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Original Research

Correlation between Submerged Plant Growth and Water Environmental Factors in Urban Restored Rivers

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Abstract

Urban rivers are vital components of the urban ecosystem, offering recreational opportunities and contributing to various ecosystem services. Nevertheless, urbanization often causes water contamination, increasing the urgency for urban river restoration. Previous research has largely been confined to laboratory scales, which may not fully represent conditions found in natural settings, thus limiting the applicability of such findings. This study evaluates how bank configurations and hydrochemical characteristics influence submerged aquatic plant biomass and biodiversity in restored urban rivers (Hangzhou, China). Partial least squares regression (PLS), redundancy analysis (RDA), and fitting analysis were applied to explore plant-environment relationships. Results indicate that engineered revetments support higher biodiversity, while semi-natural revetments promote plant biomass. Plant growth is positively correlated with factors such as optimal water depth, low NO_3^- concentrations, high conductivity, and elevated NH_3-N, but negatively affected by high turbidity. Specifically, increased DO and flow rate enhanced *Potamogeton wrightii* and *Elodea nuttallii* growth, whereas *Najas marina*, *Cabomba caroliniana*, and *Ceratophyllum demersum* favored wider channels and greater depths. Notably, *Hydrilla verticillata* demonstrated strong tolerance to nutrient stress, suggesting its potential

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as a pioneer species. This study elucidates the relationship between river environments and submerged plants, providing a "Zoning-Adaptation-Monitoring" framework for ecological restoration.

Keywords: submerged macrophytes, plant biodiversity, urban river restoration, partial least squares regression, redundancy analysis

Introduction

In recent years, rapid urbanization and industrialization have exerted severe ecological pressure on urban rivers [1]. A representative case is the Yuhangtang River in Hangzhou, historically impacted by coal transportation from the Hangzhou Thermal Power Plant in the 1980s, mineral extraction, and untreated industrial wastewater discharge [2]. These activities resulted in significant sediment contamination and biodiversity loss. However, since 2018, comprehensive restoration efforts, including dredging, bank stabilization, and submerged vegetation reintroduction, have markedly improved water quality [3]. As a densely populated Asian megacity, river restoration projects in Hangzhou exemplify the critical challenge of balancing ecological recovery with urban demands, making it a unique case for studying submerged plant adaptability in anthropogenic landscapes. The recovery of submerged macrophytes is a cornerstone of aquatic ecosystem restoration, as they directly contribute to water purification, habitat structuring, and ecosystem stability [4]. However, the relationships between key water quality parameters and the growth and diversity of submerged plants in the complex and dynamic environment of restored urban rivers remain inadequately quantified. Thus, a detailed understanding of these plant-environment interactions is essential for guiding effective restoration.

Aquatic plants play a vital role in urban river ecosystems by providing habitats, improving water quality, and enhancing biodiversity, thereby strengthening the river's ecological function [5]. Studies have shown that aquatic plants can improve water quality by absorbing excess nutrients (such as nitrogen and phosphorus), reducing water flow speed, lowering turbidity, and providing habitats for aquatic organisms [6, 7]. Additionally, the restoration of aquatic plants in urban rivers can effectively reduce the retention of pollutants, promote ecological recovery, and contribute to the health of water bodies [8]. For urban rivers impacted by stormwater runoff, the restoration of aquatic plants not only helps mitigate water quality deterioration but also enhances the river's ecological resilience [9]. Submerged plants, as primary producers in aquatic ecosystems [10], play a crucial role in ecological restoration [11] and contribute to the maintenance of aquatic biodiversity [12]. Therefore, the restoration of aquatic plants is considered a low-cost, efficient, and sustainable method for improving water quality and enhancing ecological health, especially in terms of water quality management and ecosystem restoration.

Water depth is a particularly critical hydrological factor governing the distribution and growth of submerged macrophytes, as it directly modulates light availability [13-16]. Submerged plants can often enhance water transparency, provide shelter for large invertebrates, and prevent sediment resuspension. These functions are beneficial for maintaining water clarity in eutrophic shallow lakes [17]. Submerged plants have a strong physiological dependence on the water environment and are highly sensitive to water quality changes [18]. The presence of *Ceratophyllum demersum* significantly improved water quality, reducing Total Phosphorus (TP) and ammonia nitrogen concentrations by over 60% [19]. Some types of submerged plants showed minimal variation in TN and TP removal rates under temperatures ranging from 19 to 23°C. Among them, *Najas marina* maintained a strong water purification performance, achieving TN and TP removal rates of 55% and 93%, respectively, under intermittent reclaimed water supplementation [20]. Also, water clarity is the most limiting factor affecting the community structure and biomass of submerged plants [21], as submerged plants can promote the transformation of lake ecosystems [22].

Despite extensive research on macrophyte-environment interactions in natural lakes, the specific ecological mechanisms within restored urban rivers, dynamic systems characterized by high anthropogenic stress and artificial modification, remain inadequately quantified. In particular, the potential trade-offs between engineered and semi-natural habitats in supporting biodiversity versus biomass have rarely been examined in situ. To bridge this gap, this study employs multivariate statistical approaches (PLS, RDA, and fitting analysis) to investigate submerged plant communities in Hangzhou's restored river network. This research offers three distinct contributions to the field: (1) it elucidates a distinct ecological trade-off where engineered revetments unexpectedly enhance biodiversity through habitat heterogeneity, while semi-natural banks promote biomass accumulation; (2) it quantifies in situ adaptation thresholds for pioneer species (e.g., *Hydrilla verticillata*) under nutrient stress, providing critical field evidence that complements laboratory simulations; and (3) it establishes a quantitative "Zoning-Adaptation-Monitoring" framework, translating ecological correlations into actionable engineering criteria for optimizing the restoration of complex urban landscapes.

Materials and Methods

Description of the Study Area

This study conducted a field survey of typical urban restoration rivers in Hangzhou, China (29°11′-30°34′ N, 118°20′- 120°7′ E). Since many river sections in Hangzhou are regularly dredged artificially, and to minimize the potential impacts of anthropogenic activities on the experiment, three rivers that have undergone ecological restoration, i.e., the suburban section of Yuhangtang River, the river system of Yuhang Central Park, and Shangbu River, were selected for this study.

The sampling points were strategically selected based on several key criteria to ensure the representativeness and accuracy of the data. These criteria included factors such as river intersections, which can influence hydrological dynamics, and locations distant from urban stormwater discharge points to minimize the impact of pollutants from urban runoff. Additionally, sampling sites were chosen to avoid areas heavily impacted by human activity or disturbed by regular maintenance, which could introduce confounding variables that might skew the results. This careful selection process aimed to reduce external influences and enhance the reliability of the findings regarding submerged plant biodiversity and growth.

