols, including ISO 14040 and ISO 14044, is not always clear. This methodological uncertainty is important because differences in functional units, system boundaries, inventory assumptions, impact categories, and allocation procedures can substantially influence comparative conclusions. Accordingly, claims regarding the environmental sustainability of CWs should be interpreted in light of both the reported results and the degree of methodological standardization underlying each assessment.

The sustainability narrative nevertheless requires qualification. A wetland can achieve high pollutant-removal efficiency while requiring substantial land, undergoing progressive hydraulic deterioration, or producing methane and nitrous oxide. Conversely, an intensified

wetland can reduce land requirements and improve nutrient removal while increasing electricity use and infrastructure complexity. Thus, treatment performance and sustainability are related but are not synonymous (Jiao, et al., 2025).

The contemporary evidence base also means that another generic review of “constructed wetlands for wastewater treatment” would add limited value. A 2026 systematic review identified 393 full-scale nature-based wastewater-treatment systems reported in 249 publications across 57 countries; the qualifying systems were overwhelmingly constructed wetlands, with horizontal subsurface-flow systems the most prevalent (Silva, et al., 2026). However, systematic reviews that synthesize hundreds of systems should not be interpreted as indicating that the evidence base is complete or static. Evidence from specific regions, including Sub-Saharan Africa, continues to develop, particularly as additional full-scale systems are documented and evaluated (Alagbe & Alalade, 2013; Traore, Ouattara, Zahui, Osei, & Messou, 2025). Other recent reviews have separately synthesised life-cycle assessment, environmental/economic assessment, and greenhouse-gas emissions (Garfi, Ziegler-Rodriguez, & Irene, 2026; Millaret, Olsen, Quer, & Nainggolan, 2026; Zhang, Pan, Xu, Du, & Guo, 2025). The present paper therefore takes an integrative, critical approach: it asks whether the sustainability claim remains defensible when established review evidence is considered alongside emerging regional and full-scale studies, and when treatment performance is evaluated alongside reliability, resource requirements, climate impacts, and whole-life economics.

Accordingly, this review evaluates constructed wetlands from a whole-life sustainability perspective. It synthesizes evidence on treatment performance, hydraulic reliability, clogging, land, energy, materials, greenhouse-gas emissions, economics, and resource recovery, and examines the trade-offs among these dimensions. Particular attention is given to the principle that the appropriate wetland configuration depends on the treatment objective and the dominant local resource constraint (Islam, Saeed, & Majed, 2022).

Literature Search and Selection Strategy

This critical review used a structured and transparent literature search across Web of Science, Scopus and Google Scholar to identify relevant peer-reviewed evidence. The search targeted peer-reviewed publications examining constructed wetland performance, long-term hydraulic reliability, life-cycle assessment (LCA), life-cycle costing (LCC), greenhouse gas dynamics, and regional technology implementation. Search terms combined primary keywords using Boolean operators: (“constructed wetlands” OR “treatment wetlands”) AND (“sustainability” OR “life cycle assessment” OR “clogging” OR “greenhouse gas emissions” OR “sub-Saharan Africa”). We emphasized recent systematic reviews and full-scale operational evaluations published between 2021 and 2026 to capture state-of-the-art developments. Inclusion required empirical, mass-balance, or life-cycle data regarding system performance. Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) principles served as a general reporting benchmark to

structure synthesis rigour (Page, et al., 2021). However, exceptions exist, particularly when data are unavailable within the specified time frame.

Constructed Wetlands and Treatment Mechanisms

Classification and Configuration

FWS systems maintain wastewater above the substrate and rely strongly on sedimentation, biological transformation, and plant-associated processes. HSSF systems move wastewater horizontally through porous media, normally below the surface. VSSF systems intermittently apply wastewater to the surface and allow vertical percolation through the media, promoting air exchange and oxygen transfer. Hybrid systems combine configurations to create complementary aerobic and anoxic environments, while aerated systems use forced oxygen transfer to intensify treatment. These configurations should not be treated as interchangeable because their hydraulic and redox conditions differ fundamentally (Vymazal, 2010; Langergraber, Dotro, Nivala, Rizzo, & Stein, 2020).

