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Evaluating the Potential of Mangrove Phytoremediation for Mitigating Coastal Water Eutrophication in Macao SAR: A Field and Mesocosm Study

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Abstract: Eutrophication due to anthropogenic nutrient inputs is a serious issue in many coastal and marine environments. Mangrove plants form unique intertidal forests at the edge of the land and sea, forming multifunctional ecosystems that provide an array of services, such as the phytoremediation of pollutants. The purpose of this study was to evaluate the levels of nutrients (PO_4^{3-}, NO_2^-, NO_3^-, NH_4^+) in the coastal waters around Macao SAR, in areas with and without mangroves, in order to assess their phytoremediation potential. The work was reinforced through a mesocosm experiment with various treatments with and without mangroves. The results of the field investigations indicated a high degree of eutrophication in the coastal waters of Macao, with average values of 0.30 mg/L, 0.09 mg/L, 23.8 mg/L, and 0.36 mg/L of phosphate, nitrite, nitrate, and ammonium, respectively. There were no apparent significant differences in the levels of nutrients in areas with and without mangroves, which was most likely caused by the conditions during sampling as well as the density of the mangrove forest. The mesocosm experiments, however, revealed a clearer effect of the presence of mangroves (and sediments) in the degradation of nutrients. Therefore, it is highly recommended to plant more mangroves to help mitigate coastal water eutrophication in the area as a phytoremediation approach.

Keywords: nature-based solution; nitrogen; phosphorus; phytoremediation; water management

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1. Introduction

Eutrophication is a leading cause of the impairment of many coastal estuarine and marine ecosystems worldwide due to anthropogenic nutrient inputs. Although it may occur naturally, human activities have accelerated the rate and extent of this phenomenon through both non-point loadings of limiting nutrients, (e.g., phosphorus and nitrogen) and point-source discharges into aquatic ecosystems (i.e., cultural eutrophication) [1,2]. Thus, anthropogenic water pollution associated with high concentrations of nitrogen and phosphorus plays an important role in the eutrophication of inland and coastal water bodies, resulting in long-term ecosystem disruption [3]. Changes in the aquatic ecosystem due to eutrophication include the occurrence of dead zones (hypoxic or anoxic), more frequent harmful algal blooms, habitat and species loss, and water quality decline [1]. An example of this is the Pearl River Delta (PRD), which is one of the most developed areas in China with high industrialization and urbanization, with many large cities clustered there (e.g., Shenzhen, Guangzhou, Zhuhai, Hong Kong, and Macao). The water quality deterioration has been associated with sewage and industrial wastewater discharges, increased agriculture and the use of fertilizers, and marine fish farming. Eutrophication is one of the most serious environmental problems in this area due to the high loading of anthropogenic nutrients coming from the mentioned activities [4,5]. In the case of dissolved inorganic nitrogen (DIN), the main form in most sea areas was NO_3–N, but that near Shenzhen Bay was NH_3–N. The DIN originates mainly from the runoff of four river channels and from land pollutants near Shenzhen Bay. A reduction tendency can be found from north to south, being in general over 0.30 mg/L in the Pearl River estuary and over 0.50 mg/L in most areas. Concerning phosphate, the main contributions have been determined to be land-based sources from the area near Shenzhen Bay or along the estuary, but also outside the estuary, being brought by coast currents and flood tide currents. The phosphate concentration is influenced by the tide period, being about 0.015 mg/L in most sea areas, although it exceeded 0.030 mg/L in the area near Shenzhen Bay [5]. The sensitivity of the coastal ecosystems to anthropogenic nutrient enrichment may thus vary according to the specificity of each ecosystem, including, for example, the dilution potential of nutrient inputs [1]. As part of the PRD, Macao's coastal waters are affected by upstream water sources in addition to the leakage and disposal of land reclamation and construction [6]. Macao has the highest population density per square kilometer [7], being a representative land reclamation territory in China. Thus, due to urbanization, worsening water quality and ecological degradation, including of mangrove forest ecosystems, have been observed [6]. This statement is also supported by the eutrophication index, which indicates a significant increasing trend in the past 10 years [8]. Concerning mangroves, persistent eutrophication may cause adverse effects, although they have the potential to assimilate nutrients and may be considered nutrient sinks [9]. They thus have a huge demand for nutrients to support metabolism, growth, and primary productivity [10,11]. Mangroves grow at the edge of the land and sea, forming intertidal forests, and have developed morphological and physiological adaptations to extreme conditions, delivering a wide range of ecosystem services supporting local and regional coastal communities [10,12,13]. They are of great ecological value, being among the world's most productive ecosystems, protecting and stabilizing coastlines, yielding commercial forest products, supporting coastal fisheries, and also contributing to the global carbon cycle [10]. There is an increase in mangrove valuation studies and also financial incentives to support the restoration and conservation of these ecosystems. However, there is still a loss of mangroves that is attributed primarily to human activity, particularly through degradation and deforestation, reclaimed lands for human settlements, and land conversion for agriculture and aquaculture [14]. There is also a lack of awareness concerning the value of mangrove ecosystem conservation and the benefits they provide to humans, which aggravates mangrove loss [15,16]. Nevertheless, the impact of human activity has decreased since 2000 [14].

