SUPPLEMENT

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Nature-based solutions for nutrient removal in tourism wastewater: pilot bio-gardens with red mangrove (*Rhizophora mangle*) and water hyacinth (*Eichhornia crassipes*) at Iberostar Bávaro, Dominican Republic

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ABSTRACT

Introduction: Wastewater from coastal tourism operations often retains residual nitrogen and phosphorus after conventional secondary treatment, contributing to nutrient enrichment in adjacent marine ecosystems. Nature-Based Solutions (NbS) have been proposed as low-cost polishing strategies that integrate ecological processes into wastewater management.

Objective: To evaluate the short-term nutrient attenuation potential of *Rhizophora mangle* and *Eichhornia crassipes* in constructed bio-gardens installed downstream of hotel wastewater treatment systems under operational conditions.

Methods: Four concrete bio-gardens (3.0 × 1.2 × 0.6 m) were installed downstream of an on-site wastewater-treatment facility in the Dominican Republic. Three units were planted (replicated treatments units) and one was left unplanted (control). Phase 1 evaluated *R. mangle* under continuous flow using treated effluent. Phase 2 evaluated *E. crassipes* under similar hydraulic conditions using enriched influent to simulate elevated nutrient loads. Water samples were analyzed for phosphate, total phosphorus, nitrate–nitrogen, and total nitrogen over a 48-hour hydraulic retention period.

Results: During Phase 1, *R. mangle* exhibited limited short-term nutrient attenuation consistent with early-stage system stabilization. In Phase 2, *E. crassipes* demonstrated substantial short-term phosphorus removal and moderate nitrogen attenuation under enriched conditions, whereas the unplanted control showed minimal change.

Conclusions: Plant-based bio-gardens can be physically integrated into hotel wastewater systems and may contribute to nutrient-load reduction when appropriately designed and managed. The contrasting short-term dynamics observed between species highlight functional complementarity under different loading scenarios rather than direct species superiority. These findings support further investigation of NbS as tertiary polishing modules within sustainable tourism infrastructure.

Key words: Nature-based solutions; *Rhizophora mangle*; *Eichhornia crassipes*; nutrient removal; wastewater treatment; tourism; Caribbean.

RESUMEN

Soluciones basadas en la naturaleza para la remoción de nutrientes en aguas residuales turísticas: biojardineras piloto con mangle rojo (*Rhizophora mangle*) y jacinto de agua (*Eichhornia crassipes*) en Iberostar Bávaro, República Dominicana

Introducción: Las aguas residuales provenientes de operaciones turísticas costeras pueden conservar concentraciones residuales de nitrógeno y fósforo después del tratamiento secundario, contribuyendo al enriquecimiento de nutrientes en ecosistemas marinos adyacentes. Las Soluciones Basadas en la Naturaleza (SbN) se han propuesto como estrategias de depuración terciario de bajo costo que integran procesos ecológicos al manejo de aguas residuales.

Objetivo: Evaluar el potencial de atenuación de nutrientes a corto plazo de *Rhizophora mangle* y *Eichhornia crassipes* en biojardineras construidas e integradas a infraestructura hotelera bajo condiciones operativas.

Métodos: Se instalaron cuatro biojardineras de concreto (3.0 × 1.2 × 0.6 m) aguas abajo de una planta de tratamiento en la República Dominicana. Se plantaron tres unidades (unidades de tratamiento replicadas) y una se mantuvo sin vegetación (control). La Fase 1 evaluó *R. mangle* bajo flujo continuo utilizando efluente tratado. La Fase 2 evaluó *E. crassipes* bajo condiciones hidráulicas equivalentes utilizando influente enriquecido para simular cargas elevadas de nutrientes. Se analizaron fosfatos, fósforo total, nitrato–nitrógeno y nitrógeno total durante un período de retención hidráulica de 48 horas.