Organic Matter and Suspended Solids

CWs generally reduce suspended solids and biodegradable organic matter through sedimentation, filtration, retention, and microbial degradation. Percentage removal is commonly expressed as:

$$R = [(C_i - C_e) / C_i] \times 100 \quad (\text{Equation 1})$$

C_i and C_e are influent and effluent concentrations; percentage removal alone, however, is insufficient for rigorous comparison because the same percentage can represent vastly different pollutant loads (Vymazal, 2010). Flow and concentration should therefore be reported together, with pollutant load calculated as:

$$L = QC. \quad (\text{Equation 2})$$

Nitrogen Removal

Nitrogen removal is more complex than organic-matter removal because it depends on sequential microbial transformations and the availability of an appropriate influent carbon source. Nitrification converts ammonium to nitrite and nitrate under oxygenated conditions, whereas denitrification converts nitrate to gaseous nitrogen under suitable reducing conditions. Denitrification is particularly sensitive to the influent chemical oxygen demand-to-nitrogen (COD/N) ratio because heterotrophic denitrifiers require readily biodegradable carbon as an electron donor. When wastewater is carbon-limited, an insufficient COD/N ratio can constrain denitrification and lead to inconsistent total-nitrogen removal, even when suitable anoxic conditions are present. Consequently, effective total-nitrogen removal requires an appropriate spatial or temporal combination of aerobic and anoxic conditions, along with sufficient biodegradable carbon. VSSF systems can favour nitrification due to improved oxygen transfer, whereas HSSF stages can provide more reducing conditions suitable for denitrification. Hybridization, therefore, offers a

means of combining complementary treatment conditions rather than relying on a single redox environment (Vymazal, 2010; Langergraber, Dotro, Nivala, Rizzo, & Stein, 2020).

Phosphorus Removal

Phosphorus is removed through sedimentation, adsorption, precipitation, plant uptake, and microbial processes (Shukla, Gupta, Singh, & Mishra, 2021). Unlike nitrogen, phosphorus does not normally have a permanent gaseous removal pathway within the wetland. Long-term phosphorus performance therefore depends strongly on substrate properties, reactive-surface availability, influent loading, and operational management. Although sorption-site saturation can reduce removal capacity over time, well-designed tertiary systems may maintain relatively stable phosphorus removal through appropriate media selection, hydraulic control, substrate replacement, and/or recovery strategies. Accordingly, substrate saturation should be treated as a manageable long-term risk rather than an inevitable loss of treatment performance.

Long-term Hydraulic Reliability

Clogging Mechanisms

Clogging is a major long-term constraint in subsurface-flow CWs. Recent synthesis identifies interacting physical, biological, and chemical mechanisms, including particulate accumulation, microbial biomass, extracellular polymeric substances, and mineral precipitation (Zhang, Geng, Li, Dzakupasu, & Wang, 2026). As pore spaces become occupied, porosity and hydraulic conductivity decline. Severe deterioration may produce ponding, short-circuiting, reduced effective treatment volume, and, ultimately, hydraulic failure.

Clogging should not, however, be equated automatically with total treatment failure. Hydraulic deterioration can be spatially concentrated, especially near inlet regions, while downstream portions retain treatment capacity (Hdidou, et al., 2022). The more realistic engineering objective is therefore to control and manage clogging through pretreatment, appropriate loading, accessible inlet zones, modular construction, and hydraulic monitoring rather than assuming that clogging can be eliminated.

Pretreatment, Service Life, and CAPEX-to-OPEX Shift

Screening, sedimentation, and other pretreatment processes reduce the solids burden entering the wetland. Although pretreatment increases initial cost and footprint, it may extend the wetland's service life and reduce rehabilitation frequency. The correct economic comparison is therefore between life-cycle alternatives rather than between initial construction costs alone (López-Serrano, Lakho, Hulle, & Batlles-de-laFuente, 2023).

