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The Impact of Anthropogenic Pollution on Tidal Water Quality in Mangrove Wetlands

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Abstract: Mangrove wetlands are vulnerable coastal ecosystems that provide critical habitats for aquatic life. Tai O is a popular tourist village on Lantau Island, Hong Kong, which is surrounded by mangrove wetlands with rich biodiversity; and this village is also famous for its traditional stilt houses. However, the untreated municipal sewage from some stilt houses is directly discharged into nearby tidal channels, potentially threatening health of the adjacent mangrove wetlands. In order to evaluate the anthropogenic impact on these wetlands and identify the potential sources of their pollution, this study aimed to evaluate spatial (at the sampling points) and temporal (during weekdays and weekends) differences in the quality of their tidal water, and examine relationships between the water quality and the density of the stilt houses. The results indicated that the water quality was worse during weekends. The ammonia concentrations in most samples exceeded the limits of the Hong Kong Water Quality Objectives, China's Sea Water Quality Standards, and even the U.S. EPA criterion for fish reproduction. This high ammonia input could potentially adversely affect the mangrove ecosystem, underscoring the need for further comprehensive studies. Moreover, some of the weekend water samples had lower dissolved oxygen levels and were polluted by phosphate. Our Principal Component Analysis revealed that water quality was correlated with stilt house density, suggesting that anthropogenic inputs of untreated sewage was the major source of pollution. These findings highlight that nutrients released from human activities, particularly ammonia and phosphate, must be controlled for a better protection of mangrove wetland ecosystems.

Keywords: ammonia; phosphate; mangrove wetlands; municipal sewage and treatment; water quality; human impact

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1. Introduction

Mangrove wetlands are biodiversity hotspots that support both terrestrial and aquatic animals [1], especially as important habitats for migratory birds, and support fisheries in coastal water [2]. Mangrove wetlands also provide other ecological services such as carbon sequestration and climate regulation, coastal protection, water purification, and nutrient cycling [3]. However, mangrove wetlands are particularly vulnerable to excess nutrient inputs [4,5]. Human activities such as tourism, population growth, and urbanization contribute significantly to the accumulation and transformation of pollutants, particularly nutrients in coastal wetland ecosystems [6]. It has been predicted that globally, domestic sewage will contribute more than 17 Tg/year nitrogen and 2 Tg/year phosphorus to surface waters by 2050, despite enhanced nutrient removal via sewage treatment [7]. A previous study also demonstrated that nutrient pollution significantly affects the nitrogen cycling process within mangrove wetlands, particularly the anammox activity, which converts ammonium and nitrite ions into nitrogen gas [4]. The release of untreated sewage into coastal waters can lead to a significant deterioration of water quality, threatening the health of mangrove wetlands and the livelihoods of local communities who depend on fishing and aquaculture.

The evaluation of physiochemical parameters such as water temperature, salinity, total dissolved solids, turbidity, dissolved oxygen, pH, and nutrient levels provides valuable insights into the physical, chemical, and biological characteristics of water, as well as its effects on nearby water resources and human health [8]. For example, pH levels influence not only chemical reactions but also biological processes; any deviation from the optimal pH can harm the survival and reproduction of aquatic species, disrupting the ecological balance [9]. Similarly, elevated nutrient levels, especially of nitrogenous and phosphorus compounds, can lead to eutrophication [8]. Excessive nutrient levels in water can cause ecological disruption such as harmful algal blooms and oxygen depletion [10]. Toxins produced by algal blooms endanger human wellbeing and living organisms [11]. As a result, water quality assessments are required to evaluate the impact of human activities on water quality. This type of monitoring can also aid in the early detection of water pollution, allowing for prompt interventions to avoid irreversible damages to aquatic ecosystems.

Stilt houses, which are residences built on stilts, can be found in numerous countries around the world and are particularly prevalent in coastal communities [12]. Tai O, a traditional fishing and salt-producing village in Hong Kong, is renowned for its traditional stilt houses and scenic views. The fishing and salt production industries of Tai O have decreased in recent decades. Tai O residents normally work in the city and only return during the weekends; their stilt houses are therefore relatively empty during the weekdays. On the other hand, the village has coastal wetland rich resources with a complex network of tidal creeks and more than 20 hectares of mangrove wetlands, providing diversified habitats for a variety of terrestrial, aquatic, and avian species [13]. The village is attractive to both foreign and local tourists, and has been subjected to tourism development planning by the Hong Kong government [14]. It has been estimated that about six million tourists visit Tai O every year [15], and over-crowding due to the influx of tourists has been reported [16]. Tai O is often more crowded at the weekend, with more residents and visitors staying in the stilt houses during weekends than weekdays.

Among the stilt house communities over the world, as in the Tai O village, most of the sewage from stilt houses does not undergo any treatment processes and is directly discharged into nearby waterbodies. Some sewage is collected and treated via septic tanks [17]. In the village of Tai O, stilt houses not only serve as places of residence, but also as workplaces, shops, and restaurants that support local businesses [18]. Some of them are not connected to the centralized sewer connection system; thus, the municipal sewage generated by residents and tourists is directly released into the surrounding water channels without any treatment. Although some stilt houses are equipped with Imhoff tanks that collect and treat sewage before it is discharged, the effluent from Imhoff tanks still contains substantial nutrients such as ammonia, phosphate, and enteric bacteria [19]. The major source of pollution in Tai O is the untreated domestic sewage from stilt houses. Other minor water pollution sources include primary effluent from the Tai O sewage treatment works; municipal sewage from nearby restaurants, shops, public toilets, and other upstream settlements and villages; stormwater and agriculture runoffs; and discharges from fishing vessels [20]. The untreated sewage from stilt houses being the most significant pollution source has been overlooked. The present study therefore aims to determine the spatial (across the sampling points) and temporal (between weekday and weekend) variations in the quality of tidal water entering mangrove wetlands in Tai O, as well as to examine the relationship between the water quality and stilt house density in order to evaluate the anthropogenic impacts on and identify the possible sources of Tai O's pollution. To our knowledge, no previous study has been conducted to investigate the water quality of mangrove wetlands in Tai O, particularly considering the impact of tourists and inappropriate sewage treatment. This study also provides scientific information on the impact of anthropogenic pollution from stilt house discharges and tourists on the water quality in coastal regions, as well as the conservation and protection of mangrove wetlands.