Resultados: Durante la Fase 1, *R. mangle* mostró una atenuación limitada a corto plazo, consistente con la estabilización temprana del sistema. Bajo condiciones de influente enriquecido en la Fase 2, *E. crassipes* presentó una atenuación sustancial de fósforo a corto plazo y una atenuación moderada de nitrógeno, mientras que el control sin vegetación mostró cambios mínimos.

Conclusiones: Las biojardineras con plantas pueden integrarse físicamente a sistemas hoteleros de aguas residuales y podrían contribuir a la reducción de carga de nutrientes si se diseñan y manejan adecuadamente. Las dinámicas contrastantes observadas a corto plazo entre especies indican complementariedad funcional bajo distintos escenarios de carga, más que superioridad directa entre especies. Estos hallazgos respaldan la investigación adicional de SbN como módulos terciarios de pulimiento dentro de infraestructura turística sostenible.

Palabras clave: Soluciones basadas en la naturaleza; *Rhizophora mangle*; *Eichhornia crassipes*; remoción de nutrientes; tratamiento de aguas residuales; turismo; Caribe.

INTRODUCTION

Coastal tourism infrastructure generates substantial volumes of wastewater, and even after conventional secondary treatment, effluents frequently retain measurable concentrations of nitrogen (N) and phosphorus (P). In tropical coastal destinations, residual nutrient concentrations in treated hotel wastewater may remain within ranges associated with eutrophication risk, particularly where advanced tertiary treatment is absent (Wear & Vega Thurber, 2015). When discharged into coastal environments, sewage derived nutrients can stimulate harmful algal blooms, accelerate eutrophication, and contribute to coral reef degradation by enhancing macroalgal overgrowth and disrupting coral-microbial interactions (Fabricius, 2005; Lapointe & Clark, 1992; Vega Thurber et al., 2014; Wear & Vega Thurber, 2015). In tourism-dependent coastal regions, where coral reefs provide shoreline protection, fisheries productivity, and recreational value, improving effluent quality is therefore both an ecological and socio-economic priority (Ferrario et al., 2014; Moberg & Folke, 1999).

In the Dominican Republic, wastewater discharge in tourism zones is regulated under the national environmental standard NA-AG-001-01 (Ministerio de Medio Ambiente y Recursos Naturales [MIMARENA], 2012), which establishes maximum allowable concentrations for parameters intended to protect coastal and marine ecosystems. For nutrients of high ecological relevance, the standard includes reference limits for total nitrogen and total phosphorus, underscoring the need for polishing strategies that reduce nutrient loads prior to discharge or reuse. This is particularly relevant in karstic coastal settings characterized by high subsurface permeability, where nutrient transport through groundwater pathways can strengthen land–sea connectivity and increase exposure of adjacent marine ecosystems to nutrient enrichment.

Nature-Based Solutions (NbS) provide an opportunity to incorporate ecological processes directly into wastewater management systems. Constructed wetlands and other plant-based filtration systems have been widely explored as tertiary polishing technologies capable of reducing nutrient concentrations while maintaining relatively low operational costs and energy demands. These systems rely on a combination of ecological processes, including plant uptake, microbial transformation, and sediment adsorption, to remove nutrients from wastewater streams (Kadlec & Wallace, 2009; Mitsch & Gosselink, 2015). In recent years, NbS have gained increasing attention as scalable strategies to improve wastewater management in coastal regions where conventional treatment infrastructure may be insufficient to mitigate nutrient discharge. Beyond improving water quality, these systems may also enhance on-site biodiversity, create habitat complexity, and align operational practices with sustainability frameworks increasingly adopted by the tourism sector (Cohen-Shacham et al., 2016). When integrated as polishing steps downstream of conventional treatment facilities, NbS can therefore complement existing infrastructure and contribute to regulatory compliance in coastal environments.

Two species with demonstrated potential for plant-based nutrient removal are the red mangrove (*Rhizophora mangle*) and the water hyacinth (*Eichhornia crassipes*). *R. mangle* is a keystone coastal species capable of retaining sediments and transforming nutrients through root-associated microbial processes and sediment–plant interactions that support long-term biogeochemical cycling (Alongi, 2014; Kristensen et al., 2017). However, in several jurisdictions, including Mexico, mangrove handling or planting is legally restricted under national conservation laws (Secretaria de Medio Ambiente y Recursos Naturales, 2003), which may limit its direct implementation in engineered systems.