The Yuhangtang River, a focal case in this study, spans 21.87 km through Hangzhou's urban core. Historically, it served as a coal transport route for the Hangzhou Thermal Power Plant (1980s-2000s), leading to heavy metal accumulation in sediments [2]. Despite various restoration efforts since 2018, improvements in other aspects have been limited [3]. Nevertheless, persistent challenges such as fluctuating urban runoff and nutrient influx from surrounding residential areas complicate submerged plant colonization, providing a dynamic setting to investigate plant-environment interactions under anthropogenic stress.

For empirical research, 11 sampling sites were established along the Yuhangtang River using the transect method, with one point placed approximately every 1 km. The sampling sites were strategically chosen to account for factors such as intersections with the river (Fig. 1a)).

Located in the western part of Yuhang District, the Yuhang Central Park River System covers a total area of 125,700 m^2 and aims to restore the small-scale river ecosystem. Currently under construction, this river system was surveyed using a transect method. Sampling sites were arranged approximately every 0.5 km along the river, resulting in a total of nine sampling sites (Fig. 1b)).

Shangbu River, located in West Lake District, spans 4,700 m in length, with a channel width of 15-30 m and a water area of 151,620 m^2. It used to be a flood discharge channel downstream of the Xianlin Reservoir but was later ecologically restored. The sampling sites on Shangbu River in Hangzhou were arranged using the transect method, with one sampling site placed approximately every 1 km in each sample area, resulting in a total of two sampling sites (Fig. 1c)). Due to the narrow channel width (15-30 m) and homogeneous ecological conditions of Shangbu River, two representative sampling sites were selected to minimize redundancy while capturing spatial variability.

At each sampling site, a 10-meter river section was selected as the survey sample site, and three 0.25 m^2 quadrats were randomly chosen from each site for detailed examination.

Identifying and Classifying Revetment Types

The study area included both engineered and semi-natural revetments, which were crucial for understanding submerged plant growth. Engineered revetments were characterized by hard materials such as concrete, stone, or riprap, typically used for bank stabilization. Semi-natural revetments, on the other hand, were composed of natural materials, such as sand and gravel, often supported by vegetation, and were more conducive to plant colonization.

At each sampling site, the type of revetment was recorded, noting whether it was engineered or semi-natural. The revetment type was classified based on visual assessment and the material composition of the riverbanks. The presence of submerged plants was also noted in relation to these revetments, with engineered sites typically having lower plant biomass but higher biodiversity, and semi-natural sites showing higher biomass but lower diversity due to competitive exclusion by dominant species.

Physicochemical Parameters Analysis

To obtain water quality samples and parameters at the sampling sites, water samples were collected and tested on five consecutive sunny days in August 2024. This period was selected because it corresponds to the peak growth season of submerged macrophytes in subtropical monsoon climate regions. In these regions, plants exhibit maximum biomass and metabolic activity. Although this sampling strategy represents a seasonal snapshot, it effectively captures the critical state of the restored ecosystem and the plant-environment interactions under typical summer conditions. Research indicates that strategic planning is justified when the detection probability of the target species exceeds 0.5 [23, 24]. The flow rate (FR) was measured using a flow meter placed 20 cm underwater, and turbidity (NTU) was measured with a handheld portable turbidity meter (Qiwei WGZ-1B). Water temperature (Temp), electrical conductivity (Cond), dissolved oxygen (DO), and pH were measured using an 86031 AZ IP67 Combo Water Meter (AZ Instrument Corp.). Depth was measured using a depth gauge, while phosphate (PO_4-P) and nitrate (NO_3^-) were measured using a disposable reagent