2. Materials and Methods

2.1. Study Site

Tai O village is located on the western coast of Lantau Island, Hong Kong, China, adjacent to the South China Sea and at the mouth of a mountain stream that flows into the sea and forms a small estuary (Figure 1). Stilt houses are built along the banks of three major water channels and their density varies across different parts of the village. Most of the untreated sewage from stilt houses is directly discharged into the surrounding waterbodies and subsequently dispersed into mangrove wetlands through tidal activity. To investigate the impact of municipal sewage on coastal water quality and mangrove wetland ecosystems, the number of stilt houses was counted and estimated prior to sampling, and 12 sampling points were selected based on the density of stilt houses there and the nearby water flow. Sampling point P1 (22.253991, 113.862119) was located near the mouth of the water channel, surrounded by concrete houses that are connected to the centralized municipal sewage system. Sampling points P2 (22.254514, 113.863058), P3 (22.255612, 113.863916), and P9 (22.256950, 113.862923) were in areas with a relatively low density of stilt houses and were located along the bank of the main water channel. P4 (22.255940, 113.864956), P5 (22.255806, 113.865108), P6 (22.255354, 113.865932), P10 (22.256999, 113.863225), and P11 (22.257700, 113.862872) were located in the area with the highest density of stilt houses, whose untreated domestic sewage was regularly discharged into a semi-enclosed mangrove wetland with limited tidal flushing, as shown in Figure 1. Among these sampling points, the stilt houses in P10 and P11 had a higher vacancy rate than in the other points, while P4 was located near a sluice gate that controls the influx of tidal water. P12 (22.255853, 113.864851) was also in an area with a high stilt house density, but its sewage was discharged into a tidal channel that is flushed twice a day. Although both P7 (22.253205, 113.869193) and P8 (22.258909, 113.862700) were in areas with no or few buildings nearby, P8 was located in the mouth of a water channel facing the South China Sea, while P7 was at the entrance of the stream close to some concrete houses without public sewer connection. Some stilt and concrete houses in P1, P2, and P3 were connected to a public sewer system, and their sewage was treated through a primary treatment process in the primary sewage treatment works north of Tai O before being discharged [21] (Figure 1).

2.2. Sample Collection and Preparation

Water samples were collected from each sampling point using a 2 L Van Dorn water sampler on a weekday and a weekend in December 2022. At each sampling point, two liters of water were sampled from approximately 50 cm below the water surface, and this was repeated thrice to obtain three independent replicates. For each replicate, 100 mL of homogenized water was extracted and stored in two 50 mL sterile centrifuge tubes for laboratory analysis of its nutrients, and the remaining samples were used for in situ measurements, as described below. The samples for the nutrient analysis were kept in an icebox and transported to the laboratory within 6 h, where they were filtered through a 0.45 µm nylon filter and preserved at −20 °C to prevent degradation, according to standard methods [22].

2.3. In-Situ Water Quality Measurements

The water temperature (Temp), pH, salinity (Sal), dissolved oxygen (DO), total dissolved solids (TDS), and turbidity (Tur) were measured in situ at each of the same sampling points using a Horiba U-50 series multi-parameter water quality checker (U52, Horiba Ltd., Kyoto, Japan) with an automatic calibration function.

2.4. Analysis of Nutrients in the Water Samples

The concentrations of total nitrogen (TN), ammonia (NH_3), nitrate (NO_3-N), nitrite (NO_2-N), total phosphorus (TP), and orthophosphate (PO_4-P) in the water samples were measured using a Lachat Quikchem 8500 Flow Injection Analyzer (FIA, Hach Co. Loveland, CO, USA), following the manufacturer's instructions. Total organic carbon (TOC) was measured with a TOC Analyzer TOC-L CSN (Shimadzu Corp., Kyoto, Japan). To ensure measurement accuracy and precision, duplicate sample spikes, measurements of blank samples (deionized water), and calibration checks were performed for each batch of samples. For each parameter, the sample spike recovery was between 80 and 120%.