Mangroves have been considered for phytoremediation purposes due to their associated sediments, which house a variety of bacteria and fungi that assist in the cycling of nutrients and the immobilization and stabilization of several types of contaminants, minimizing and preventing their spread [10,11]. Furthermore, due to their large biomass, they can accumulate high amounts of contaminants while also reaching deep sources of contamination due to their extensive root system. The phytoremediation of inorganic and organic compounds, using mangroves, can be achieved mainly through phytoextraction, phytostabilization, phytostimulation or rhizofiltration, and phytodegradation [11]. Using mangroves as a phytoremediation tool can be considered a phytotechnology to support the phytomanagement of extensive areas. The concept of phytomanagement is usually based on the interactions among plants, microorganisms, and soil amendments with the intent to minimize environmental risks while maximizing economic and ecological revenues, i.e., generating both valuable biomass and ecosystem services [17].

The aim of this study was to investigate the role of mangroves to support mitigation strategies, based on their phytoremediation ability, for coastal water eutrophication. To address this, the study (i) assessed the nutrient content and other water quality parameters in various coastal sites around Macao with and without mangroves, (ii) assessed the potential phytoremediation ability of mangroves for nutrient pollution reduction through a mesocosm experiment, and (iii) provided suggestions for mangrove management and protection strategies in Macao. This study is the first to combine field and mesocosm investigations to evaluate the potential of mangroves for the phytoremediation of nutrients in a coastal urban environment. Our findings provide valuable insights into the ability of mangroves (and substrates) to mitigate pollution in this specific context. It also demonstrates the importance of using multiple approaches to fully understand the potential of this phytoremediation strategy.

2. Materials and Methods

2.1. Field Investigations—Study Sites

Three sampling sites (Taipa, Ecozone, and Coloane) with and without mangroves in Macao coastal waters were included in this study (Figure 1). Taipa is situated on the waterfront adjacent to a public recreational area with cycling and walking tracks. It is a mangrove restoration site along a narrow channel, with 6 species (*Avicennia marina*, *Kandelia obovata*, *Aegiceras corticulatum*, *Acanthus ilicifolius*, *Sonneratia apetala*, and *Bruguiera gymnorrhriza*) of mostly young plants sparsely spread along the coastline (Figure 2a). The Ecozone is a protected area managed by the Macao Environmental Protection Bureau (DSPA, https://www.dspa.gov.mo/place3.aspx, accessed on 26 February 2023), with the highest mangroves density and diversity, and the greatest forest cover compared to the 2 other sites (Figure 2b,c). It is located along the same narrow channel and is midway between Taipa and Coloane. Coloane is a site adjacent to a village with restaurants and shops, and a small patch of mangroves (consisting of 3 species only: *K. obovata*, *A. corniculatum*, and *S. apetala*) and reeds (Figure 2c).