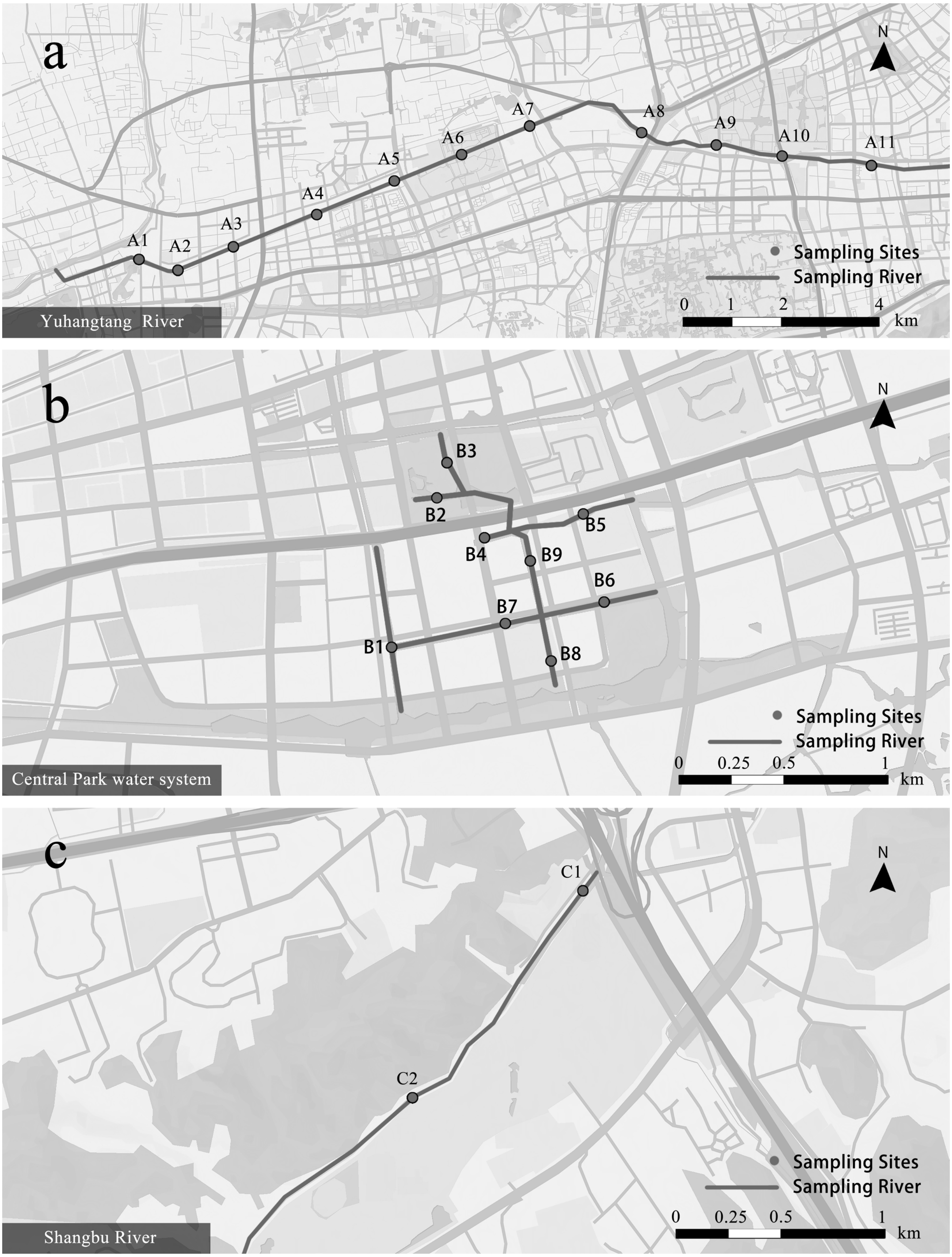


Fig. 1. Map of the study area and sampling sites in Hangzhou. a) Distribution of 11 sampling sites along the Yuhangtang River; b) The 9 sampling sites located within the Central Park water system; c) Distribution of 2 sampling sites along the Shangbu River.

kit. Channel width (CW) was measured with a high-precision remote sensing (RS) image. Total Phosphorus (TP), ammonia nitrogen (NH_3-N), and chemical oxygen demand (COD) were collected using a water sampler and transported to the laboratory for analysis. All water samples were collected at a depth of 10 cm in the center of the river, according to similar empirical research [25].

Collection and Identification of Submerged Plants

Submerged plants were collected from sampling sites using a quadrat method. Plants within each quadrat were uprooted with a sampling rake, thoroughly washed, and cleared of dead branches and leaves. Fresh weight biomass was determined by weighing the samples immediately in a non-dripping state, using the homogeneous experiment design [21]. The identification of submerged plants was conducted in situ, according to the "List of Flora of China (2022 edition)".

Statistical Analysis

Data processing and gra phing were conducted using Microsoft Excel 2021, SPSS, Canoco 5, and Origin 2024 software. The diversity of submerged plants was analyzed using the α-diversity index, which measures both the number of species within a community and their relative abundance. Four indicators were selected to analyze the species diversity characteristics of the sampling sites: Margalef's Species Richness Index (d) [26], Shannon-Wiener Index (H') [27], Simpson Index (D) [28], and Pielou's Evenness Index (J) [29]. The calculation methods for each are as follows:

$$d = (S - 1)/\ln N$$

$$H' = -\sum_{i=1}^{S} P_i ln P_i$$

$$D = 1 - \sum_{i=1}^{S} {P_i}^2$$

$$J = H'/lnS$$

Where S represents the number of species within the quadrat, P_i is the proportion of individuals of the i-th species relative to the total number of individuals of all species in the sample, and N denotes the biomass at the sampling site.

Partial Least Squares (PLS) regression and Redundancy Analysis (RDA) were employed to assess the relationships between submerged plant diversity, biomass, and environmental factors. PLS and RDA have been widely applied in water ecology to solve multicollinearity [30, 31].

Results

In PLS regression analyses, covariance may lead to instability in the regression coefficients, which may allow the effects of certain variables to be overestimated or underestimated. For example, TP and NH_3-N are both important indicators of eutrophication in urban rivers, and when there is high covariance, the effect of NH_3-N may be absorbed by TP, resulting in a large fluctuation in the significance (VIP value) of NH_3-N under different model runs. In addition, in the RDA dimensionality reduction analysis, covariance may lead to overlapping information in some variables, which may affect the explanatory power of the principal components. For example, both water depth and turbidity affect light transmittance, but if they are highly covariant, the model may have difficulty distinguishing their independent effects on submerged plant biomass. In addition, the results of the fitting analysis showed that the regression coefficient for NH_3-N was significantly lower when both NH_3-N and TP were entered into the model, suggesting that the effect of NH_3-N was partially explained by TP.

To reduce the impact of covariance on the model, this study used dimensionality reduction techniques (e.g., variable projection importance analysis, VIP, in PLS) to ensure that the contribution of each variable could be reasonably distinguished. In addition, variables with high redundancy were removed from the RDA analysis, such as selecting TP as a representative variable between TP and NH_3-N, to reduce the effect of covariance between variables and improve the stability and interpretability of the model.

Composition and Distribution of Submerged Plant Communities

Seven submerged plant species were recorded from 22 sampling sites, including *Ceratophyllum demersum, Potamogeton wrightii, Vallisneria natans, Hydrilla verticillata, Najas marina, Elodea nuttallii,* and *Cabomba caroliniana*. These species belong to 7 genera across 4 families, with one species from the family Ceratophyllaceae, one from the family Potamogetonaceae, four from the family Hydrocharitaceae, and one from the family Cabombaceae. Among all the collected plants, *Ceratophyllum demersum* and *Vallisneria* accounted for the largest proportion (Table 1).

Effects of Revetment Types on Submerged Plant Biomass and Biodiversity

The revetment types in the investigated area were divided into engineered revetments and semi-natural revetments, and the classification and summary of

Table 1. Distribution of submerged plants at sampling sites.

Species name	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	B1	B2	B3	B4	B5	B6	B7	B8	B9	C1	C2
Ceratophyllaceae																						
Ceratophyllum demersum		+	+	+	+	+	+	+	+	+	+		+	+	+	++	+	+	+	+	+	
Potamogetonaceae																						
Potamogeton wrightii	+																					
Najadaceae																						
Vallisneria natans	+++	+	++	+	+	++	+	+	+	++	+	+		+	+	++	+	+	+	+	+	+
Hydrilla verticillata		+											++	+	+	+	+	+		+	+	+
Najas marina					+		++															
Elodea nuttallii	+																					
Cabombaceae																						
Cabomba caroliniana							+															

Abundance: "+" = 1–50 individuals; "++" = 51–100; "+++" = >100.

revetment types and submerged plant biodiversity at the sampling sites (Table 2) showed that engineered revetments were more conducive to submerged plant diversity in urban rivers.

According to the classification and summary of revetment types and submerged plant biomass in the sample plots (Table 3), it can be found that semi-natural revetments are more conducive to the growth of submerged plants in urban river channels.

An analysis of variance (ANOVA) test was conducted to investigate the differences between the revetment types and the biomass of submerged plants. As shown in Table 4, the samples of different revetment types did not show statistical significance ($p>0.05$) for all of the samples of *Vallisneria natans, Ceratophyllum demersum, Najas marina, Potamogeton wrightii, Hydrilla verticillata, and Cabomba caroliniana*, implying that there was no significant difference in the biomass of the samples of different revetment types for the samples of *Vallisneria natans, Ceratophyllum demersum, Najas marina, Potamogeton wrightii, Hydrilla verticillata,* and *Cabomba caroliniana*. All samples showed no significant differences between revetment types.