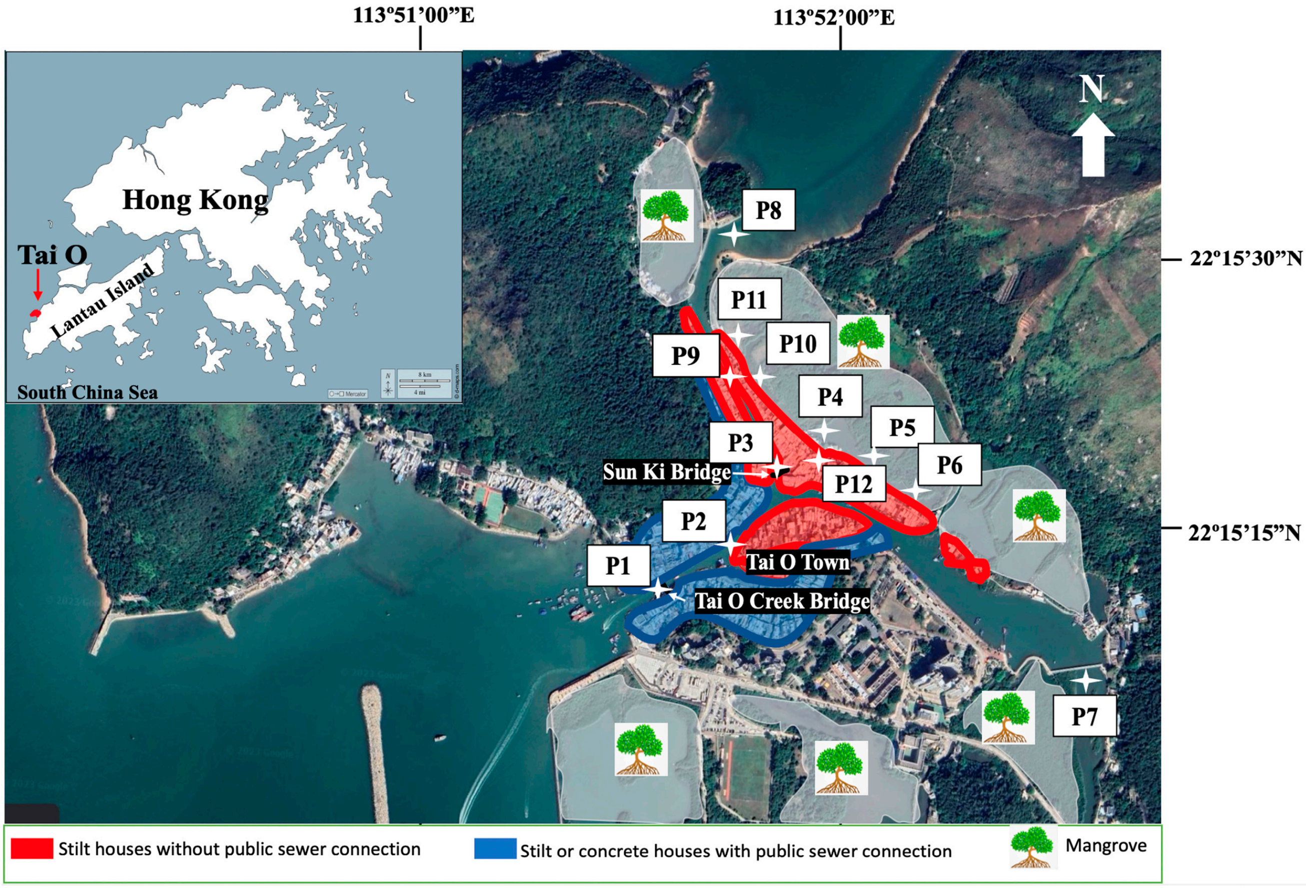

Figure 1. Map showing the location of Tai O and the different sampling points. P1-12 with star symbols indicate the sampling locations.

2.5. Statistical Analyses

The physicochemical parameters of the water samples were measured and these results were presented as the mean and standard deviation (SD) values of three independent replicates at each sampling point and time. A parametric two-way ANOVA was used to assess differences in each of the measured physiochemical parameters across the sampling points and between weekdays and weekends. If a significant interaction was found between the sampling points and times, a one-way ANOVA was performed to determine the difference among the sampling points in each sampling time, and a *t*-test was employed to test the difference between two sampling times. If a significant difference was found in the ANOVA results, a Tukey post hoc test was carried out to find out exactly where the difference lies. All data fulfilled the assumptions of parametric tests; no data transformation was needed. The statistical software used for these analyses was IBM SPSS Statistics (Version 27). To explore the relationship between the water quality and the density of the surrounding stilt houses, a multivariate statistical method, namely a Principal Component Analysis (PCA), was employed. All data were transformed using their Z-score to ensure they exhibited a normal distribution. The PCA was conducted using PAST software (Version 4) to identify the underlying patterns in the dataset and to identify the complex relationships between the measured multi-parameters, which can provide insight into the underlying factors that contributed to the water quality and source of pollution.

3. Results and Discussions

3.1. Variations in the Physical Parameters of Tai O's Tidal Waters during a Weekday and Weekend

The *t*-test results showed that the average Temp, DO, and pH values in the samples measured during the weekend (Temp: 17.56 ± 0.74 °C; DO: 5.54 ± 1.17 mg L^{-1}; pH: 7.66 ± 0.31) were significantly lower than those measured during the weekday (Temp: 22.10 ± 0.59 °C; DO: 5.71 ± 0.75 mg L^{-1}; pH: 7.82 ± 0.20) (Figure 2 and Table 1). In contrast, no significant differences in the average Sal, TDS, and Tur values were observed between the two sampling times. According to Hong Kong Observatory's records, the air temperature was 19 °C during the studied weekend and 22 °C during the studied weekday. The difference in water temperature between the two sampling times was most likely due to a change in the air temperature. Although the average DO concentration in water samples collected on the weekday and the weekend met the Hong Kong Water Quality Objectives (>4 mg L^{-1}), the average DO concentration in the samples fell within the requirements of Category II (relatively clean water) of China's Sea Water Quality Standards (GB 3097-1997) [23], which requires DO concentrations around 5 mg L^{-1}. However, several water samples, particularly those collected during the weekend, fell into Category III (slightly polluted), with DO concentrations around 4 mg L^{-1} (P2: 4.70 mg L^{-1}; P3: 4.47 mg L^{-1}; P10: 4.40 mg L^{-1}; and P12: 4.36 mg L^{-1}). These results show that the concentration of DO was the only physical parameter that declined during the weekend, which needs more attention. DO in water is required for aquatic animals to breathe, and a low DO concentration in water is an indicator of water pollution [24]. Negative effects on marine larvae start be observed if the DO concentration falls below 4 mg L^{-1} [25]. One of the major causes of low DO concentrations in water is the excessive growth of algae due to high-nutrient concentrations in the water, particularly nitrogen and phosphorus, as algal death stimulates bacterial activity, leading to a depleted DO content [26].