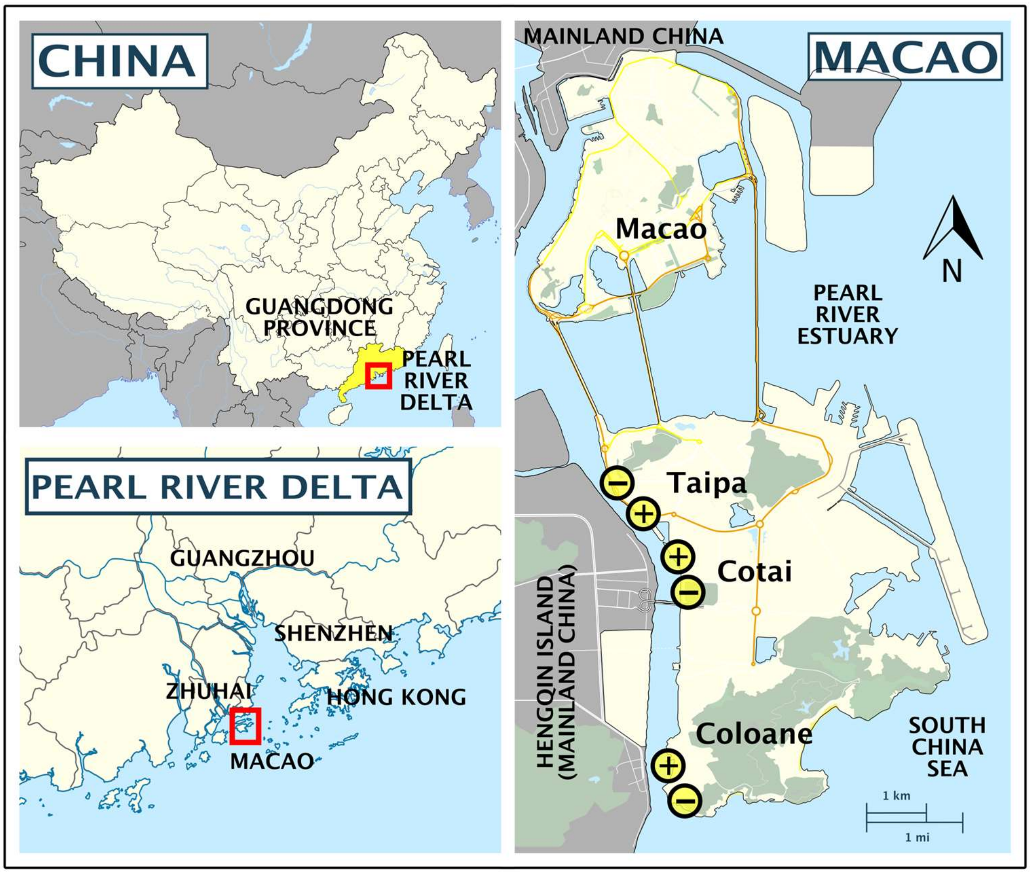

Figure 1. Map of the three sampling sites in reference to the location of Macao: Taipa, Ecozone, and Coloane; (−) without mangroves and (+) with mangroves.

Figure 2. Study sites in Macao: (**a**) Taipa, (**b**) Ecozone, and (**c**) Coloane.

Samples for water characterization were collected monthly during low tide from the three sites (Taipa, Ecozone, and Coloane), from October 2020 to April 2021. At each site, 3 replicate water samples were taken from spots with and without mangroves, equivalent to 6 samples per site. Water was taken using pre-rinsed amber glass bottles from the little ponds within the mudflats. The samples were thermally preserved during transport from the site to the laboratory and then stored in the freezer until further analysis. In every sampling, physicochemical parameters, including temperature, pH, and salinity, were measured using a transportable multi-parameter (YSI Professional Plus, Yellow Springs, OH, USA). Photographs were taken during every sampling to record the condition of mangroves, the surrounding environment, and biodiversity.

2.2. Mesocosm Experiment

To complement the field data, a mesocosm experiment was set up in greenhouse-controlled conditions to compare the water characteristics over time when in contact with mangroves and when in contact with mangroves and sediment. Mangrove seedlings from the same cohort (age) and sediments were collected from the Ecozone for this experiment. The roots of seedlings were flushed with tap water to unload sediment matter before the experiment. Pots made of opaque propylene (19 × 26 × 15 cm) were exposed to three different experimental treatments, with 4 replicates for each (Figure 3). The experimental treatments comprised:

Treatment A: tap water (control—no mangroves) (A1, A2, A3, A4);
Treatment B: tap water + mangroves (B1, B2, B3, B4);
Treatment C: tap water + mangroves + sediment (C1, C2, C3, C4).

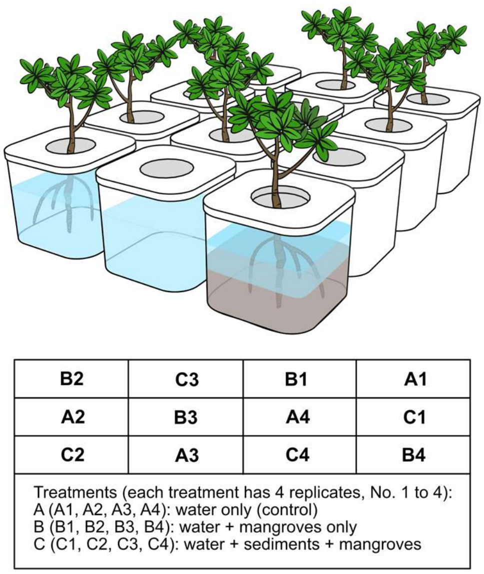

Figure 3. Schematic representation of the mesocosm experiment in greenhouse conditions.