Because clogging is often spatially concentrated near the inlet zones of subsurface-flow systems (Hdidou, et al., 2022), downstream zones frequently retain substantial treatment capacity. Managing this progression rather than assuming indefinite passive performance is a key sustainability requirement. Implementing robust pretreatment processes

represents a deliberate trade-off: it increases the initial land footprint and capital cost but can significantly extend the operational lifetime of the primary wetland bed. Although this CAPEX-to-OPEX shift is an important economic consideration, its favourable assessment should not be attributed to operating-cost savings alone. Life-cycle economic analyses also derive substantial benefits from monetising environmental externalities, with one study estimating a difference in environmental cleaning costs of approximately €1.98 million between a vertical-flow constructed wetland and a conventional alternative (López-Serrano, Lakho, Hulle, & Batlles-de la Fuente, 2023). Clarifying how overall economic benefit depends on these monetised externalities provides a more comprehensive sustainability assessment than focusing on the CAPEX-to-OPEX shift alone. The upfront investment in pretreatment may therefore reduce the present value of maintenance and replacement costs by delaying the disruptive and expensive excavation, cleaning, or total replacement of clogged filter media, while its broader economic favourability depends on the selected valuation framework and assumptions regarding environmental benefits.

Land Requirement and Energy Demand

Land is a defining constraint of passive CWs. A simplified relationship between area, flow, and hydraulic loading rate is:

$$A = Q / \text{HLR} \quad (\text{Equation 3}) \quad (\text{Anigrou, Bahlami, \& Khelifi, 2022})$$

Where A is the wetland area, Q is the wastewater flow, and HLR is the hydraulic loading rate. Lower loading generally requires a larger area for a given flow rate, although the actual design must also satisfy pollutant loading and treatment constraints.

Recent full-scale evidence illustrates the configuration trade-off. In the 2026 global review, aerated and vertical-flow systems had the highest reported hydraulic loading rates and the lowest specific surface area requirements among the major configurations, while horizontal subsurface-flow systems were the most prevalent (Silva, et al., 2026). These observations support the general principle that intensification can reduce land requirements, but they do not establish that intensification is universally more sustainable.

Passive systems generally exchange relatively low external energy demand for larger land requirements. Intensified systems can reduce land demand through vertical flow, recirculation, or aeration, but may introduce additional electricity consumption, equipment, and maintenance (Brunhoferová, Venditti, Hansen, & Gallagher, 2024). The preferred configuration, therefore, depends on the dominant site constraint: land scarcity may justify intensification, whereas unreliable electricity and abundant land may favour passive treatment.

Greenhouse Gas Emissions

Emission Fluxes and Environmental Drivers

These are literature ranges, not universal emission factors, and should not be used as design constants. Earlier work and subsequent reviews show that wastewater composition, redox conditions, temperature, vegetation, carbon availability, and configuration influence

greenhouse gas generation (Fuchs, Mihelcic, & Gierke, 2011; Hu, et al., 2023; Zhang, Pan, Xu, Du, & Guo, 2025). Influent chemistry—particularly the COD/N ratio, with approximately three identified as an optimal threshold—and geographic location may also regulate GHG emissions (Wu, et al., 2025). Including these factors strengthens the interpretation of emission heterogeneity. Accordingly, climate performance should be evaluated through a system boundary that includes construction, operation, and direct emissions, rather than electricity consumption alone.

$$GHG_{total} = GHG_{construction} + GHG_{operation} + GHG_{direct} - GHG_{avoided} \quad (\text{Equation 4})$$

Operationalizing Lifecycle Climate Impact Calculation

For comparative life-cycle evaluations, explicitly define and justify the assessment period based on the expected service life of the constructed wetland, maintenance requirements, and component-replacement assumptions. Present-value calculations should similarly use a locally appropriate discount rate based on the relevant national or infrastructure-appraisal framework (Otani, Sado, Konno, Tsuchiya, & Maki, 2013). Sensitivity analysis should use alternative project horizons and discount-rate assumptions to assess the robustness of comparative economic conclusions.

Materials and Life-cycle Environmental Performance

The environmental footprint of CWs begins before wastewater enters the system. Construction may require gravel, sand, concrete, liners, pipes, pumps, vegetation, and excavation. Life-cycle assessment is therefore necessary to capture upstream material production, transport, construction, operation, maintenance, and end-of-life effects.

However, a comprehensive LCA should also establish a complete mass balance for carbon, nitrogen, and phosphorus across the air, water, and soil compartments. This balance should quantify inputs, transformations, storage, emissions, and outputs, including carbon dioxide, methane, and nitrous oxide emissions; nitrogen removal, volatilisation, and gaseous losses; and phosphorus retention, accumulation, and potential recovery. Without such accounting, assessments may overlook important environmental hotspots and may incorrectly treat pollutant retention within substrates or biomass as permanent removal or genuine resource recovery. Integrating these mass balances into the proposed framework would therefore help distinguish short-term pollutant sequestration from effective treatment and support a less reductive evaluation of CW sustainability.