An analysis of variance (ANOVA) was conducted to investigate the differences between revetment types and plant abundance. From Table 5, it can be seen that the samples of different revetment types do not show statistical significance ($p>0.05$) for six species: *Vallisneria natans, Najas marina, Potamogeton wrightii, Hydrilla verticillata, Cabomba caroliniana,* and *Elodea nuttallii*, indicating that there were no significant differences between revetment types for these species.

In addition, there was a significant difference between revetment types for *Ceratophyllum demersum* ($F = 4.478$, $p = 0.047$), and further comparison showed that the mean value for engineered revetments (20.11) was significantly higher than that for semi-natural revetments (7.00).

Drivers of Submerged Plant Growth: Hydrological and Water Quality Factors

To reveal the relationship between submerged plant diversity and water quality and hydrological factors, the Partial Least Squares (PLS) regression was employed. PLS regression is commonly used in in situ studies with small sample sizes (e.g., fewer than 100) and when multicollinearity issues may arise. Using FR, NTU, Temp, COD, DO, Cond, CW, Depth, PO_4-P, NO_3^-, NH_3-N, TP, and pH as independent variables, and Shannon-Wiener (H'), Pielou (J), Simpson (D), and Margalef (d) as dependent variables, we analyzed the cross-validation results (Table 6), RMSEP plot (Fig. 2), and Variable Importance in Projection (VIP) analysis (Table 7). When the number of components >1, the increase in VIP values is limited; if the Qh^2 value is greater than 0.0975, the number of principal components

Table 2. Classification and summary of revetment types and submerged plant biodiversity at sampling sites.

Diversity index	Revetment type		Sum
	Engineered	Semi-Natural	
Shannon-Wiener (H')	0.706	0.552	0.615
Pielou (J)	0.790	0.590	0.672
Simpson (D)	0.388	0.312	0.343
Margalef (d)	2.778	1.688	2.134

Table 3. Classification and summary of revetment types and submerged plant biomass at sampling sites.

Species	Revetment type		Sum
	Engineered	Semi-Natural	
Vallisneria natans	0.394	0.458	0.432
Ceratophyllum demersum	0.191	0.085	0.128
Najas marina	0.000	0.099	0.059
Potamogeton wrightii	0.000	0.001	0.000
Hydrilla verticillata	0.046	0.096	0.075
Cabomba caroliniana	0.000	0.001	0.000
Elodea nuttallii	0.000	0.002	0.001

Table 4. Analysis of variance (ANOVA) of revetment type and submerged plant biomass.

	Revetment type (mean ± standard deviation)		F	p
	Engineered (n=9)	Semi-Natural (n=13)		
Vallisneria natans	0.39±0.41	0.46±0.43	0.121	0.732
Ceratophyllum demersum	0.19±0.20	0.08±0.13	2.229	0.151
Najas marina	0.00±0.00	0.10±0.24	1.479	0.238
Potamogeton wrightii	0.00±0.00	0.00±0.00	0.682	0.419
Hydrilla verticillata	0.05±0.06	0.10±0.22	0.455	0.508
Cabomba caroliniana	0.00±0.00	0.00±0.00	0.682	0.419
Elodea nuttallii	0.00±0.00	0.00±0.01	0.682	0.419

Note: * $p<0.05$ ** $p<0.01$.

can be confirmed as 1, thus enabling further PLS analysis.

Subsequently, PLS regression analysis was performed with FR, NTU, Temp, COD, DO, Cond, CW, Depth, PO_4-P, NO_3^-, NH_3-N, TP, and pH as independent variables, and Shannon-Wiener (H'), Pielou (J), Simpson (D), and Margalef (d) as dependent variables, with the number of principal components set to 1. The results indicated that CW, Depth, and NO_3^- had the greatest influence on submerged plant diversity. Additionally, the impact of water quality and hydrological factors on Shannon-Wiener (H'), Pielou (J), and Simpson (D) was found to be opposite to their effect on Margalef (d) (Fig. 3).

Table 5. Analysis of variance (ANOVA) of revetment type and submerged plant population.

	Revetment type (mean ± standard deviation)		F	p
	Engineered (n=9)	Semi-Natural (n=13)		
Vallisneria natans	30.89±32.84	33.92±31.89	0.047	0.831
Ceratophyllum demersum	20.11±20.46	7.00±7.82	4.478	0.047*
Najas marina	0.00±0.00	7.00±18.68	1.244	0.278
Potamogeton wrightii	0.00±0.00	0.15±0.55	0.682	0.419
Hydrilla verticillata	4.33±5.79	11.08±24.22	0.662	0.425
Cabomba caroliniana	0.00±0.00	0.08±0.28	0.682	0.419
Elodea nuttallii	0.00±0.00	0.31±1.11	0.682	0.419

Note: * $p<0.05$ ** $p<0.01$.

Table 6. Cross-validation analysis.

Ingredient	SS	PRESS	Qh^2
1	61.151	88.676	1.000
2	56.377	91.679	-0.499
3	55.950	112.248	-0.991
4	49.564	112.257	-1.006
5	42.736	122.419	-1.470
6	42.258	109.243	-1.556
7	42.170	132.423	-2.134
8	41.313	148.666	-2.525
9	39.295	157.884	-2.822
10	34.740	150.532	-2.831
11	34.379	139.976	-3.029
12	34.345	146.416	-3.259
13	34.244	234.405	-5.825

The model equation is shown below.

Shannon-Wiener (H') = –0.013*FR + 0.066*NTU + 0.011*Temp + 0.041*COD-0.019*DO + 0.074*Cond – 0.122*CW – 0.114*Depth + 0.018*PO_4-P + 0.005*NO_3^-+ 0.100*NH_3-N + 0.074*TP + 0.027*pH

Pielou (J) = –0.004*FR + 0.022*NTU + 0.004*Temp + 0.014*COD –0.006*DO + 0.025*Cond – 0.041*CW – 0.038*Depth + 0.006*PO_4-P + 0.002*NO_3^- + 0.033*NH_3-N + 0.025*TP + 0.009*pH

Simpson (D) = –0.013*FR + 0.067*NTU + 0.011*Temp + 0.042*COD-0.020*DO + 0.075*Cond – 0.125*CW – 0.116*Depth + 0.018*PO_4-P + 0.005*NO_3^-+ 0.102*NH_3-N + 0.075*TP + 0.028*pH

Margalef (d) = 0.016*FR – 0.078*NTU – 0.013*Temp – 0.049*COD + 0.023*DO – 0.088*Cond + 0.146*CW + 0.136*Depth – 0.021*PO_4-P – 0.005*NO_3^- – 0.119*NH_3-N – 0.088*TP – 0.033*pH

The water quality and hydrological factors are closely related to the growth status of submerged plants and influence their diversity. To explore the relationship between the growth condition of submerged plants and hydraulic environmental factors, redundancy analysis (RDA) and fitting analysis were used for correlation analysis.