In contrast, *E. crassipes*, a freshwater floating macrophyte widely used in phytoremediation systems, exhibits rapid biomass production and high nutrient uptake capacity. Removal efficiencies exceeding 70–90 % have been reported under controlled experimental conditions (Rezania et al., 2016; Valipour et al., 2015). Nevertheless, its application requires strict containment, periodic biomass harvesting, and responsible governance, given its well-documented invasive potential, making controlled operational contexts essential for safe deployment.

Within the Wave of Change Innovation Hub, Iberostar Group implemented a pilot NbS system at its Bávaro complex (Dominican Republic) to evaluate the short-term nutrient attenuation performance of constructed biogardens integrated into operational hotel wastewater infrastructure. The units were installed immediately downstream of an on-site wastewater-treatment facility to assess their capacity to attenuate nitrogen and phosphorus under continuous-flow conditions. Phase 1 evaluated *R. mangle* under treated effluent conditions, representing an early-stage mangrove-based filtration module. Phase 2 evaluated *E. crassipes* under comparable hydraulic configurations, using influent enrichment to simulate elevated nutrient loads representative of effluents lacking tertiary polishing.

Given these design characteristics, this study presents an exploratory pilot-scale evaluation of the nutrient-removal efficiency of both species under real hotel operational conditions. Rather than aiming to establish strict confirmatory inter-species comparisons, the objective is to assess short-term functional performance and practical feasibility. By integrating ecological filtration into hotel infrastructure, this approach contributes evidence on scalable NbS strategies capable of reducing nutrient discharge and mitigating downstream impacts on sensitive coastal ecosystems, including coral reefs.

MATERIALS AND METHODS

Study site: This pilot study was conducted at the Iberostar Bávaro complex on the eastern coast of the Dominican Republic (18°42’ N, 68°26’ W). The resort is a high-occupancy Caribbean tourism operation with continuous wastewater treatment and four on-site wastewater treatment plants providing secondary treatment prior to discharge. A pilot Nature-Based Solution (NbS) system was installed immediately downstream of one treatment facility to evaluate a tertiary polishing strategy suitable for hotel infrastructure in a karstic coastal setting where high subsurface permeability may facilitate land–sea connectivity via groundwater pathways.

Bio-garden construction and configuration: Four reinforced-concrete bio-gardens were constructed, each measuring 3.0 m (length) × 1.2 m (width) × 0.6 m (height) (Fig. 1). Each unit contained two substrate layers: (i) a 30-cm bottom layer of coarse gravel to facilitate drainage and hydraulic conductivity, and (ii) a 20-cm upper layer of fine gravel to provide root support and promote nutrient adsorption. A continuous-flow distribution system delivered influent evenly to all units under constant pressure. Hydraulic retention time (HRT) was maintained at 48 h. The experimental configuration comprised three planted bio-gardens representing treatment units (n = 3) and one unplanted unit used as a control (n = 1). The three planted units were established under the same physical configuration, substrate composition, plant density, and hydraulic conditions within each phase, and therefore functioned as replicates of a single treatment rather than as different treatments. All units were hydraulically independent and operated as tertiary polishing modules downstream of conventional treatment.

Experimental design and phases: The system was operated sequentially in two phases under identical physical configuration and hydraulic settings. Each phase included three replicated planted units and one control. Because influent nutrient concentrations differed between phases, between-phase comparisons were framed as exploratory assessments of short-term performance under distinct nutrient-loading scenarios rather than confirmatory tests of interspecific equivalence.