The volume of water in each tank was maintained at 2 L during the experiment. The volume of sediment in each pot of treatment C was 3 L. One seedling per pot was considered (treatment B and C). The polypropylene plastic pots were placed in a clear plastic greenhouse, under a half-day light/half-day dark photoperiod with natural sunlight. The experiment was carried out for 4 days (24~27 March 2021), with the periodicity of water collection for analysis at 0, 24, 48, and 72 h.

2.3. Water Analysis

Water samples from the 3 field sampling sites and from the mesocosm experiment were analyzed concerning the following parameters: total suspended solids (TSS) following APHA [18] standard methodology, ammonium (NH_4^+, mg/L), nitrate (NO_3^-, mg/L), nitrite (NO_2^-, mg/L), and phosphate (PO_4^{3-}, mg/L), following Palintest methodology (YSI 9500 Photometer, Yellow Springs, OH, USA.).

2.4. Data Analysis

Mean and standard deviation values of three replicates for each sample were calculated for both field and mesocosm experiment data. For the field data, 2-way ANOVA ($p \leq 0.05$) was performed to determine any significant differences in the concentrations of each pollutant between the three sites and between the water with and without mangroves. For the mesocosm experiment, a 2-way ANOVA was also performed to determine differences among the 3 treatments (A: water only (control), B: water + mangroves, and C: water + sediments + mangroves), as well as time of exposure. All statistical analyses were performed by SPSS Statistics version 28.

3. Results

3.1. Field Investigations

Table 1 presents the mean and standard deviation of the physicochemical parameters measured across all three sites, with and without mangroves. Temperature and pH measurements were stable and consistent across all sites, regardless of the presence of mangroves. However, salinity exhibited greater variability among the sites, with the most noticeable difference observed in Coloane, where the contrast between the presence and absence of mangroves is more pronounced.

Table 1. Physicochemical parameters measured at each study site (Taipa, Ecozone, and Coloane), with and without mangroves (mean values ± standard deviation).

	Salinity (‰)		**pH**		**Temperature (°C)**	
Sites	**Without Mangroves**	**With Mangroves**	**Without Mangroves**	**With Mangroves**	**Without Mangroves**	**With Mangroves**
Taipa	12.15 ± 5.60	10.56 ± 5.07	7.57 ± 0.28	7.63 ± 0.38	22.34 ± 3.80	22.25 ± 3.68
Ecozone	16.29 ± 5.58	16.36 ± 7.84	7.97 ± 0.38	7.70 ± 0.40	24.66 ± 4.30	24.44 ± 4.02
Coloane	14.37 ± 8.25	6.53 ± 4.68	7.96 ± 0.20	7.65 ± 0.17	24.55 ± 3.81	24.10 ± 3.76

The concentrations of nutrients in the three sampling sites, in areas with and without mangroves, are presented in Figure 4. The results indicate that most parameters do not show significant differences among the three sites (Taipa, Ecozone, and Coloane). Only the means of nitrite and phosphate concentration show significant differences at both sites with and without mangroves (Table 2, $p < 0.05$). Nitrite concentrations are lower in areas with mangroves compared to those without mangroves, and Ecozone (the site with the densest mangrove vegetation) has the lowest values compared to the other two sites (Figure 4).