The RDA was used for dimensionality reduction to extract the main characteristic components of the data. The correlation between water quality and hydrological indicators, biodiversity indices, and the growth status of submerged plants was explored. The growth of submerged plants was represented by their biomass. RDA of submerged plant biodiversity indices and water quality environmental factors revealed significant positive correlations between the Simpson and Shannon-Wiener indices and NH_3-N, NTU, and COD, while they

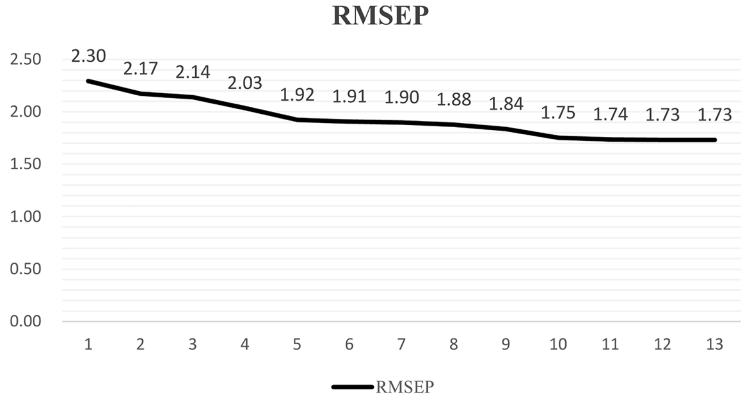


Fig. 2. Root Mean Square Error of Prediction (RMSEP) plot for determining the optimal number of components in the PLS model.

Table 7. Summary of Variable Importance in Projection (VIP).

Variable	VIP value
FR	0.198
NTU	0.997
Temp	0.163
COD	0.623
DO	0.291
Cond	1.117
CW	1.855
Depth	1.726
PO_4-P	0.268
NO_3^-	0.069
NH_3-N	1.516
TP	1.117
pH	0.416

showed significant negative correlations with DO. The Margalef index was significantly positively correlated with pH, CW, and depth, and negatively correlated with conductivity (Cond) and PO_4-P. Among these, NH_3-N, NTU, CW, depth, and DO have the greatest impact on biodiversity (Fig. 4).

Based on the results of the biomass and water quality-hydrology fitting analysis (Fig. 5), the following conclusions can be drawn: Biomass is highest when COD is approximately 8.5 mg/L and depth is approximately 2.6 m. Conversely, biomass is lowest when conductivity (Cond) is around 500 µS, flow rate (FR) is approximately 0.04 m/s, nitrate (NO_3^-) is approximately 20 mg/L, and phosphate (PO_4-P) is approximately 0.10 mg/L. Ammonia nitrogen (NH_3-N) generally presented a positive correlation with submerged plant biomass, while NTU and temperature (Temp) exhibited a negative correlation. Other factors showed no significant impact on biomass.

Species-specific responses to nutrient stress were further elucidated through the integration of RDA and fitting analyses. As shown in Fig. 4b), the projection of *Hydrilla verticillata* exhibited a strong positive vector alignment with key eutrophication indicators, specifically ammonia nitrogen (NH_3-N) and Total Phosphorus (TP). Unlike *Potamogeton wrightii*, which showed a preference for flow rate (FR), *Hydrilla verticillata* was the primary species sustaining high abundance in nutrient-enriched niches. This observation is quantitatively supported by the fitting analysis (Fig. 5), where total biomass demonstrated a positive trend with increasing NH_3-N concentrations (ranging from 0.2 to 1.4 mg/L). Specifically, in sampling sites with elevated NH_3-N (>1.0 mg/L) and TP levels, *Hydrilla verticillata* was consistently identified as the dominant species, providing field-based evidence of its high tolerance and adaptation to nutrient stress compared to other submerged macrophytes.

Discussion

Trade-Offs between Engineered and Semi-Natural Revetments in Submerged Plant Colonization

In this study, we categorized the revetments in the survey area into two types: engineered revetments and semi-natural revetments. Our analysis of submerged plant biodiversity and biomass in sample plots (Tables 2 and 3) revealed that engineered revetments tend to support higher biodiversity, whereas semi-natural revetments appear to provide more favorable conditions for plant biomass. The difference in plant growth and diversity between revetment types can be attributed to the structural characteristics of the riverbeds. Riverbeds with semi-natural revetments, which typically consist of sand and gravel, offer a more stable and nutrient-rich substrate, supporting greater biomass accumulation [32, 33]. On the other hand, engineered revetments, often composed of stones or other hard materials, tend to create more heterogeneous environments that support a greater variety of species, although they may limit the

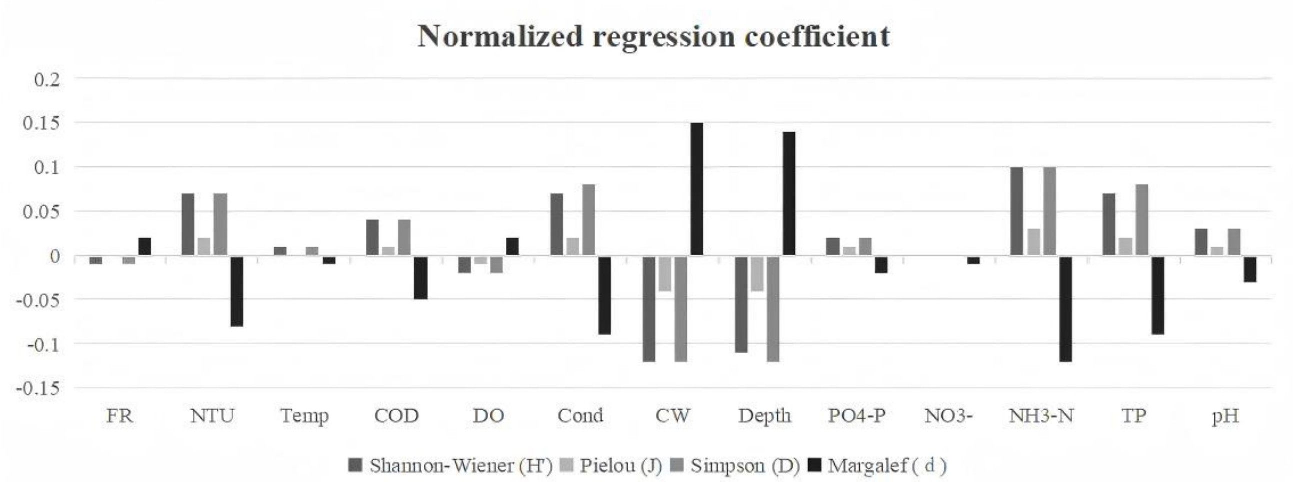


Fig. 3. Normalized regression coefficient.