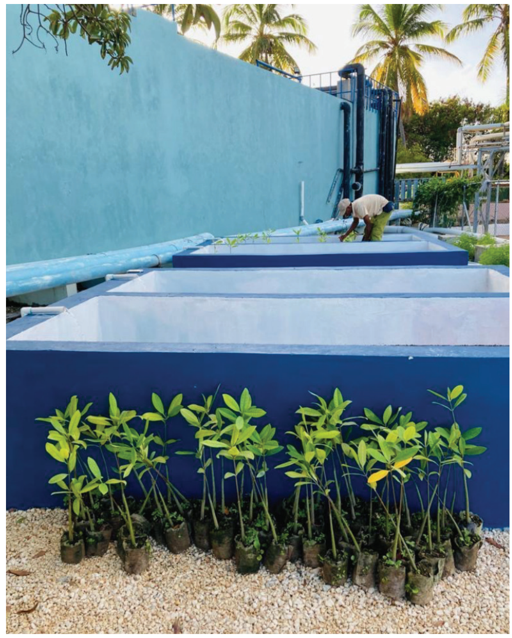

Fig. 1. Pilot bio-gardens constructed downstream of the wastewater-treatment facility at Iberostar Bávaro (Dominican Republic), immediately after construction and prior to planting.

Phase 1: *Rhizophora mangle*: Each treatment unit was planted with 30 juvenile *R. mangle* propagules (50–60 cm tall) obtained from a certified nursery in accordance with national environmental regulations. A two-week stabilization period preceded sampling to allow acclimation to the substrate and salinity conditions. Treated effluent from the wastewater treatment plant was then continuously circulated through the bio-gardens at an HRT of 48 h. Sampling points were established at the inlet (C_in) and outlet (C_out) of each unit. Phase 1 represents an early operational stage;

therefore, results reflect short-term performance rather than mature system capacity.

Phase 2: *Eichhornia crassipes*: After Phase 1, *R. mangle* propagules were removed, and treatment units were replanted with *E. crassipes* (30 individual plants per treatment unit), maintaining the same hydraulic configuration and HRT (48 h). To simulate elevated nutrient loads relevant to tertiary polishing scenarios, influent water was enriched upstream of the experimental units using fertilizers commonly used in golf-course management within tourism complexes: 600 g of monoammonium phosphate (MAP) and 40 g of calcium nitrate dissolved into the influent tank. The enriched solution was homogenized prior to distribution to ensure consistent influent conditions across treatments and controls. The intent of the enrichment was to evaluate the bio-garden's response to elevated loads, not to establish direct equivalence with Phase 1 influent concentrations.

Sampling and water quality analysis: Sampling was conducted at 0, 24, and 48 h during each phase under continuous-flow conditions. Influent and effluent samples were collected from each treatment unit and the control. Nutrient parameters analyzed were phosphate (PO_4^{3-}), total phosphorus (P^-), nitrate–nitrogen (NO_3^-–N), and total nitrogen (N^-). Physicochemical variables (pH, temperature, salinity, dissolved oxygen) were monitored in situ to document environmental stability during sampling. These variables were not experimentally controlled, as the objective of the study was to evaluate system performance under real operational conditions of hotel wastewater treatment. Consequently, temperature, salinity, and other environmental parameters reflected the natural characteristics of the treated effluent during the experimental period. Laboratory analyses were performed by an accredited laboratory (GSALab) using Standard Methods (American Public Health Association, 2017).

Data processing and statistics: Mean concentrations (mg L^{-1}) and standard errors (± SE) were calculated for treatments (n = 3). Removal efficiency was calculated as:

$$\text{Removal (\%)} = 100 \times ((C\_in - C\_out) / C\_in)$$

where C_in and C_out represent the inlet and outlet concentrations, respectively.

Statistical analyses focused primarily on treatment effects within each phase (planted units vs. control) and on nutrient-specific removal patterns. Normality was evaluated using Shapiro–Wilk tests, and homogeneity of variances was evaluated using Levene's tests. Within each phase, treatment units were compared descriptively with the unplanted control, and variability among planted units was evaluated using a one-way ANOVA with Tukey's HSD post hoc test when applicable; otherwise, Kruskal–Wallis tests were used. Between-phase comparisons were treated as secondary exploratory analyses, using independent-samples t-tests or Mann–Whitney U tests when assumptions were not met, and were interpreted cautiously due to differences in influent concentrations. Differences in removal among nutrient types within species were assessed using repeated-measures ANOVA with Greenhouse–Geisser corrections when appropriate, or Friedman tests for non-parametric data. Statistical significance was set at $p < 0.05$. Analyses were conducted in IBM SPSS Statistics 29.0 and cross-validated in R version 4.3.3. (R Core Team, 2024).