More contemporary evidence is provided by a recent systematic review (Millaret, Olsen, Quer, & Nainggolan, 2026), which concluded that CW life-cycle assessments generally report lower environmental impacts than conventional solutions while emphasizing the importance of construction materials, energy use, aeration, full life-cycle costing, broader treatment of social benefits, and clearly defined methodological boundaries. The review, which reviewed 101 peer-reviewed environmental and/or economic studies, also found substantial heterogeneity in functional units, system boundaries, cost accounting, and uncertainty analysis.

Substrate selection is consequently both a treatment and sustainability decision. Locally available or recycled materials may reduce transport and production burdens, but their hydraulic stability, potential for contaminant release, and long-term performance must be demonstrated before adoption.

Economic Sustainability

The economic attractiveness of CWs depends on land cost, excavation, substrate, pretreatment, pumping, aeration, maintenance, and rehabilitation. Life-cycle cost is more informative than initial capital cost:

$$LCC = CAPEX + PV(OPEX) + PV(Maintenance) + PV(Replacement) \text{ (Equation 5)}$$

Published economic studies are difficult to compare because they use different price years, discount rates, system boundaries, project lifetimes, land assumptions, and labour costs. Millaret, Olsen, Quer, & Nainggolan, (2026) identified this methodological heterogeneity as a major limitation of the environmental/economic literature. The life-cycle assessment component should also follow the principles and framework established in ISO 14040 and ISO 14044, while life-cycle costing should transparently report cost categories, assumptions, discounting procedures, and sensitivity analyses alongside the environmental assessment. Consequently, claims such as “constructed wetlands are cheaper than conventional treatment” should be stated conditionally and supported by a clearly defined functional unit and life-cycle boundary, using explicitly justified discount rates, project horizons, and sensitivity analyses.

Resource Recovery and Co-benefits

Potential CW co-benefits include treated-water reuse, biomass production, nutrient retention, habitat creation, landscape enhancement, and local employment. These benefits can improve overall sustainability, but they should not be conflated with pollutant removal. For example, phosphorus retained in wetland biomass is not necessarily recovered as a useful product if the biomass is contaminated or must be disposed of.

Resource recovery should therefore be demonstrated through mass balances, product-quality assessment, and a realistic beneficial-use pathway. Mass balances are essential not only for quantifying recovery efficiency but also for identifying environmental hotspots across air, water, and soil compartments, which assessments of nature-based solutions often represent incompletely. They should account for pollutant inputs, transformations, storage, emissions, and outputs, thereby distinguishing genuine recovery from simple retention or redistribution within the system. This distinction is especially important for wastewater containing heavy metals, pathogens, or persistent organic contaminants.

To prevent conflating simple pollutant retention with genuine resource recovery, CW designs must establish contaminant-safe product pathways backed by rigorous mass balances (Biswal & Balasubramanian, 2022). These mass balances are also essential to the validity of the life-cycle assessment framework proposed above: without balanced flows across the air, water, soil, biomass, and residual-stream compartments, an LCA may

misrepresent pollutant fate, overlook emissions and transfers, and incorrectly classify internal sequestration as treatment or resource recovery. For example, phosphorus and heavy metals accumulated in wetland substrates or plant tissues remain sequestered within the system boundaries; they are not recovered until they are safely extracted, their quality is verified, and a beneficial-use pathway is demonstrated. The primary barrier to establishing such a pathway is contamination by heavy metals, persistent organic pollutants, and active pathogens. If harvested biomass exceeds regulatory safety thresholds, it cannot be land-applied or composted and must instead be routed to hazardous-waste landfills or specialized thermal-destruction facilities (Popoola, Olawale, & Salami, 2023). Therefore, future recovery frameworks should integrate comprehensive mass-balance accounting with LCA and evaluate technical processes, such as controlled thermal conversion (Pandey et al., 2024) or advanced chemical extraction (Wang et al., 2021), to safely separate valuable nutrients from hazardous co-pollutants. This integrated approach would help prevent reductive sustainability narratives that present pollutant retention as genuine recovery without accounting for downstream risks, emissions, and end-of-life burdens.