Table 1. Water quality comparison between the two sampling times (during the weekday and the weekend) using a student's *t*-test. Bold font indicates statistical significance at the *p*-value < 0.05 level.

	Groups	Mean	SD	*p*-Value	WQO	CSWQS (Class 1)	CSWQS (Class 2)	CSWQS (Class 3)	CSWQS (Class 4)
Temp °C	before	22.10	0.59	**<0.001**	-				
	after	17.56	0.74						
Sal (ppt)	before	28.30	1.59	0.263	-				
	after	28.62	0.66						
DO (mg L^{-1})	before	5.71	0.75	**<0.01**	>4	6	5	4	3
	after	5.54	1.17						
TDS (g L^{-1})	before	26.84	1.32	0.127	-	≤10		≤100	≤150
	after	27.21	0.56						
Tur (NTU)	before	17.42	27.99	0.959	-				
	after	17.14	17.02						
pH	before	7.82	0.20	**0.015**	6.5–8.5	7.8–8.5		6.8–8.8	
	after	7.66	0.31						
TN (mg L^{-1})	before	0.25	0.08	**0.013**	-				
	after	0.33	0.18						
NH4-N (mg L^{-1})	before	0.07	0.03	0.076	0.021	0.020			
	after	0.08	0.05						
NO3-N (mg L^{-1})	before	0.06	0.02	**0.027**	-				
	after	0.07	0.02						
NO2-N (mg L^{-1})	before	0.019	0.006	**<0.001**	-				
	after	0.024	0.004						
TIN (mg L^{-1})	before	0.15	0.04	**0.02**	0.30	0.20	0.30	0.40	0.50
	after	0.17	0.05						
TP (mg L^{-1})	before	0.02	0.02	0.087	-				
	after	0.03	0.03						
PO4-P (mg L^{-1})	before	0.008	0.006	**<0.01**	-	0.015	0.030		0.045
	after	0.014	0.010						
TOC (gm L^{-1})	before	17.88	7.75	0.334	-				
	after	19.29	4.03						

WQO: Hong Kong Water Quality Objective; CSWQS: Chinese Sea Water Quality Standard.