RESULTS

Nutrient attenuation by *Rhizophora mangle* (Phase 1): Over the 48-h hydraulic retention period, nutrient concentrations in *R. mangle*-planted bio-gardens showed limited net change relative to influent values. Mean inlet and outlet concentrations and calculated removal efficiencies are summarized in Table 1 (treatments; n = 3). Phosphate (PO_4^{3-}) changed from 9.30 ± 0.28 mg L^{-1} to 9.60 ± 0.11 mg L^{-1}, while total phosphorus (P^-) varied from 3.04 ± 0.09 mg L^{-1} to 3.13 ± 0.04 mg L^{-1}. Nitrate–nitrogen (NO_3^-–N) changed from

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Table 1
Mean nutrient concentration and removal efficiency after 48 h during Phase 1 (*Rhizophora mangle*). Values are presented as mean ± SE (n = 3).

Parameter	Initial concentration (mg L^{-1})	Final concentration (mg L^{-1})	Removal (%)
Phosphate (PO_4^{3-})	9.30 ± 0.28	9.60 ± 0.11	−3.40 ± 4.24
Total phosphorus (P^-)	3.04 ± 0.09	3.13 ± 0.04	−3.37 ± 4.21
Nitrate-nitrogen (NO_3^-–N)	7.33 ± 1.67	7.05 ± 1.25	−3.20 ± 25.16
Total nitrogen (N^-)	8.55 ± 0.03	8.43 ± 0.23	1.32 ± 3.05

7.33 ± 1.67 mg L^{-1} to 7.05 ± 1.25 mg L^{-1}, and total nitrogen (N^-) from 8.55 ± 0.03 mg L^{-1} to 8.43 ± 0.23 mg L^{-1}.

Calculated removal efficiencies after 48 h were low and variable across replicates, with small positive or negative values (Table 1). These patterns are consistent with early-stage performance of mangrove-based filtration modules, in which measurable nutrient attenuation may require longer stabilization periods as rhizosphere development and sediment–microbe interactions mature. Temperature and pH remained stable during monitoring, indicating that short-term variability in nutrient concentrations was not associated with physicochemical instability. Fig. 2 presents mean removal efficiencies (± SE) after 48 hours of continuous flow.

Nutrient attenuation by *Eichhornia crassipes* (Phase 2): Under enriched influent conditions, bio-gardens planted with *E. crassipes* exhibited marked short-term reductions in phosphorus concentrations and moderate reductions in nitrogen variables over the 48-h monitoring window. Mean phosphate (PO_4^{3-}) concentrations decreased from 310.33 ± 99.62 mg L^{-1} to 93.86 ± 6.98 mg L^{-1}, and total phosphorus (P^-) declined from 96.83 ± 34.39 mg L^{-1} to 30.58 ± 2.19 mg L^{-1}. Nitrate–nitrogen (NO_3^-–N) decreased from 15.80 ± 0.52 mg L^{-1} to 12.47 ± 2.16 mg L^{-1}, and total nitrogen (N^-) from 219.67 ± 4.48 mg L^{-1} to 165.92 ± 26.01 mg L^{-1}.

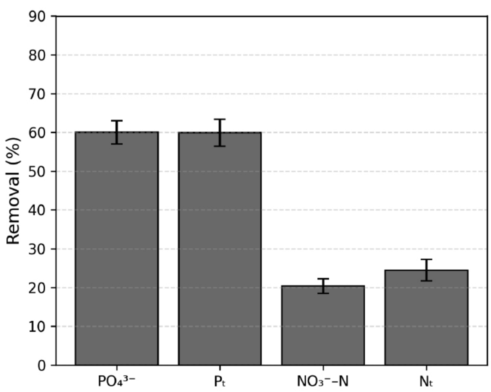

Fig. 2. Nutrient removal by *Rhizophora mangle* in pilot bio-gardens during Phase 1. Bars represent mean ± SE after 48 h of continuous flow.