Integrated Sustainability Assessment

The evidence indicates that CW sustainability is a multidimensional property (Chen, et al., 2024; Attri, Singh, Dhar, & Powar, 2022). Constructed-wetland sustainability can be represented as a multi-criteria function:

$$S = f(P, R, L, E, M, G, C, RR) \quad (\text{Equation 6})$$

where P is treatment performance, R is reliability, L is land requirement, E is energy demand, M is material requirement, G is greenhouse-gas emissions, C is life-cycle cost, and RR is resource recovery.

Because these criteria are expressed in different physical and economic units, they should first be converted to dimensionless normalised scores before aggregation. The overall sustainability score may then be expressed using a weighted additive multi-criteria decision analysis model:

$$S = \sum_{j=1}^n w_j z_j$$

subject to

$$\sum_{j=1}^n w_j = 1, 0 \leq w_j \leq 1$$

where z_j is the normalized score of the sustainability criterion j , and w_j is the corresponding weighting factor reflecting its relative importance under the local decision context.

For benefit criteria, such as treatment performance, reliability, and resource recovery, a higher normalized score represents better sustainability performance. For **burden criteria**, such as land requirement, energy consumption, greenhouse-gas emissions, material demand, and life-cycle cost, reverse the normalization direction so that lower

environmental or economic burdens receive higher sustainability scores. This lets one compare criteria measured in incompatible units, such as hectares, kWh, kg CO₂-eq, and monetary cost, on a common dimensionless scale.

Select criterion weights transparently based on site-specific priorities. For example, land requirement may receive greater weight in densely populated urban areas, whereas energy demand and operational simplicity may receive greater weight in locations with unreliable electricity supply or limited technical capacity. Sensitivity analysis should vary the weighting factors to determine whether the preferred wetland configuration changes substantially under alternative decision priorities.

The resulting sustainability score should therefore be interpreted as a decision-support index rather than an absolute measure of sustainability. Its principal value is to make trade-offs among treatment efficiency, reliability, land, energy, greenhouse-gas emissions, materials, costs and resource recovery explicit rather than allowing one favourable criterion, such as pollutant-removal efficiency, to dominate the assessment.

For a beneficial criterion:

$$z_j = \frac{x_j - x_{j,\min}}{x_{j,\max} - x_{j,\min}}$$

and for a burden criterion:

$$z_j = \frac{x_{j,\max} - x_j}{x_{j,\max} - x_{j,\min}}$$

where x_j is the observed value, while $x_{j,\min}$ and $x_{j,\max}$ represent the minimum and maximum values used for comparison.

No single dimension should serve as a proxy for sustainability (Omran, Al-Saati, Al-Saati, Hashim, & Al-Saati, 2021). The most appropriate configuration is the one that provides acceptable treatment and reliability while meeting the dominant environmental, spatial, energy, and institutional constraints of the site (Chen, et al., 2024).

Table 2: Qualitative Comparison of Constructed Wetland Configurations

Criterion	FWS	HSSF	VSSF	Hybrid	Aerated
Organic/TSS removal (Hdidou, et al., 2022)	Good	Good–high	High	High	Very high
Nitrogen removal	Moderate	Moderate	High nitrification	High	High
Land demand	High	High	Moderate	Moderate	Low–moderate
External energy	Very low	Very low	Low–moderate	Moderate	High
Clogging concern	Moderate	High	Moderate	Moderate	Variable
Operational complexity	Low	Low	Moderate	Moderate–high	High
Remote/low-resource suitability	High	High	High	Moderate	Low

Criterion	FWS	HSSF	VSSF	Hybrid	Aerated
Land-constrained suitability	Low	Low	Moderate	High	High

Source: Authors' qualitative synthesis of the literature cited in Sections 2–8. The classifications are intended for comparative decision support and do not constitute a statistical ranking or pooled meta-analysis.

Discussion

Are Constructed Wetlands Genuinely Sustainable?

Nutrient removal varies with specific biogeochemical conditions and, for phosphorus, with substrate characteristics and loading history. Phosphorus removal depends strongly on substrate characteristics, loading history, and the availability of reactive sorption sites. Because retention capacity may decline as substrates age, assess long-term phosphorus sustainability using longitudinal removal data, phosphorus mass balances, cumulative substrate loading, and evidence of breakthrough (Zhao, et al., 2024). Stable phosphorus performance should therefore be demonstrated empirically rather than inferred from short-term removal efficiency.