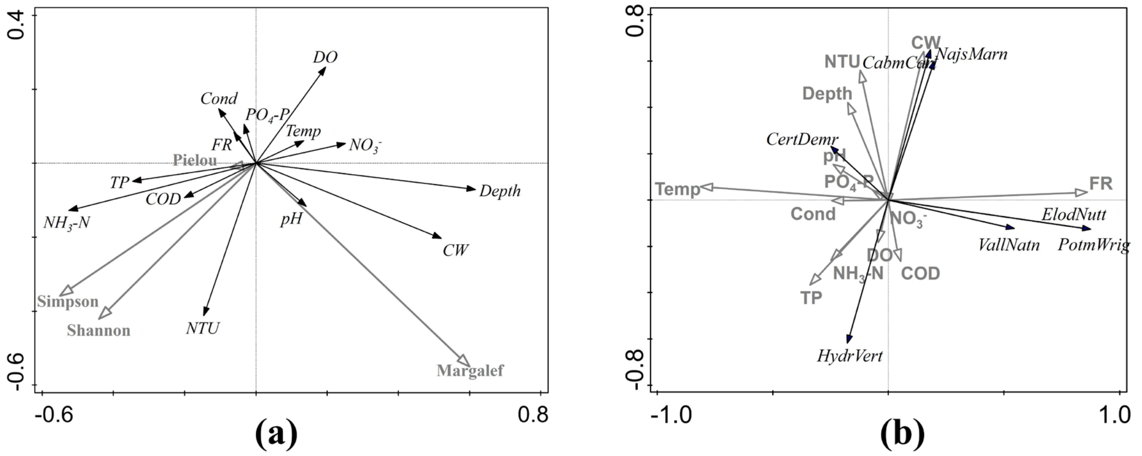
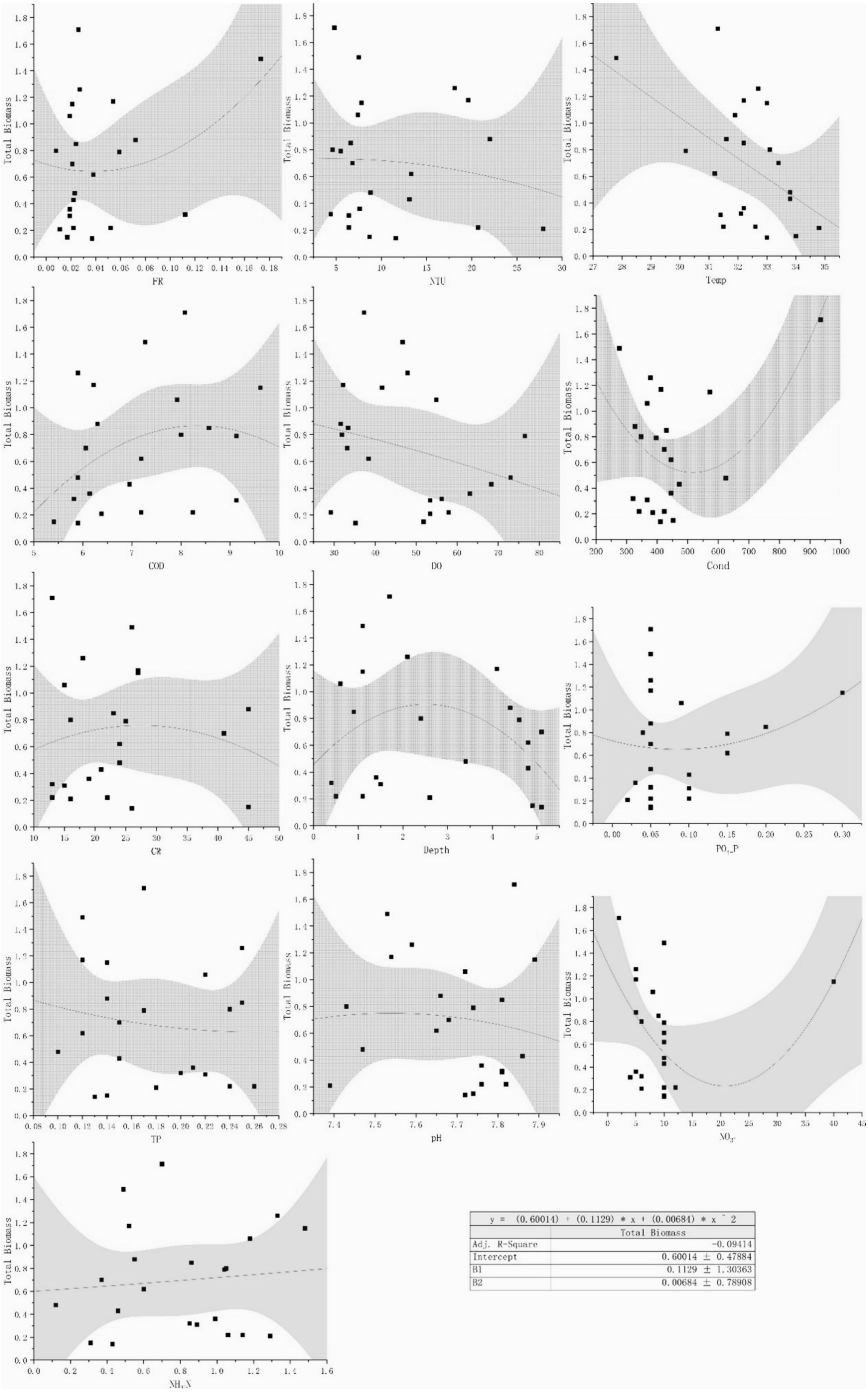


Fig. 4. RDA diagrams showing the relationship between environmental factors and submerged plant characteristics. a) Relationship between biodiversity indices and environmental variables; b) Relationship between species biomass and environmental variables.

overall biomass due to reduced habitat suitability for some plants [34]. These findings suggest that the type of revetment influences submerged plant communities in complex ways, with semi-natural revetments favoring plant growth and engineered revetments promoting diversity.