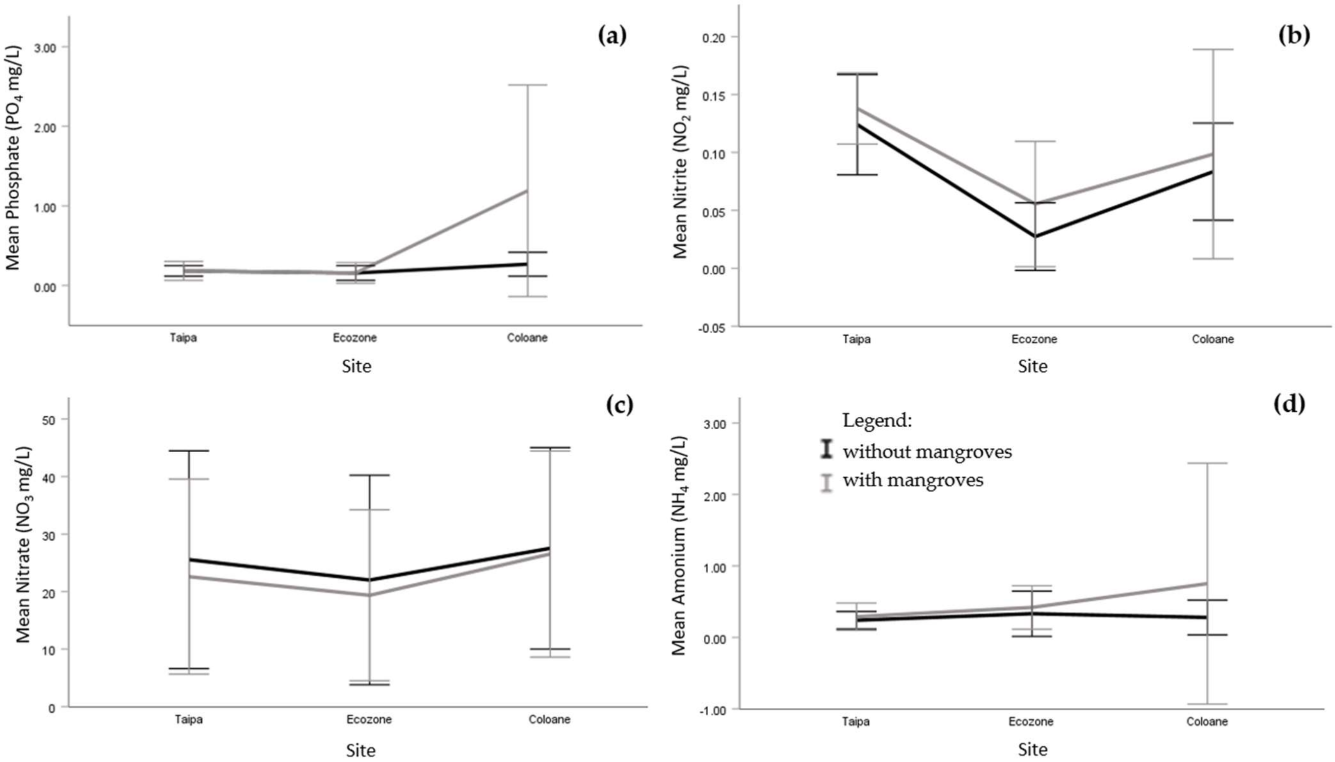

Figure 4. Concentrations of nutrients in the water analyzed at the three sampling sites (Taipa, Ecozone, and Coloane): (**a**) phosphate, (**b**) nitrite, (**c**) nitrate, and (**d**) ammonium.

Table 2. Results of 2-way ANOVA (F-values) comparing nutrients at sites with and without mangroves.

Parameters				
	PO_4^{3-}	**NO_2^-**	**NO_3^-**	**NH_4^+**
Site	17.475 ***	34.279 ***	1.123	1.315
Mangroves	13.138 ***	4.178 *	0.420	2.791
Site × Mangrove	11.886 ***	0.255	0.030	1.136

* $p < 0.05$; *** $p < 0.001$.

3.2. Mesocosm Experiments

Table 3 presents the physicochemical parameters measured across the three treatments throughout the duration of the mesocosm experiment. The values are stable and consistent, except for salinity, with a decrease in levels over time upon exposure to sediments and mangroves.

Table 3. Physicochemical parameters measured in each treatment during the mesocosm experiment (mean values ± standard deviation).

Treatments	**Salinity (‰)**	**pH**	**Temperature (°C)**
A = water only (control)	18.72 ± 0.15	8.08 ± 0.15	26.32 ± 3.10
B = water + mangroves only	18.67 ± 0.18	7.94 ± 0.10	26.22 ± 3.04
C = water + sediments + mangroves	15.38 ± 1.83	7.97 ± 0.26	25.78 ± 2.64

The means of phosphate, nitrite, nitrate, and ammonia among the three treatments (control, mangroves only, mangroves + sediments) are presented in Figure 5a–d. The results of the ANOVA analysis show that all forms of nitrogen significantly changed over time and that there are significant differences between treatments (Table 4). The concentrations of these nutrients decreased over time, except for phosphate. With regards to the effect of treatments, the concentrations remained highest with the water (control) only, followed by those with mangroves. The most significant change was seen in the one with water, mangroves, and sediments (Figure 5).