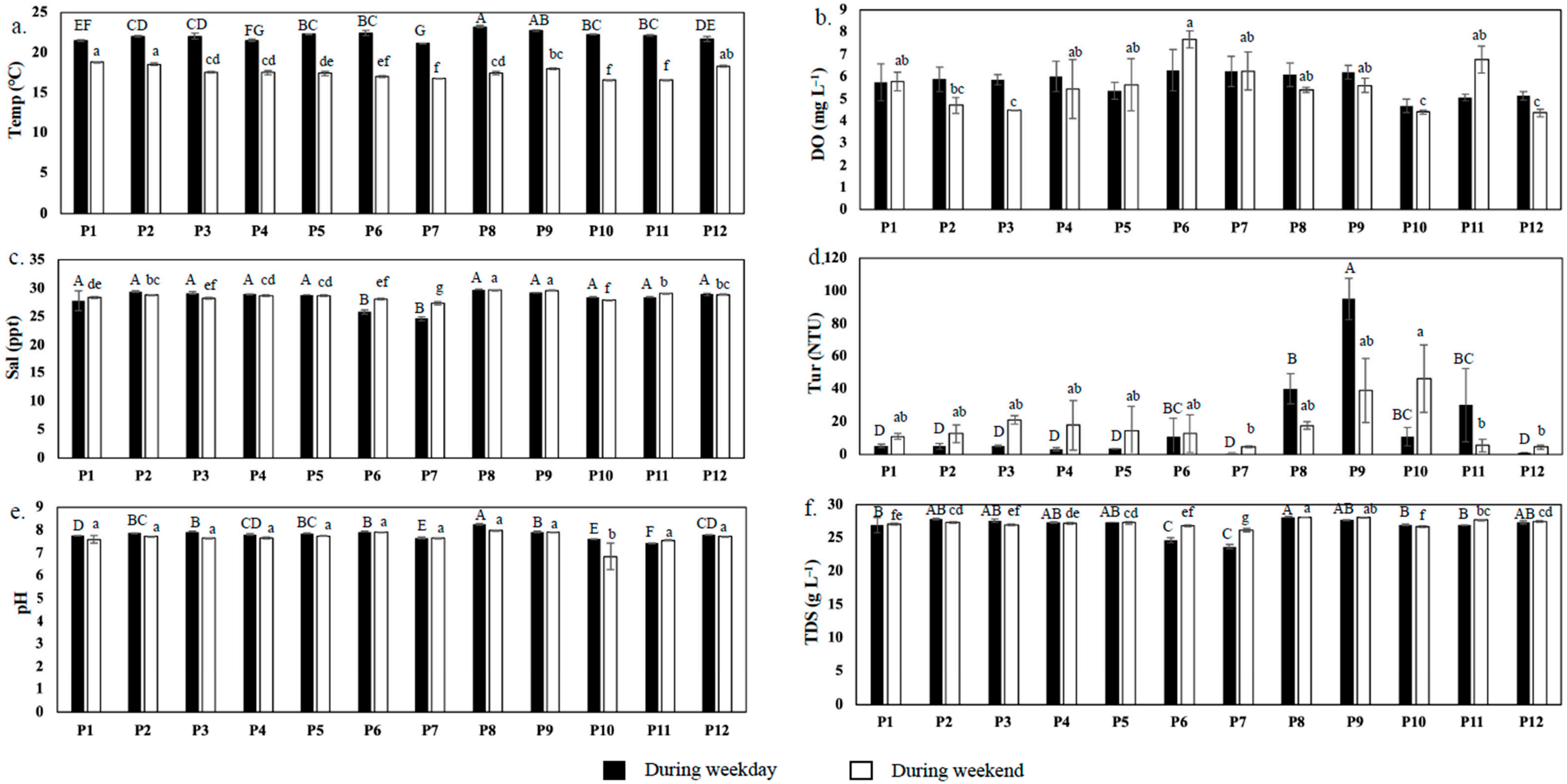

Figure 2. Bar charts showing the (**a**) average temperature (Temp), (**b**) dissolved oxygen (DO), (**c**) salinity (Sal), (**d**) turbidity (Tur), (**e**) pH, and (**f**) total dissolved solid (TDS) of the water samples collected from Tai O during a weekday and weekend ($n = 3$, mean ± SD) across the 12 sampling points. Different uppercase letters denote statistically significant differences among the weekday sampling points, while the lowercase letters indicate significant differences among the weekend sampling points (Tukey, $p < 0.05$). An absence of any letters signifies no difference among the sampling points.

3.2. Variations in the Nutrient Concentrations of Tidal Waters during a Weekday and Weekend

The average levels of TN, NO_3-N, NO_2-N, total inorganic nitrogen (TIN), and PO_4-P in the water samples collected during the weekend were significantly higher than those in the water samples collected during the weekday (*t*-test, $p < 0.05$), particularly the TN and PO_4-P levels, which showed average concentrations of 0.33 and 0.014 mg L^{-1}, respectively, in the weekend samples (Figure 3 and Table 1). On the other hand, no significant differences in the concentrations of NH_3, TP, and TOC were observed between the two sampling times (*t*-test, $p > 0.05$) (Figure 3 and Table 1). Notably, the average concentration of PO_4-P in water samples obtained during the weekend was nearly double that of samples collected during the weekday. In comparison with the Category I standards of the Chinese Sea Water Standards (GB 3097-1997), our results indicated phosphate concentrations at sites P3, P4, P5, P6, and P11 during the weekend that exceeded the recommended threshold (0.015 mg L^{-1}) [23]. Among these sites, P6 and P11 presented the highest phosphate levels, reaching or exceeding the more-degraded Category III standard of 0.03 mg L^{-1}. These data indicated that most sampling points were highly polluted by PO_4-P during the weekend. The two main sources of phosphorus pollution in aquatic ecosystems are natural and anthropogenic activities, and the use of detergents and the discharge of domestic sewage have been identified as significant contributors to water pollution [27]. Phosphate contamination in water ecosystems can promote the growth of algae and other plant species, resulting in a decrease in the water's DO concentration [28]. The problem of anthropogenic pollution and excessive plant growth leading to a deterioration in tidal water of mangrove wetlands cannot be neglected.

The concentrations of NH_3 in all samples, except P8 during the weekday and P9 during the weekend, far exceeded the requirements of the China Sea Water Quality Standards and the Hong Kong Water Quality Objectives, which require that ammonia in sea water should not exceed 0.021 mg L^{-1} in all water quality categories [23,29], indicating that ammonia caused the most significant form of nitrogen contamination in Tai O's water. High levels of NH_3 in marine ecosystems pose direct or indirect risks to marine animals, and its concentration in tidal waters should be as low as possible [30]. Ammonia in water causes damage to fish organs such as the gills, kidney, and spleen [31]. The U.S. EPA suggests that water deemed safe for fish reproduction should have ammonia concentrations of 0.02 mg L^{-1} or below [32]. Marine species, such as horseshoe crabs and juvenile fish, that thrive in mangrove wetlands could be adversely affected by high concentrations of ammonia in coastal water [33]. In addition to its impact on aquatic life, a high ammonia input can also affect other ecological functions of mangrove wetlands, such as causing increased emissions of greenhouse gases like methane and nitrous oxide [4,34,35]. On the contrary, some reports show that nitrogen input can significantly enhance carbon storage and stimulate plant growth [36]. These conflicting findings underscore the need for further research to explore the impact of nitrogen inputs, particularly ammonia, on the ecological functions of Tai O mangrove wetlands.

Municipal sewage in Tai O is discharged directly into adjacent waterbodies without any treatment, or only has limited treatment such as screening and/or sedimentation before entering the sea through mangrove wetlands. Nutrient pollution in the Tai O water, particularly of NH_3 and PO_4-P, is likely due to the combination of inadequate sewage treatment and the direct discharging of municipal sewage. Untreated or partially treated sewage is known to have significant negative impacts on water quality and pose risks to aquatic organisms that rely on mangrove habitats [37–39]. To better protect the mangrove wetlands in Tai O, it is necessary to take immediate actions to reduce human loading of excessive nutrients, such as building sewage infrastructure and high-efficiency sewage treatment plants.