Removal efficiencies after 48 h averaged 65.12 ± 7.32% for phosphate and 61.39 ± 10.39% for total phosphorus, whereas nitrogen removal was lower and more variable (Table 2).

The unplanted control exhibited minimal attenuation over the same period, indicating that nutrient reduction patterns in planted units were primarily associated with biological uptake and plant-mediated processes rather than passive hydraulic effects. Fig. 3 illustrates mean removal efficiencies (± SE) after 48 hours.

Exploratory comparison between phases: Both species were evaluated under identical physical and hydraulic configurations; however, because Phase 2 used enriched influent, between-phase contrasts are presented as exploratory comparisons of short-term dynamics under distinct nutrient-loading scenarios rather than confirmatory tests of inter-species equivalence. Within the 48-h window, *E. crassipes* showed higher short-term phosphorus attenuation under elevated nutrient availability, whereas *R. mangle* exhibited minimal

Table 2
Mean nutrient concentrations and removal efficiency after 48 h during Phase 2 (*Eichhornia crassipes*). Values are mean ± SE (n = 3).

Parameter	Initial concentration (mg L^{-1})	Final concentration (mg L^{-1})	Removal (%)
Phosphate (PO_4^{3-})	310.33 ± 99.62	93.86 ± 6.98	65.12 ± 7.32
Total phosphorus (P^-)	96.83 ± 34.39	30.58 ± 2.19	61.39 ± 10.39
Nitrate–nitrogen (NO_3^-–N)	15.80 ± 0.52	12.47 ± 2.16	20.08 ± 16.47
Total nitrogen (N^-)	219.67 ± 4.48	165.92 ± 26.01	24.05 ± 13.13

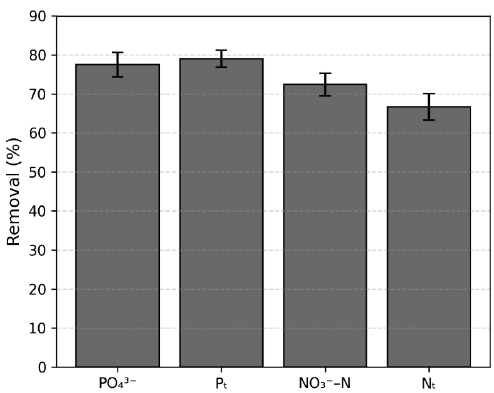

Fig. 3. Nutrient removal by *Eichhornia crassipes* in pilot bio-gardens during Phase 2. Bars represent mean ± SE after 48 h.

net change during an early stabilization stage. These differences reflect contrasting functional dynamics and system maturity and should not be interpreted as definitive evidence of "species superiority" across operational contexts. Fig. 4 presents the exploratory comparison of removal efficiencies (mean ± SE) between phases.

DISCUSSION

Overview and interpretation framework: This study provides an exploratory evaluation of plant-based bio-gardens integrated into hotel wastewater infrastructure under operational conditions in a Caribbean tourism context. The

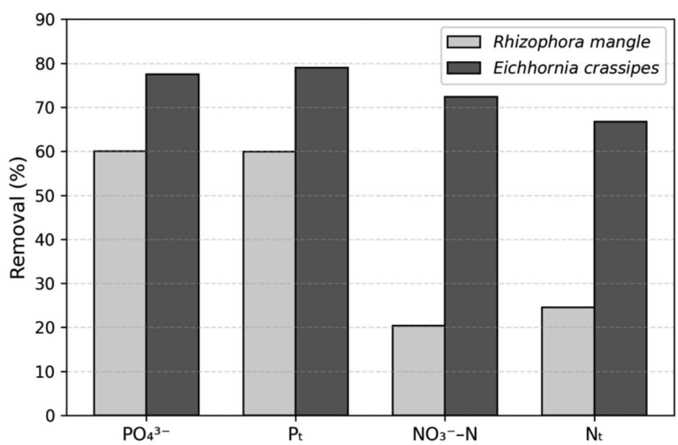

Fig. 4. Exploratory comparison of mean removal efficiencies (± SE) between Phase 1 (*R. mangle*) and Phase 2 (*E. crassipes*) after 48 h.