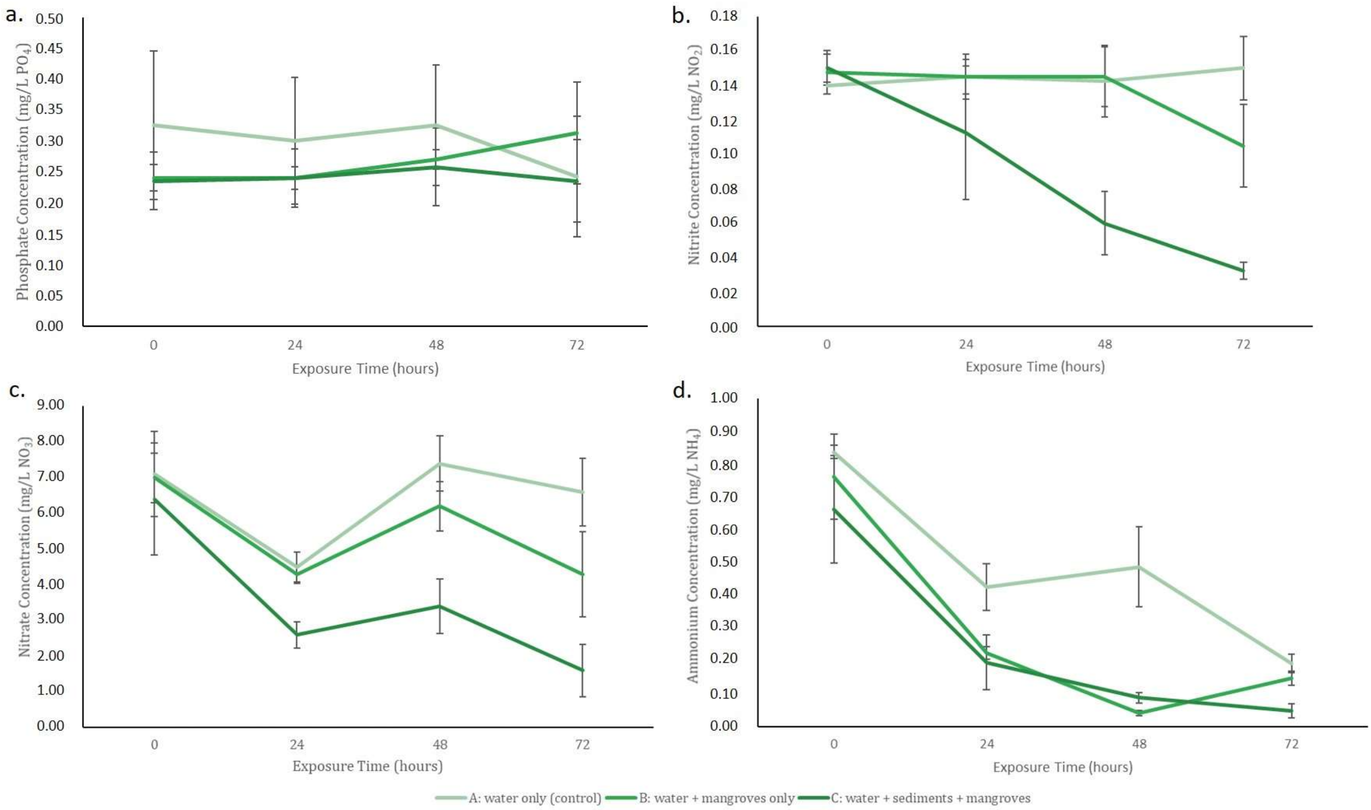

Figure 5. Concentrations of nutrients ((**a**) phosphate; (**b**) nitrite; (**c**) nitrate; (**d**) ammonium) in the water among the 3 treatments (A: water only (control), B: water + mangroves only, C: water + sediments + mangroves) over time.

Table 4. Results of 2-way ANOVA (F values) comparing time of exposure and treatments.

Parameters				
	$\mathbf{PO_4^{3-}}$	$\mathbf{NO_2^-}$	$\mathbf{NO_3^-}$	$\mathbf{NH_4^+}$
Time	0.411	17.370 ***	30.530 ***	155.300 ***
Treatments	2.074	43.305 ***	45.354 ***	41.531 ***
Time × Treatments	0.968	10.708 ***	5.130 ***	5.607 ***

*** $p < 0.001$.

4. Discussion

4.1. Field and Mesocosm Studies

The results of this study show that the concentration of nutrients is high, which indicates eutrophication. The values that were recorded in this study (with average values of 0.30 mg/L, 0.09 mg/L, 23.8 mg/L, and 0.36 mg/L of phosphate, nitrite, nitrate, and ammonium, respectively) are much higher than those of a recent study in Macao by Ivorra et al. [19] (average of 0.14 mg/L dissolved inorganic phosphate (DIP) and 1.58 mg/L DIN), as well other studies in the Pearl River Delta [20]. Excess phosphate in the water is likely due to human activity [21]. In certain parts of Macao, some sewage networks could be damaged, and people resort to surface drainage to dispose of sewage, potentially contributing to nutrient input, including nitrogen and phosphorus, at these sites [8]. The values we observed in our study are considerably higher than the limits set by the Environmental Protection Agency [22]. This indicates a potential threat to the organisms living in Macao's coastal waters, which could be adversely affected by these elevated levels.