Treatment Performance Versus Sustainability

A central finding is that high removal efficiency does not necessarily imply superior sustainability (Brunhoferová, Venditti, Hansen, & Gallagher, 2024). A highly intensified system may achieve stringent nutrient limits with a small footprint but consume more electricity and require more complex maintenance. A passive system may use more land but require little external energy. Sustainability assessments should therefore be supported by comprehensive mass-balance accounting that tracks nutrient flows across water, air, soil, biomass, and residual streams; otherwise, pollutant transformation, redistribution, and associated greenhouse-gas emissions may be overlooked. The preferred option, therefore, depends on local resource constraints and whole-system environmental burdens rather than on a universal technology ranking.

The Land–Energy Trade-off

This trade-off should be quantified explicitly rather than hidden within a single sustainability score. Assessments should integrate site-specific influent characteristics, including COD/N ratio, salinity, nutrient loading, and redox conditions, with geographical variables such as climate, elevation, coastal proximity, land opportunity cost, and receiving-water vulnerability. The potential for an influent COD/N ratio of approximately three and coastal positioning to reduce greenhouse gas emissions is promising (Wu et al., 2025).

The Reliability–Maintenance Trade-off

Hydraulic deterioration and clogging are key determinants of constructed wetlands' long-term reliability. The accumulation of suspended solids, excessive biofilm growth, root

development, and the deposition of organic or mineral particles can progressively reduce pore connectivity, increase hydraulic resistance, alter flow paths, and shorten effective hydraulic retention. These processes may cause surface ponding, preferential flow, reduced contact between wastewater and reactive media, odour, and declining treatment performance. Because clogging develops gradually and may not be evident from effluent concentrations alone, assess it using hydraulic indicators such as water-level profiles, infiltration behaviour, pressure gradients, flow distribution, and changes in hydraulic retention characteristics. Hydraulic monitoring should therefore be linked to predefined inspection, cleaning, and corrective-action procedures rather than treated as a stand-alone measurement activity.

The reliability–maintenance trade-off is therefore not simply a choice between passive and intensified treatment. Passive systems generally reduce energy demand and operational complexity, but they still require appropriate pretreatment, vegetation management, inspection of inlet and outlet structures, removal of accumulated solids, and periodic hydraulic monitoring. More intensive interventions, including mechanical aeration, adjustable flow control, or media replacement, may mitigate specific performance losses but increase energy use, equipment dependence, and maintenance requirements. The appropriate balance depends on wastewater strength, solids loading, land availability, local technical capacity, and the consequences of treatment failure.

Long-term design should consequently treat hydraulic aging as an expected operating condition rather than an exceptional failure. This requires sufficient pretreatment, accessible units for inspection and maintenance, provisions for resting or alternating treatment beds, and a clear schedule for responding to declining hydraulic performance. Report maintenance requirements alongside removal efficiencies so apparent treatment performance is not separated from the labour, downtime, and material inputs needed to sustain it. Multi-year full-scale studies are particularly important because short-term experiments may not capture the gradual development of clogging or the effectiveness of maintenance interventions (Kumwimba, et al., 2023). Reliability should ultimately be evaluated as the capacity to maintain acceptable treatment under realistic hydraulic and operational conditions over the intended service life, rather than as initial removal efficiency alone.

Clogging can create a maintenance–energy trade-off: passive systems may minimize external energy use but require periodic hydraulic monitoring, pretreatment, and maintenance to preserve flow and treatment capacity (Suhaib & Bhunia, 2021). Conversely, measures such as mechanical aeration or more intensive hydraulic management may reduce some performance losses but increase energy demand and operational complexity (Ávila, et al., 2021). Future design should therefore focus on maintainability and controlled hydraulic ageing rather than assuming indefinite passive performance.