experimental design intentionally maintained identical physical and hydraulic configurations across phases; however, influent nutrient concentrations differed due to enrichment in Phase 2. Accordingly, between-phase contrasts are interpreted as functional comparisons under distinct loading scenarios rather than confirmatory evidence of inter-species equivalence.

Plant-based wastewater treatment systems, including constructed wetlands and bio-garden configurations, have been widely implemented across a variety of climatic and socio-ecological contexts, ranging from rural sanitation and decentralized wastewater treatment to urban stormwater management and tourism infrastructure. Lessons from these systems consistently highlight the importance of hydraulic retention time, plant biomass development, and microbial community establishment in determining nutrient removal performance (Kadlec & Wallace, 2009; Mitsch & Gosselink, 2015). When appropriately designed and managed, these ecological filtration approaches can complement conventional treatment systems while providing additional ecosystem services, including habitat creation, landscape integration, and improved water quality in downstream environments. In rapidly developing coastal tourism regions, where wastewater infrastructure expansion often lags behind tourism growth, such approaches may be practical strategies for reducing land-based nutrient pollution that affects sensitive marine ecosystems, such as coral reefs.

Rhizophora mangle: early operational stage: In Phase 1, *R. mangle* bio-gardens exhibited limited short-term nutrient attenuation over 48 h. Mangrove-based treatment systems typically rely on sediment retention and rhizosphere-mediated microbial pathways, which can require longer periods to develop and stabilize before yielding measurable treatment efficiency (Alongi, 2014; Kadlec & Wallace, 2009; Kristensen et al., 2017). The short monitoring window and early operational status of the planted units likely constrained detection of consistent net nutrient removal. These findings should therefore be interpreted as representative of early system establishment rather than maximum performance.

Consequently, the limited nutrient attenuation observed during Phase 1 should not be interpreted as evidence of low treatment potential in Rhizophora mangle, but rather as a reflection of the system's early operational stage. Mangrove-based filtration systems depend on the progressive development of root structures, sediment accumulation, and associated microbial communities that drive nutrient transformation processes. As these ecological interactions mature, treatment performance may increase substantially. Longer operational periods are therefore required to properly evaluate the full nutrient removal capacity of mangrove-based bio-garden systems.

The use of *R. mangle* in bio-garden configurations is supported by its ecological role as a foundation species in tropical coastal ecosystems, where its complex root structures enhance sediment trapping, promote microbial activity, and facilitate long-term nutrient retention within mangrove sediments. However, successful implementation of mangrove-based treatment systems requires appropriate technical and ecological conditions, including sufficient hydraulic retention time, stable substrate development, adequate plant density, and long-term system maintenance. Under these conditions, mangrove filtration modules could represent a viable nature-based approach to complement conventional wastewater treatment infrastructure in coastal tourism settings while contributing to nutrient attenuation and improved water quality in downstream ecosystems.

***Eichhornia crassipes*: short-term polishing under elevated load and management constraints:** Under enriched influent conditions in Phase 2, *E. crassipes* showed substantial short-term phosphorus attenuation and moderate nitrogen attenuation. This pattern aligns with reports of rapid nutrient uptake by floating macrophytes, supported by high root surface area and fast biomass turnover (Rezania et al., 2016; Valipour et al., 2015).

Nevertheless, short-term efficiency does not by itself demonstrate long-term stability. Sustained performance requires active operational management, including periodic biomass harvesting, prevention of hydraulic short-circuiting, and monitoring to avoid nutrient saturation or re-release.