The mangrove ecosystem plays a crucial role in nutrient cycling at the land–ocean boundary. However, the intricate nature of nutrient removal in an open system such as the coast is not well understood. Interestingly, at all three sites in the present study, the nitrite concentration in water with mangroves was higher than that without mangroves. During nitrification, nitrite and nitrate are formed, and nitrite oxidizes to nitrate in particular conditions with the presence of bacteria, enzymes, and oxygen [23]. In addition, mangrove soils have an abundance of denitrifying bacteria. Due to the high organic content in the sediment and anaerobic conditions, denitrification rates in mangroves can be substantial. These high rates result in nitrate and nitrite depletion and the production of ammonia, which then forms ammonium, a regular form of nitrogen present in mangrove sediments. The high rates of denitrification indicate that the microbial community in the mangroves draws nitrate from the plants, and therefore, nitrate may not be the main form of N nutrition observed in mangrove trees in the wild [24]. In a study in Daya Bay, China [25], investigating how seawater–groundwater exchange affects nitrogen cycling in a coastal mangrove swamp, the authors found that the tidal creek zone had the highest exchange rates, which facilitated nitrification processes. In contrast, the mangrove zone had the lowest exchange rates, creating an anoxic environment that led to nitrogen loss through anammox and denitrification processes. They estimated that denitrification accounted for 90% of the total nitrogen loss, and anammox accounted for the remaining 10%. Their study highlights the importance of considering the differences in physicochemical characteristics across hydrologic subzones for understanding nutrient cycling processes in coastal mangroves. This is important to consider for further understanding the dynamics of nutrients in Macao's coastal waters. The sites (Taipa, Ecozone, and Coloane) in this study only were evaluated for some general physicochemical parameters (salinity, pH, and temperature) but not specific to hydrologic subzones. Consequently, the removal of nitrite and nitrate by mangroves was not significantly shown in the results of the water analysis from the field sampling.

In a 6-month wastewater treatment study in Hong Kong SAR, China, it was clearly shown that the mangrove microcosm, with intermittent subsurface horizontal flow, was effective in withdrawing nitrogen and phosphorus [26]. The nitrogen and phosphorus removal efficiencies of planted mangroves for municipal wastewater (after primary sedimentation) treatment were in the range of 70~97%. The mangrove plants K. candel treated primary settled municipal wastewater under two hydraulic retention times (5 and 10 days) in PVC tanks and without regular tidal cycles. The present case study, however, was carried out in natural and open coastal water sites with regular tidal cycles. There was no evidence showing that the coastal water source was directly from municipal wastewater, and the purification ability of mangroves was not clearly shown. Considering the open sources of the water samples, the natural tide cycle, and the continuous nutrient absorption by mangroves, the analysis of the concentration and composition of pollutants is complex. The concentration of phosphate in water with mangroves at the Coloane site was the highest among the three sampling sites. Excess phosphate in water mainly came from human activities, including partially treated and untreated sewage, industrial discharge, runoff from agricultural sites, and over-fertilization [22]. Among the three sampling sites, the Coloane site is located near a village, nearest to a human habitat and economic activities. Restaurants and coffee shops are located on the coast. Coloane village is an old community, so part of the sewage network may be in poor condition or damaged. Leakage of untreated sewage may be the reason that the phosphate concentration in water with mangroves at the Coloane site was higher than the other two sampling sites. On the other hand, the Taipa and Ecozone sites are located in coastal waters far away from dining venues and domestic sewage discharges, so the phosphate concentrations of these two sites were lower.

The field sampling reflects the actual environment of Macao, so it is likely that the increase in nutrients outweighs the nutrient absorption capacity of the mangroves. Furthermore, considering the small amount or low density of mangroves at the three sampling sites, it is possible that the quantity of nutrients or pollutants is much greater than the corresponding size of the coastal mangroves present in the area. There are several local anthropogenic factors at the sampling sites. The Coloane sampling site is close to a sightseeing area of Coloane village, with dense living and frequent business activities. In Macao, there are reports of wastewater and pollutant leakage directly into the coastal water due to the old or imperfect sewage system in the north area of the Macao Peninsula and the interior harbor. It is likely that a similar situation occurred in Coloane's coastal waters. In Taipa, the mangroves grow along the coastline as a restoration site. When the waves wash the coastal mangroves, the water near and far away from the mangroves mixes well since the plants are mostly small and the density is not high. Furthermore, the channel/waterway connecting the Taipa, Ecozone, and Coloane sites (Figure 6) is always very busy, with regular transit of boats or ships. These boats or ships displace water, producing small waves along the very narrow channel, which could affect the circulation and confluence of the water near and far from the mangroves. Thus, there are several anthropic factors in the environment that interfere with the results of the water sampling in this experiment.