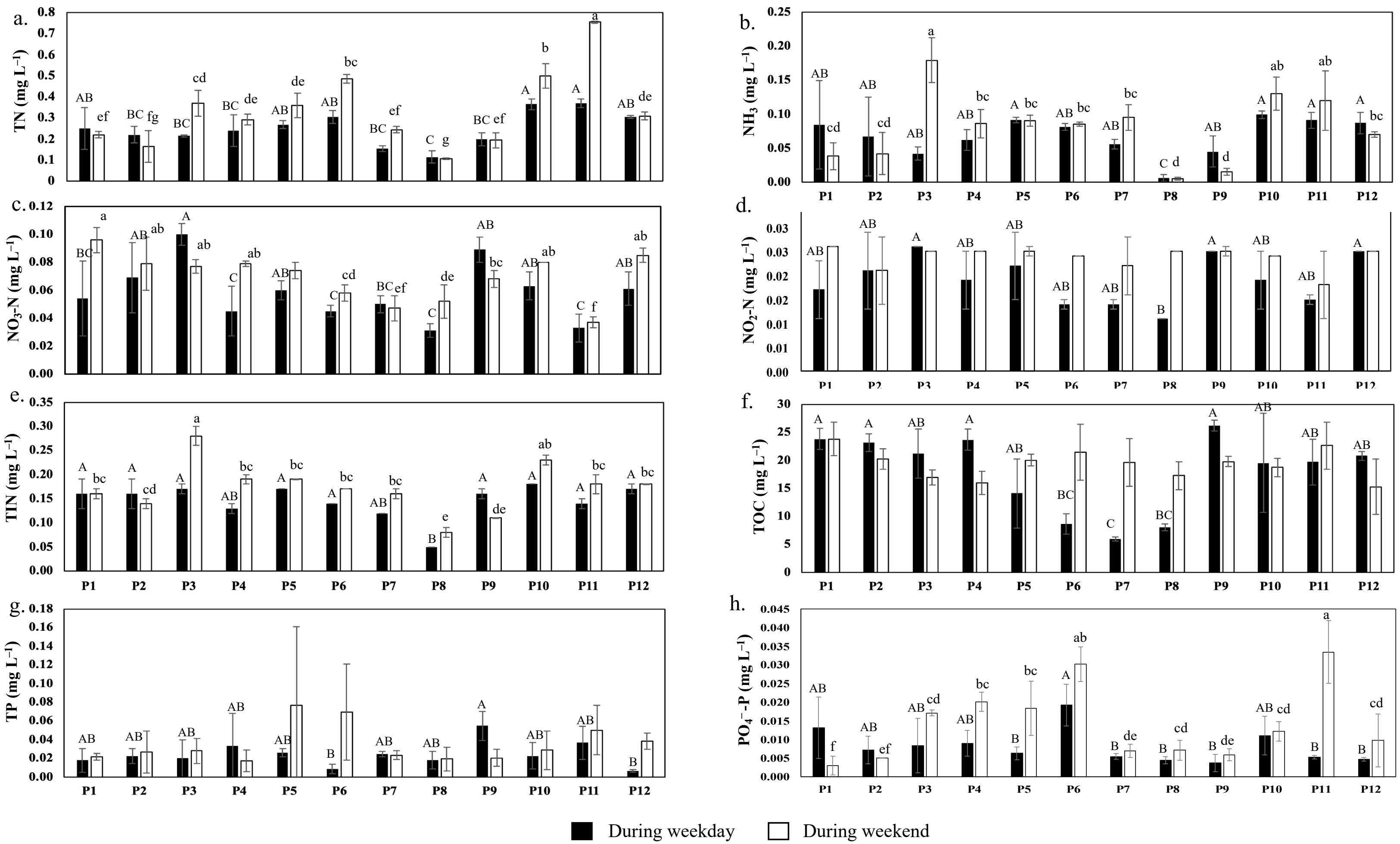

Figure 3. Bar charts showing the (**a**) average total nitrogen (TN), (**b**) ammonia (NH_3), (**c**) nitrate (NO_3-N), (**d**) nitrite (NO_2-N), (**e**) total inorganic nitrogen (TIN), (**f**) total organic carbon (TOC), (**g**) total phosphorus (TP), and (**h**) orthophosphate (PO_4-P) content in water samples collected from Tai O during a weekday and a weekend ($n = 3$, mean ± SD) across the 12 sampling points. Different uppercase letters denote statistically significant differences among the weekday sampling points, while lowercase letters indicate significant differences among the weekend sampling points (Tukey, $p < 0.05$). An absence of any letters signifies no differences among the sampling points.

3.3. Spatial Variation of Water Quality among the Different Sampling Points

The physiochemical parameters of samples collected from the weekday and weekend exhibited significant spatial variation, with the exception of the DO concentration in the weekday samples and the concentrations of NO_2-N, TOC, and TP in the weekend samples (Figures 2 and 3) (one-way ANOVA, $p < 0.05$). These findings suggest that the concentrations of DO on the weekday and NO_2-N, TOC, and TP on the weekend were not influenced by the density of the stilt houses. However, the average DO concentrations in the samples collected from sampling points with the most densely populated stilt houses (sites P3, P10, and P12) were significantly lower than those in other samples during the weekend (one-way ANOVA, $p < 0.05$). Moreover, the average concentration of NO_3-N in the weekend samples collected from the regions with more tourists (P1, P2, P3, P4, P5, P12, P10) was significantly higher than that collected in the regions with relatively fewer tourists during weekends (P6, P7, P8, P11) (one-way ANOVA, $p < 0.05$). These findings suggest that the decrease in DO concentration and increase in NO_3-N levels in Tai O's water could be attributed to increased human activity in the densely populated stilt house areas and regions with more tourists during weekends. Furthermore, the concentrations of NH_3 in the samples collected at site P8 were significantly lower than those collected from the downtown area and from the regions lacking centralized sewage systems, except for site P9, during weekends (one-way ANOVA, $p < 0.05$). This indicated that the elevated level of ammonia pollution in the water samples of Tai O's downtown area could be attributed to human activities, particularly in areas without proper sewage treatment.