Because *E. crassipes* is widely recognized as an invasive species in many regions, responsible application in engineered treatment systems requires explicit governance measures, including strict containment, biosecurity protocols, and documented procedures for biomass handling and disposal. These considerations should be incorporated into feasibility assessments when evaluating NbS implementation in coastal tourism infrastructure. Similar management requirements have been documented in phytoremediation and constructed wetland systems employing floating macrophytes (Rezania et al., 2016).

Where ecological risk or regulatory constraints limit the use of *E. crassipes*, alternative macrophyte species may provide comparable nutrient uptake functions while presenting lower environmental risk. Species such as *Pistia stratiotes*, *Typha* spp., or other emergent wetland plants have been explored in engineered wetland systems for nutrient removal under comparable operational conditions (Kadlec & Wallace, 2009; Rezania et al., 2016). Selection of appropriate plant assemblages should therefore consider both treatment efficiency and ecological risk in the context of local environmental regulations and management capacity.

Regulatory relevance and potential ecosystem implications: Wastewater discharge in Dominican tourism zones is regulated under NA-AG-001-01, which establishes reference limits for effluent quality, including total nitrogen and total phosphorus, to reduce nutrient inputs to coastal ecosystems. While this pilot was not designed as a regulatory compliance trial, the results illustrate how NbS modules may contribute as tertiary polishing steps, capable of reducing residual nutrient concentrations prior to discharge or reuse, particularly in coastal environments where conventional secondary treatment may not fully remove dissolved nutrients.

Such additional attenuation may be particularly relevant in karstic coastal settings, where subsurface permeability can facilitate land–sea transport pathways and increase the exposure of adjacent marine ecosystems to nutrient enrichment. Coral reefs are highly sensitive to chronic nutrient inputs, which can promote macroalgal proliferation, disrupt coral-microbial interactions, and ultimately compromise reef resilience (Fabricius, 2005; Lapointe & Clark, 1992; Vega Thurber et al., 2014). In this context, integrating NbS polishing modules within wastewater treatment infrastructure may represent a complementary strategy to reduce nutrient loads reaching coastal environments and mitigate downstream ecological impacts.

Future work should quantify nutrient mass balances and evaluate how observed reductions translate into load decreases at discharge points and potential downstream exposure.

Limitations and next steps: The main limitations are the short temporal scale (48 h), the early stabilization stage in *R. mangle*, and differences in influent concentrations between phases. These constraints justify a conservative interpretation of statistical comparisons and support framing conclusions around feasibility and functional complementarity rather than definitive ranking of species. Multi-season monitoring, biomass management trials (especially for *E. crassipes*), nutrient mass-balance approaches, and cost–benefit analyses are recommended to guide scaling across tourism destinations.

This pilot study provides an exploratory assessment of constructed bio-gardens integrated into hotel wastewater infrastructure in a Caribbean tourism setting. Over a 48-h hydraulic retention period, *Rhizophora mangle* showed limited net nutrient attenuation consistent with early system establishment, while *Eichhornia crassipes* exhibited substantial short-term phosphorus attenuation and moderate nitrogen attenuation under enriched influent conditions. Because influent nutrient concentrations differed between phases, these outcomes are best interpreted as evidence of functional complementarity under different loading contexts rather than as confirmatory evidence of inter-species superiority.

Overall, the study demonstrates the operational feasibility of installing modular NbS polishing units downstream of conventional treatment using locally available materials. For future implementation, *E. crassipes*-based modules require explicit containment, biosecurity, and biomass management protocols to mitigate invasive risk, while *R. mangle* modules likely require longer stabilization periods to express their treatment potential. Multi-season monitoring, nutrient mass-balance quantification, and operational cost–benefit evaluation are recommended prior to broader replication across Caribbean and Latin American tourism destinations.

Ethical statement: The authors declare that they all agree with this publication and made significant contributions; that there is no conflict of interest of any kind; and that we followed all pertinent ethical and legal procedures and requirements. All financial sources are fully and clearly stated in the acknowledgments section. A signed document has been filed in the journal archives.

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