Figure 6. The narrow channel where the sites are located showing ferry passing which creates regular displacement and mixing of water.

In the mesocosm experiment, we investigated the impact of time of exposure on the concentrations of ammonium, nitrate, nitrite, and phosphate. The results indicate that the time of exposure had a significant effect on the concentrations of all nutrients, except for phosphate. Treatments with mangroves showed lower nutrient concentrations over time, but this effect was even more pronounced when mangroves and sediments were combined together. This suggests that the presence of mangroves and sediments can lead to nutrient uptake or utilization. The growth rate of mangroves is known to be related to the silt plus clay content and the interstitial nutrient concentration of the sediments [27]. Mangroves that suffer from an imbalance of sediment supply are likely to lose their efficiency in cleaning water [28]. Therefore, it is important for mangroves to tap their roots into stable sediments in order to maintain their growth and water-cleaning efficiency. The concentration of nutrients in the water decreased over time in the present study, which lasted for 72 h. A similar study conducted in Hong Kong SAR [25] showed that a longer hydraulic retention time (HRT) of 10 days led to higher pollutant removal efficiency than a shorter HRT of 5 days. This suggests that longer treatment times for mangroves can result in a higher percentage of pollutant removal. In Guangzhou City, China, a study using aquatic plants such as Ipomoea aquatica and Salvinia natans demonstrated high efficiency in removing nitrogen and phosphate, respectively, from slightly and highly polluted wastewater [29]. The study also highlighted the importance of using a combination of various aquatic plants to effectively treat high concentrations of pollutants. This emphasizes the need for plant diversity in phytoremediation efforts rather than relying solely on a single species. For the mangroves in Macao, it is also important to take this into consideration since there is a tendency to plant similar species in restoration projects.

4.2. Mangrove Management and Protection Strategies in Macao

The findings of this study suggest that mangroves possess a certain degree of phytoremediation potential for nutrient pollution. The mesocosm experiment demonstrates that the presence of mangroves positively affects phytoremediation. However, the field results indicate that the density of mangroves correlates with their efficacy in remediation. Thus, it is crucial to increase the planting of mangroves to enhance their capacity to remove nutrient pollution along the coast of Macao.

The local authorities have taken proactive measures by implementing restoration works along the Taipa coast and designating the Ecozone as a protected area. Additionally, they have collaborated with academic institutions and other community members to organize regular mangrove planting activities (e.g., https://www.usj.edu.mo/en/news/mangrove-planting-activity/; accessed on 15 February 2023). These efforts have proven successful in managing and maintaining mangrove populations in Macao and should be sustained to ensure their continued benefits in nutrient pollution remediation as well as enhance the various ecosystem services that mangroves provide.

Environmental education and community engagement are crucial components for promoting the conservation and protection of mangroves. Recent research conducted in the city has demonstrated the effectiveness of environmental education activities in raising awareness and promoting conservation efforts for mangrove ecosystems [30]. The study reported consistently positive evaluations of mangrove-related environmental education programs, including exhibitions and field trips to coastal sites where mangroves grow. These findings suggest that such activities should be continued and further developed. In addition to environmental education, community engagement activities are also essential for promoting the value of mangroves. By involving local communities in the conservation efforts and highlighting the benefits of mangroves, community engagement initiatives can encourage sustainable practices that will help protect these important ecosystems. Effective community engagement activities may include awareness-raising campaigns, participatory decision-making processes, and collaboration with local stakeholders such as local businesses and tourism sectors. Such efforts are already being implemented by academic institutions and should also continue (e.g., https://ise.usj.edu.mo/research/projects/nature-based-solutions-for-a-cleaner-and-safer-macao/; accessed on 15 February 2023).

Overall, the integration of environmental education and community engagement activities is key to promoting the conservation and protection of mangroves. Through continued efforts in these areas, it is possible to ensure the long-term sustainability of these vital ecosystems and the benefits they provide, such as the phytoremediation of coastal water pollution.

5. Conclusions

In conclusion, this study highlights the high concentration of nutrients in the coastal waters of Macao, which suggests eutrophication. Although mangroves did not show significant removal of nutrients in the field investigation, the mesocosm study demonstrated the phytoremediation capability of mangroves and emphasized the importance of sediment and retention time in the process of water purification. The study suggests expanding the mangrove forests in Macao as a practical solution for managing coastal water pollution. A comprehensive strategy including mangrove restoration, community engagement, and environmental education is recommended for sustainable coastal ecosystem management in Macao.

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