Ammonia and nitrite are common toxic nitrogenous pollutants for organisms in aquatic ecosystems, and dissolved oxygen is important for living organisms. These three parameters are crucial to the health of aquatic organisms [40,41]. Our findings further demonstrate that the deterioration in water quality in Tai O Village, caused by inadequate sewage treatment and the influx of tourists, could potentially threaten the adjacent coastal wetland ecosystems in Tai O. Therefore, it is crucial to address these issues in order to mitigate the impact of nitrogenous compound contamination on the water quality and increase its DO levels.

3.4. The Relationship between Stilt House Density and Water Pollution in Tai O

The concentrations of various nutrients, including TN, TIN, NH_3, NO_3-N, NO_2-N, TP, and PO_4-N, can be dramatically worsened by untreated sewage disposal, while DO and pH are crucial water quality indicators [13]. In the present study, these parameters were incorporated into our PCA to evaluate the impact of stilt houses on water quality (Figure 4a,b). The PCA's result revealed that these factors explained almost 90% of the variability of the sampling points for water collected during the weekday (Figure 4a) and on the weekend (Figure 4b). During the weekday, the concentrations of TN, TIN, and NH_3 were more prevalent in the sampling points with a high density of stilt houses, including P5, P6, P10, P11, and P12, which were clustered in one group. Based on the water quality parameters, the samples collected during the weekend could be categorized into three groups: The first group consisted of P3, P4, P5, P10, and P12, which were associated with high TIN, NH_3, NO_3-N, and PO_4-P concentrations but a low DO concentration. They were situated in an area with a high density of stilt houses and three of them were next to an semi-enclosed mangrove with a limited tidal flow. The second group, which included P1, P7, P8, and P9, was influenced by a high pH but low nutrients (TIN, NH_3, NO_3-N, and PO_4-P) in the water. These points were in places with a low density of stilt houses and water channels with a high flow, with P1 and P8 being located at the mouths of water channels, while P7 was located at the mouth of a stream. The third group, comprising P11 and P6, was related to elevated values of DO, TN PO4-P, and TP. P11 and P6, when compared to P10 and P5, were in locations with a lower density of stilt houses, and some were even empty of stilt houses. The PCA analysis clearly implied that water pollution was substantially linked to the density of stilt buildings (anthropogenic inputs) and tidal flow. These findings showed that untreated or partially treated municipal sewage discharged into water channels in Tai O directly deteriorated the water quality of tidal water in Tai O. The reduced tidal flow near the village center and the semi-enclosed mangrove wetland also negatively affected the water quality. Other than affecting nearby wildlife, sewage could also be a significant source of infectious pathogens such as SARSCOV-2 [42]. Some stilt houses in Tai O do not have access to proper sewage treatment, and releasing untreated municipal sewage directly into waterbodies could pose health risks to other residents and tourists. Therefore, the currently untreated sewage from stilt houses must be treated properly in order to safeguard the health of the general public.