In semi-natural riverbanks, abundant sediments provide nutrients that support submerged plant growth. It has been indicated that the condition of sediments directly affects the reproduction, rooting, and growth of plants [11, 35], leading to a higher biomass. However, species with lower dominance are more likely to be outcompeted by more dominant species, leading to a decrease in biodiversity [36]. In contrast, engineered riverbanks limit the growth area of plants, resulting in smaller overall biomass. However, due to weaker interspecies competition, the biodiversity in engineered riverbanks is higher than in natural riverbanks.

It is noteworthy that although no significant biomass differences were found between revetment types for most species (Table 4), this could be attributed to limited statistical power, especially for low-abundance species like *Potamogeton wrightii* and *Cabomba caroliniana*. The relatively small sample size (n = 22 total sampling points) likely reduced the ability to detect subtle differences. Furthermore, while engineered revetments were expected to enhance biodiversity, the lack of observed biomass differences across revetment types could reflect a more complex interaction between revetment characteristics and plant growth that was not fully captured in this study. Future studies with larger sample sizes and more diverse sampling points should aim to enhance statistical power and better understand the nuanced ecological trade-offs between engineered and semi-natural revetments, which may involve factors such as sediment composition, hydrodynamic conditions, and plant species adaptability.



y = (0.60014) + (0.1129) * x + (0.00684) * x ^ 2	
	Total Biomass
Adj. R-Square	-0.09414
Intercept	0.60014 ± 0.47884
B1	0.1129 ± 1.30363
B2	0.00684 ± 0.78908

Fig. 5. Results of fitting analysis of biomass and water environmental factors.

These findings suggest that a hybrid restoration strategy could optimize ecological outcomes: engineered revetments with porous substrates (e.g., gabion baskets) should be prioritized in river segments requiring biodiversity conservation, whereas semi-natural revetments with nutrient-rich sediments are more suitable for reaches targeting biomass accumulation (e.g., downstream of wastewater treatment plants). Additionally, species with high turbidity tolerance, such as *Najas marina* and *Ceratophyllum demersum* (NTU > 30), could be artificially introduced during initial restoration phases to accelerate colonization. This zoning-species-specific management framework provides a scientific basis for balancing ecological functions and urban landscape demands in restored rivers.

Relationship between Water Environment Factors and Submerged Plants

Understanding the relationship between water environment factors and submerged plants is critical for optimizing the ecological health of urban rivers. In our study, key water quality parameters such as dissolved oxygen (DO), ammonia nitrogen (NH_3-N), and turbidity (NTU) were found to significantly influence submerged plant diversity and biomass. Dissolved oxygen is a well-known determinant of aquatic plant health, as it supports aerobic respiration and nutrient uptake [37]. The positive correlation between NH_3-N and plant growth observed in this study aligns with previous research suggesting that nitrogen is an essential nutrient for submerged plants, although excessive concentrations can lead to eutrophication [38, 39]. Conversely, turbidity (NTU), which is often associated with high levels of suspended solids and reduced light penetration, showed a negative relationship with submerged plant biomass. This supports findings by Van Onsem and Triest [40], who noted that high turbidity can significantly reduce the photosynthetic capacity of submerged plants, limiting their growth. These results underscore the complex interplay between nutrient availability, water clarity, and plant growth, and highlight the need for effective management of water quality to support submerged plant communities in restored urban rivers.

Relationships between water quality, hydrological conditions, and submerged plants were explored using methods such as PLS regression analysis, redundancy analysis (RDA), and fitting analysis. For submerged plant communities, factors such as water depth, NO_3^-, conductivity, NTU, and NH_3-N have the greatest impact on plant diversity. Submerged plant growth was most favorable when COD was around 8.5 mg/L, and the water depth was approximately 2.6 m. Conversely, growth was hindered when conductivity was about 500 μS, flow rate (FR) was around 0.04 m/s, nitrate (NO_3^-) was around 20 mg/L, and phosphate (PO_4-P) was approximately 0.10 mg/L. High NH_3-N concentrations and low NTU values favor the growth of submerged plants. As water transparency decreases, the light available to submerged plants also diminishes. Pollutants can adhere to the stems and leaves of submerged plants, weakening their photosynthetic efficiency and potentially promoting bacterial growth, which can ultimately lead to plant death. Turbid waters were also found to reduce the abundance of submerged plants, similar to the findings in homogeneous research [40]. Notably, the positive effects of NH_3-N and dissolved oxygen (DO) on submerged plant growth observed in our study are consistent with their roles as critical factors for macrophyte vitality and nutrient cycling in aquatic ecosystems, as reported in previous studies [41].

Water depth has a significant effect on the growth of submerged plants. In temperate regions, Bai [42] found that water depth was a key factor affecting the growth of *Vallisneria natans*, which is in line with the effect of water depth on the growth of submerged plants found in this study. In tropical regions, Xiong [43] also indicated that water depth had a significant effect on seedling germination and early growth of *Vallisneria natans*, further confirming the importance of water depth in the growth of submerged plants. In addition, Jing [44] found that certain submerged plants exhibited an escape strategy at 2 m water depth, while adopting a stationary strategy at higher water depths of 5-9 m. These findings collectively emphasize the importance of water depth as a crucial factor in regulating submerged plant growth, with species-specific responses depending on the depth and environmental conditions.

In terms of turbidity, studies have shown that high turbidity negatively impacts the growth of submerged plants. In temperate regions, Van Onsem and Triest found that high turbidity reduces the abundance of submerged plants, likely due to decreased light availability and poor photosynthetic efficiency in turbid waters [40]. This is consistent with the inhibitory effect of high turbidity on submerged plant growth observed in our study. In the tropics, pollution and increased turbidity from urbanization had a significant negative effect on submerged plant growth, further reinforcing the impact of water clarity on plant health [45, 46]. In contrast, submerged plants can reduce sediment resuspension, thereby improving water clarity [47]. This aligns with our findings, where submerged plants contributed to water transparency, likely enhancing photosynthetic activity by reducing sediment load and increasing light penetration [18]. Additionally, water flow has been shown to affect submerged plant communities, with higher flow velocities often reducing plant establishment and biomass due to increased turbulence and sediment disturbance [48]. However, in areas with moderate flow, submerged plants benefit from enhanced nutrient delivery, which promotes growth. Thus, water flow, like turbidity, plays a complex role in shaping submerged plant communities.