The Treatment–GHG Trade-off

Improving oxygen availability can enhance nitrification and, in some systems, overall nitrogen removal. However, shifts in redox conditions can also alter the balance between aerobic and anaerobic pathways, thereby affecting CH_4 and N_2O formation and emission (Wu, et al., 2025). Recent empirical findings further indicate that greenhouse-gas emissions are regulated not only by system configuration but also by influent chemical ratios, such as the COD/N ratio, and by site characteristics, including coastal versus inland location (Wu, et al., 2025). These factors can alter carbon availability, nitrogen-conversion pathways, salinity, hydrological conditions, and the potential for gaseous losses. Consequently, the configuration with the highest removal efficiency is not automatically the configuration with the lowest climate impact.

A multidimensional assessment should therefore integrate treatment performance, greenhouse-gas emissions, energy demand, maintenance requirements, resource use, and risks associated with persistent, mobile, and toxic micropollutants. Established decision-support approaches, including AHP-based sustainability frameworks, show how technical, environmental, economic, and social criteria can be weighted systematically in evaluating constructed wetlands (Masoud, Alfarra, & Sorlini, 2022). The proposed framework extends this approach by explicitly incorporating water-stress conditions, hydraulic ageing, restorative maintenance capacity, greenhouse-gas fluxes, and micropollutant fate. This distinction clarifies its novelty: sustainability is not a direct synonym for removal efficiency, but a context-dependent outcome shaped by trade-offs among treatment effectiveness, resource constraints, long-term reliability, and environmental risk.

Implications for Developing Countries, Sub-Saharan Africa, and Nigeria

CWs can be attractive in developing-country contexts characterized by unreliable electricity supply, limited technical capacity, rapid peri-urbanization, and a need for decentralized treatment (Buhnyuy, William, Bishoge, Maineh, & Théophile, 2025). Their deployment should nevertheless be adapted to local wastewater characteristics, climate, material availability, land economics, and maintenance capacity.

Although the 2026 full-scale review identified substantial geographical gaps, particularly across Sub-Saharan Africa (Silva, et al., 2026), recent empirical evidence indicates that the regional evidence base is emerging rather than entirely absent (Torrens, Ndiaye, Coundoul, & Senghor, 2025). This evidence includes operational data from a full-scale treatment plant in Nigeria reported by Alagbe and Alalade, (2013), as well as recent findings by Traoré et al. (2025) on substrate performance under Sahelian conditions. These studies directly challenge the characterization of the region as lacking empirical data, while also demonstrating that the available evidence remains geographically fragmented and insufficiently standardized. Their inclusion therefore supports a more precise conclusion: the principal gap is not the complete absence of regional data, but the limited availability of comparable, longitudinal, full-scale datasets spanning diverse climatic, infrastructural, and operational contexts.

This under-representation nonetheless highlights the need for more longitudinal and standardized research across diverse climate zones, settlement types, and operating conditions. Such research should document not only pollutant-removal efficiencies but also operational deterioration and failure pathways, including clogging, declining hydraulic conductivity, inadequate solids management, maintenance frequency, and associated downtime.

Positioning Nigeria as a primary case study for Sub-Saharan Africa is well justified, given its diverse tropical and semi-arid climate zones, severe urban–rural sanitation divide (Mobolaji & Akinwumiju, 2025), and capital constraints. However, the available full-scale evidence should not be characterized as absent. Regional evidence includes studies from Senegal by Ndiaye et al. (2024) and Coundoul et al. (2024), along with Nigerian operational-cost data from the full-scale treatment plant at Covenant University reported by Alagbe and Alalade (2013). Recent work by Traore, Ouattara, Zahui, Osei, & Messou (2025) also provides empirical evidence for using locally available West African geomaterials, including shale and laterite, as wetland substrates. These studies provide an important foundation for localized research, while also illustrating that the Nigerian evidence base remains limited in scope, duration, and comparability.

Future research must consequently build on this foundation by developing more comprehensive performance datasets that account for the unique hydro-climatic variability and decentralized sanitation infrastructure prevalent across the Nigerian landscape (Masoud, Alfarra, & Sorlini, 2022). Such work should validate and extend existing findings through multi-year monitoring, systematic assessment of operational and life-cycle costs, and comparative evaluation of locally sourced substrates under diverse Nigerian conditions. High-value research in this context should therefore complement existing full-scale work by extending monitoring over multiple years at installations serving actual communities in rural and peri-urban settlements, as well as academic institutions. This requires consistent reporting of influent and effluent concentrations, flow rates, mass loading, hydraulic loading and retention characteristics, treatment reliability, maintenance requirements, and monitoring duration. It also requires localized assessments of locally sourced or recycled substrates to replace costly imported media, long-term investigations of hydraulic aging and clogging, and direct measurements of methane (CH₄) and nitrous oxide (N₂O) fluxes under tropical and semi-arid conditions. Furthermore, life-cycle costing based on localized Nigerian labour, land, energy, and transport tariffs is essential to provide realistic economic benchmarks for regional planners.