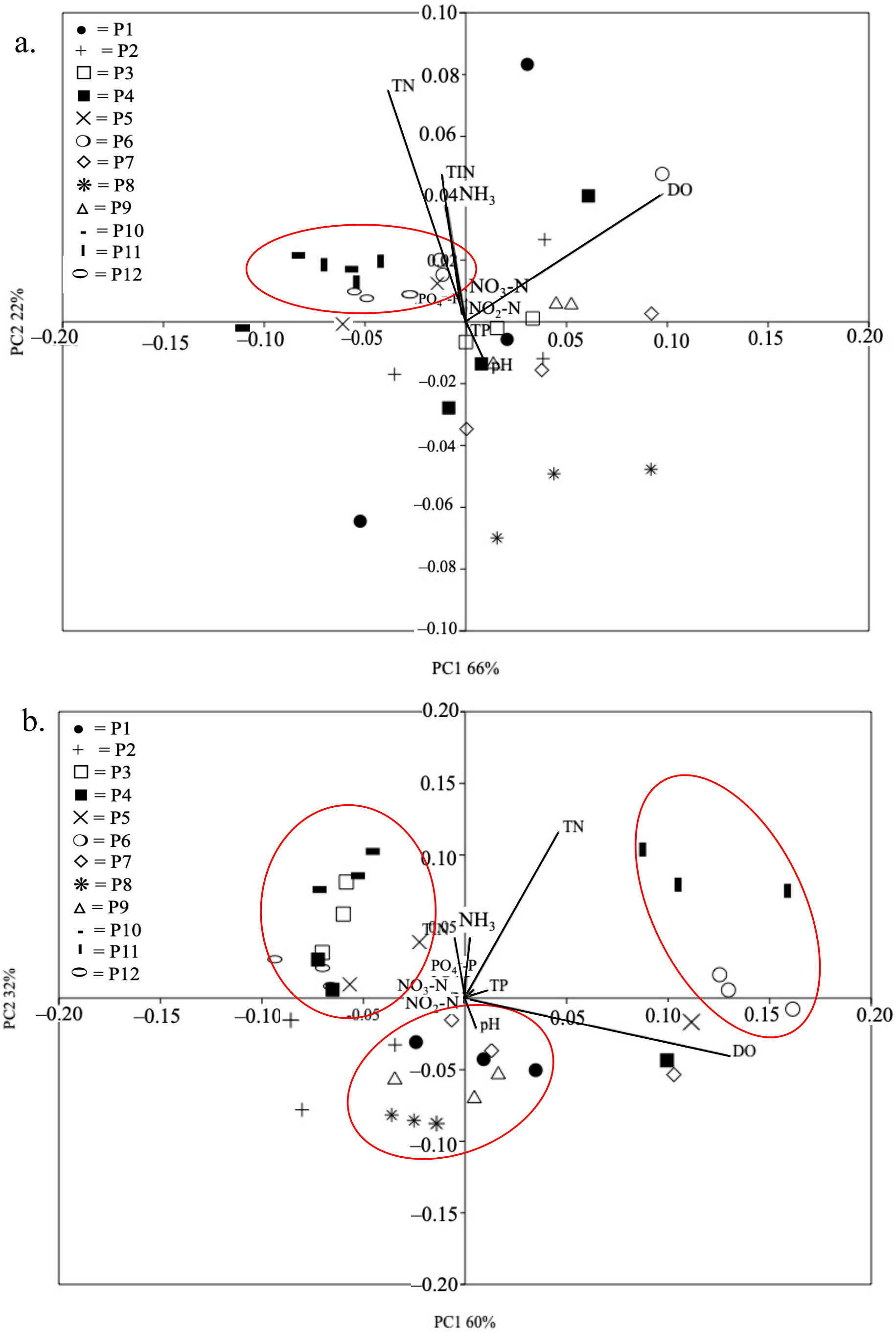

Figure 4. PCA biplots ((**a**): during the weekday and (**b**): during the weekend) are used to indicate the relationship between various water parameters (TN, TIN, NH_3, NO_3-N, NO_2-N, TP, PO_4-P, DO, pH) across the sampling points (symbols). Red circles represent correlation of variables a with the first two principal components.

To improve this situation, the Hong Kong government has proposed expanding public sewer connections to most stilt houses and upgrading the existing sewage treatment plant from primary to secondary processes by the mid-2030s [21]. Nevertheless, the effluents from secondary sewage treatment plants still contain significant levels of pollutants, including multiple species of nitrogen- and phosphorus-containing compounds, posing health concerns to aquatic life and coastal wetland ecosystems [43,44]. Tertiary sewage treatment processes can be used to further remove nitrogenous and phosphorus compounds from treated effluent [37]. However, significant infrastructure construction will be needed for adopting these conventional sewage treatment methods. Such construction work would be challenging and expensive, given that the stilt houses are scattered throughout Tai O and the streets are narrow and crowded.

As Tai O provides a suitable environment for mangroves and is surrounded by large areas of mangrove wetlands, treating sewage using a constructed wetland could be a cost-effective solution. Constructed wetlands have increasingly been used in the removal of nitrogenous and phosphorus compounds in various water ecosystems [38,45]. Building a constructed wetland to treat raw sewage from stilt houses without a public sewer connection could significantly reduce the infrastructure construction needed for sewage treatment. The secondary effluent from the sewage treatment work could also be further treated with the constructed wetland to lower nitrogen and phosphorous loading in the future. These are some possible strategies for mitigating nutrient pollution in Tai O without destroying its scenic views. To ensure the success of this solution, it is crucial to educate the general public and residents of Tai O about the importance of not discarding untreated sewage into nearby water channels. Promoting responsible sewage disposal practices can significantly contribute to maintaining the water quality in the area. Additionally, there is a need for monitoring the water quality in Tai O. Currently, Tai O is not one of the sampling points for Hong Kong's Water Quality Objectives. By expanding this monitoring network to include Tai O, authorities can gain valuable insights into the effectiveness of the constructed wetlands and the overall impact on the local ecosystem. Nonetheless, the issue of over-tourism presents significant challenges, notably the pressure it exerts on sewage treatment systems. This could result in water quality deterioration and negatively influence wetland ecosystems in Tai O village in the future. Therefore, the adoption of a tourism control policy should also be considered to alleviate these potential environmental consequences.

4. Conclusions

The present study demonstrates that both the influx of tourists and the discharge of untreated sewage from stilt houses are the key sources of water pollution and pose significant impacts on the tidal water quality of mangrove wetlands in Tai O, especially during weekends. The DO concentrations of Tai O's water during weekends decreased significantly and approached levels that cause risks to marine organisms. Concurrently, there was a significant increase in PO_4-P concentrations, contributing to the deterioration of water quality. The NH_3 concentrations in most samples exceeded the limits of the Chinese National Sea Water Quality Standards and Hong Kong Water Quality Objectives. Such elevated levels of NH_3 pose a significant threat to marine organisms. Our findings also reveal significant correlations between water pollution levels and the density of stilt houses, indicating that sewage discharge from stilt houses, as an example of the anthropogenic activities analyzed in this paper, is a significant source of pollution, introducing high-nutrient inputs and affecting mangrove functions. Further research should be conducted to develop appropriate strategies for the protection of mangrove wetlands and the sustainable development of their surrounding neighborhoods.

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