Water flow plays a critical role in regulating submerged plant growth across diverse climatic regions, a phenomenon well documented in both temperate and tropical ecosystems. In temperate regions, the study of Madsen pointed out that water flow is a key factor affecting the growth of submerged plants [48], which is consistent with the promotional effects of flow rate (FR) and dissolved oxygen (DO) on the growth of *Potamogeton wrightii* and *Elodea nuttallii* found in this study. In tropical regions, Xu [49] also indicated that water flow had a significant effect on the growth of submerged plants, further confirming the importance of water flow in the growth of submerged plants. It was also noticed that water flow can regulate the growth and metabolism of submerged plants [50], which is consistent with the effect of water flow on the growth of submerged plants found in this study.

Nutrient dynamics play a critical role in submerged plant ecophysiology, with distinct regulatory patterns observed across temperate and tropical ecosystems. In temperate regions, *Ceratophyllum demersum* significantly improved water quality by reducing Total Phosphorus (TP) and ammonia nitrogen (NH_3-N) concentrations by more than 60%, demonstrating the plant's ability to take up excess nutrients from the water [19]. Similarly, our study observed that high concentrations of NH_3-N and TP supported the growth of *Hydrilla verticillata*, highlighting how nutrient enrichment can promote the growth of submerged plants. In tropical ecosystems, certain submerged plants, such as *Najas marina*, showed strong water purification performance, removing total nitrogen (TN) and TP by 55% and 93%, respectively, under intermittent reclaimed water supplementation [20]. This is consistent with our findings, where elevated NH_3-N and TP levels were found to enhance submerged plant growth, underscoring the nutrient uptake potential of these species. Additionally, the role of submerged plants in nutrient cycling is further supported by Li, who highlighted the ability of *Hydrilla verticillata* to influence nutrient removal, particularly in relation to leaf surface epiphytic biofilms that interact with water depth and nutrient dynamics [51]. These studies collectively emphasize that while nutrients play a crucial role in supporting plant growth, submerged plants also actively participate in regulating nutrient levels in aquatic ecosystems.

For individual plant species, an increase in flow rate (FR) and dissolved oxygen (DO) promotes the growth of *Potamogeton wrightii* and *Elodea nuttallii*, while an increase in channel width (CW), water depth (Depth), and turbidity (NTU) benefits the growth of *Najas marina*, *Cabomba caroliniana*, and *Ceratophyllum demersum*. The increase in NH_3-N and TP supports the growth of *Hydrilla verticillata* [48-50].

Mechanisms of Species-Specific Adaptations to Restored River Environments

Our results indicated distinct niche differentiation among dominant species driven by physiological adaptations. Firstly, hydrodynamic adaptations likely explain the positive association of *Potamogeton wrightii* and *Elodea nuttallii* with flow rate (FR). This association is likely linked to the reduction of the diffusive boundary layer (DBL) on leaf surfaces. Moderate flow facilitates gas exchange and nutrient uptake by thinning the DBL, which is often a limiting factor in stagnant waters [52, 53]. Furthermore, these species exhibit high phenotypic plasticity, developing streamlined morphology to minimize drag while maximizing photosynthetic efficiency under flowing conditions [54].

Secondly, regarding tolerance to turbidity and low light, *Najas marina* and *Ceratophyllum demersum* showed a preference for deeper, more turbid waters. This distribution pattern is supported by their extremely low light compensation points (LCP), allowing them to maintain a positive carbon balance even when light penetration is reduced by suspended solids [55]. Additionally, *Cabomba caroliniana* employs a "canopy-forming" strategy, rapidly elongating shoots to concentrate biomass near the surface, effectively escaping light limitation in the benthic zone [56, 57].

Thirdly, the observed dominance of *Hydrilla verticillata* in nutrient-rich segments (characterized by high NH_3-N and TP) provides strong ecological evidence of its physiological adaptation to eutrophic stress (Fig. 4b)). This distribution pattern correlates well with the species' unique nitrogen metabolism described in the literature. Unlike species sensitive to ammonium toxicity, *Hydrilla verticillata* possesses a highly active GS/GOGAT cycle, enabling rapid assimilation of excess ammonium into amino acids [58]. The positive correlation between *Hydrilla verticillata* biomass and NH_3-N levels found in our study confirms that this physiological trait translates into a competitive advantage in restored urban rivers receiving nutrient inputs. Moreover, it can upregulate antioxidant enzymes (e.g., SOD, POD) to scavenge reactive oxygen species generated by eutrophic stress, making it an efficient pioneer species for phytoremediation [59, 60].

Finally, the correlation with conductivity likely reflects bicarbonate utilization. Species identified in this study are capable of utilizing bicarbonate (HCO_3^-) via carbon concentrating mechanisms (CCMs) when free CO_2 is depleted by algal blooms, a common trait in alkaline urban rivers [61].

Adaptive Management Strategies in a Changing Environment

While zoning based on revetment types provides a foundational framework, sustainable restoration must also account for future stressors identified in this study.

To achieve a climate-resilient species configuration, it is essential to note that our results highlight the sensitivity of species like *Elodea nuttallii* to temperature. In the context of global warming, management strategies should prioritize thermal-tolerant species (e.g., *Najas marina* or specific genotype*s* of *Vallisneria natans*) for engineered revetments where water temperature fluctuations are more pronounced. Conversely, cold-water species should be restricted to deeper, shaded refugia to prevent summer die-offs that lead to secondary pollution.

The strong correlation between NTU, DO, and plant diversity found in our model underscores the need for technology-driven precision maintenance, in which real-time monitoring is crucial. We recommend integrating IoT-based sensor networks to monitor dissolved oxygen and turbidity anomalies. When turbidity exceeds critical thresholds (e.g., > 30 NTU as noted in our results), harvesting operations should be suspended to prevent sediment resuspension. Furthermore, for hard-to-access urban river sections, remote sensing (UAV) should be employed to dynamically monitor biomass density, shifting maintenance from a fixed, calendar-based schedule to a "condition-based" approach.

Conclusions

This study elucidates the distinct trade-offs between engineered and semi-natural revetments in urban river restoration: the former supports higher biodiversity through habitat heterogeneity, while the latter promotes biomass accumulation via nutrient-rich substrates. To bridge the gap between ecological function and urban demands, we propose a dynamic "Zoning-Adaptation-Monitoring" management strategy.

Specifically, engineered revetments should be managed as biodiversity hotspots by introducing substrate enhancements (e.g., eco-gabions) and integrating climate-resilient species to withstand urban heat island effects. Semi-natural sections require nutrient export management (e.g., rotational harvesting) to prevent eutrophication. Furthermore, the integration of smart technologies – such as IoT sensors for real-time water quality tracking and remote sensing for biomass estimation – is essential to transition from static maintenance to adaptive management. This holistic approach ensures that restored urban rivers remain resilient against both anthropogenic disturbances and climate change uncertainties.

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Conflict of Interest

The authors declare no conflict of interest.

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