Evidence Gaps and Research Priorities

Long-term full-scale evidence: Short laboratory and pilot studies remain easier to generate than multi-year full-scale datasets (Kumwimba, et al., 2023). Long-term monitoring should become a higher priority.

Standardized performance reporting: Studies should consistently report flow, influent/effluent concentrations, mass loading, hydraulic loading rate, hydraulic retention/residence characteristics, and monitoring duration.

Quantitative clogging assessment: A standardized hydraulic-deterioration framework would improve comparability and help translate clogging mechanisms into maintenance schedules.

Greenhouse gas measurement: CO₂, CH₄, and N₂O measurements require more harmonized sampling, seasonal coverage, and reporting in both areal and treatment-normalized units.

Life-cycle costing: Economic studies should report the year of the price, the discount rate, land assumptions, service life, energy costs, maintenance, and replacement.

Comprehensive Mass Balances

Studies should quantify carbon, nitrogen, and phosphorus flows across air, water, and soil compartments. Accounting for these flows is essential to validate the true environmental impacts of constructed wetlands and avoid omitting pollutant transfers and greenhouse-gas emissions.

Climate and Regional Evidence

Although full-scale evidence from Sub-Saharan Africa remains limited, it is beginning to emerge. A more precise priority is to conduct long-term, multi-year monitoring across diverse tropical, arid, and semi-arid microclimates, including sites in Sub-Saharan Africa.

Climate resilience: Future work should assess performance under flooding, drought, extreme rainfall, temperature change, and shock loading.

Resource recovery: Recovery claims should be supported by contaminant-safe product pathways and mass balances rather than by assumptions about pollutant retention.

Conclusions

Constructed wetlands are technically effective wastewater treatment systems with substantial potential for sustainable, decentralized wastewater management. Their strongest advantages include relatively low external energy requirements, operational simplicity, effective removal of suspended solids and organic matter, and potential ecological and resource-recovery co-benefits.

However, the evidence does not support the unqualified characterization of CWs as inherently sustainable (Chen, et al., 2024). Sustainability depends on configuration, hydraulic loading, wastewater characteristics, climate, land availability, substrate selection, maintenance, and operational lifetime. Although the performance of some treatment parameters may vary with these conditions, nutrient removal should not be characterized as uniformly inconsistent. Phosphorus performance is strongly configuration- and substrate-dependent, and longitudinal monitoring should demonstrate its long-term

stability rather than assuming it from short-term removal efficiency; variability may be more pronounced for other parameters and under less controlled conditions.

The central lesson is that removal efficiency alone is an inadequate proxy for sustainability (Brunhoferová, Venditti, Hansen, & Gallagher, 2024). A sustainable CW must provide adequate treatment and long-term reliability while maintaining acceptable land demand, resource use, greenhouse-gas performance, and life-cycle cost.

Passive systems remain particularly attractive where land is available, and energy is constrained (Brunhoferová, Venditti, Hansen, & Gallagher, 2024). Vertical-flow, hybrid, and aerated systems can improve nutrient removal and land efficiency, but may require additional infrastructure, electricity, and maintenance (Silva, et al., 2026).

Future research should prioritize long-term, full-scale monitoring, standardized hydraulic and treatment reporting, quantitative assessment of clogging, harmonized greenhouse gas measurements, mass-balance accounting for carbon, nitrogen, and phosphorus across air, water, and soil compartments, life-cycle costing, and greater representation of tropical, arid, and developing-country systems. Mass-balance accounting is essential for evaluating sustainability beyond removal efficiency and for ensuring that pollutant transfers and greenhouse gas emissions are not overlooked.

Constructed wetlands should therefore be regarded not as a universally superior replacement for conventional wastewater treatment, but as adaptable treatment platforms whose sustainability must be demonstrated through whole-life, context-specific assessment.

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