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RESEARCH

Ecological Disturbances and Adaptation of Mangroves in High-Disturbance Urban Areas of Navi Mumbai in India

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Abstract

Mangroves are coastal ecosystems characterized by salt-tolerant intertidal forest structures that serve as vital buffer zones between the coastal waters and human habitats. They expose an evolutionary course spanning around 60 million years, leading to the emergence of tailored adaptations like salt-excreting glands and prop roots. Despite widespread acknowledgment of their value, mangroves are swiftly declining due to coastal development and climate change. Rapid urbanization has increased anthropogenic pressures on these ecosystems, yet comprehensive assessments of their resilience in highly disturbed environments remain limited. This study looks at the ecological health of mangrove populations across three sites in Navi Mumbai, areas facing high urban and industrial growth. The analysis revealed elevated Zn (-0.88, $p < 0.001$), Cu (-0.73, $p < 0.01$), Pb (-0.70, $p < 0.05$), and Mn (-0.76, $p < 0.01$) correlating with reduced plant height, alongside consistently acidic water pH (mean = 5.93) and high salinity (range: 35–40 PSU). These conditions amplify metal mobility and toxicity, disrupting pneumatophore function, and lowering DO (mean = 3.8 mg/L), reflecting ecological degradation. Despite these stressors, mangrove populations exhibited decent growth traits, demonstrating a capacity for urban adaptation. Regulations of industrial discharge to reduce heavy metal specifically zinc contamination, coupled with targeted restoration efforts focusing on enhancing mangrove density and structural integrity, are essential to sustain these ecosystems.

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Statement of Sustainability: In exploring the relationship between urban expansion and mangrove ecosystems, this research contributes to the Sustainable Development Goals (SDGs) by emphasizing the importance of sustainable land-use strategies. By investigating the effects of urbanization on mangrove health, our findings aim to inform conservation efforts that protect these vital ecosystems (SDG 14: Life Below Water) while fostering nature-based urban design (SDG 11: Sustainable Cities and Communities). This work may serve as a resource for policymakers and stakeholders, advocating for approaches that harmonize development with ecological integrity.

1. Introduction

Coastal ecosystems are invaluable yet vulnerable landscapes, heavily relied upon by humanity. Currently, around 75% of the global population resides within 50 km of coastlines, emphasizing our dependence on these areas for resources, recreation, and livelihoods (Broom, 2022). However, this proximity also means that environmental pollution and human-induced changes have heightened impacts in coastal zones. Climate change compounds these pressures, manifesting in rising sea levels, recurring storm surges, and shifting wave dynamics—all of which threaten coastal regions and have broader implications beyond them (Ranasinghe, 2016; Zhang et al., 2020).

In response, ecosystem-based approaches aimed at sustainable development have become focal points of environmental strategy, giving rise to frameworks like nature-based solutions, green infrastructure, ecosystem-based adaptation, and ecosystem management (Renaud et al., 2016; O'Higgins et al., 2020; Seddon et al., 2020; Stefanakis et al., 2021). Mangrove forests are particularly significant within these frameworks, offering natural defenses against such environmental challenges. The importance of mangroves, however, gained attention not only for their benefits but also through the ecological losses observed following their degradation. The large-scale exploitation of mangroves for aquaculture in the mid-to late-20th century revealed their essential ecosystem functions, as communities recognized the loss of services they provided, such as coastal protection and biodiversity support (Valiela et al., 2001; Richards and Friess, 2016). This trend highlighted mangroves' role in ecosystem health, as their absence brought adverse impacts to light (Narayan et al., 2016; Hochard et al., 2019; Richards et al., 2020).

The Navi Mumbai mangroves provide critical ecosystem services such as coastal protection, carbon sequestration, habitat for biodiversity, and support for local fisheries, contributing to ecological balance and community livelihoods. (Figure 1). This is the very first study that bridges this broader global narrative of mangrove ecosystem degradation to the specific case of Navi Mumbai in India, a rapidly urbanizing region. While extensive literature exists on the ecological functions of mangroves, there is a gap in understanding the long-term ecological consequences of mangrove degradation in rapidly urbanizing coastal zones. This study addresses this gap by examining how the loss of mangrove covers in Navi Mumbai, coupled with heavy metal pollution, affects the coastal ecosystem's health. The analysis reveals consistent exposure to acidic conditions and heavy metal contamination, with elements such as zinc, copper, lead, and manganese detected, with zinc notably linked to reduced mangrove coverage. Despite these stressors, mangrove populations exhibit promising growth characteristics, suggesting an adaptation potential to urban environments.

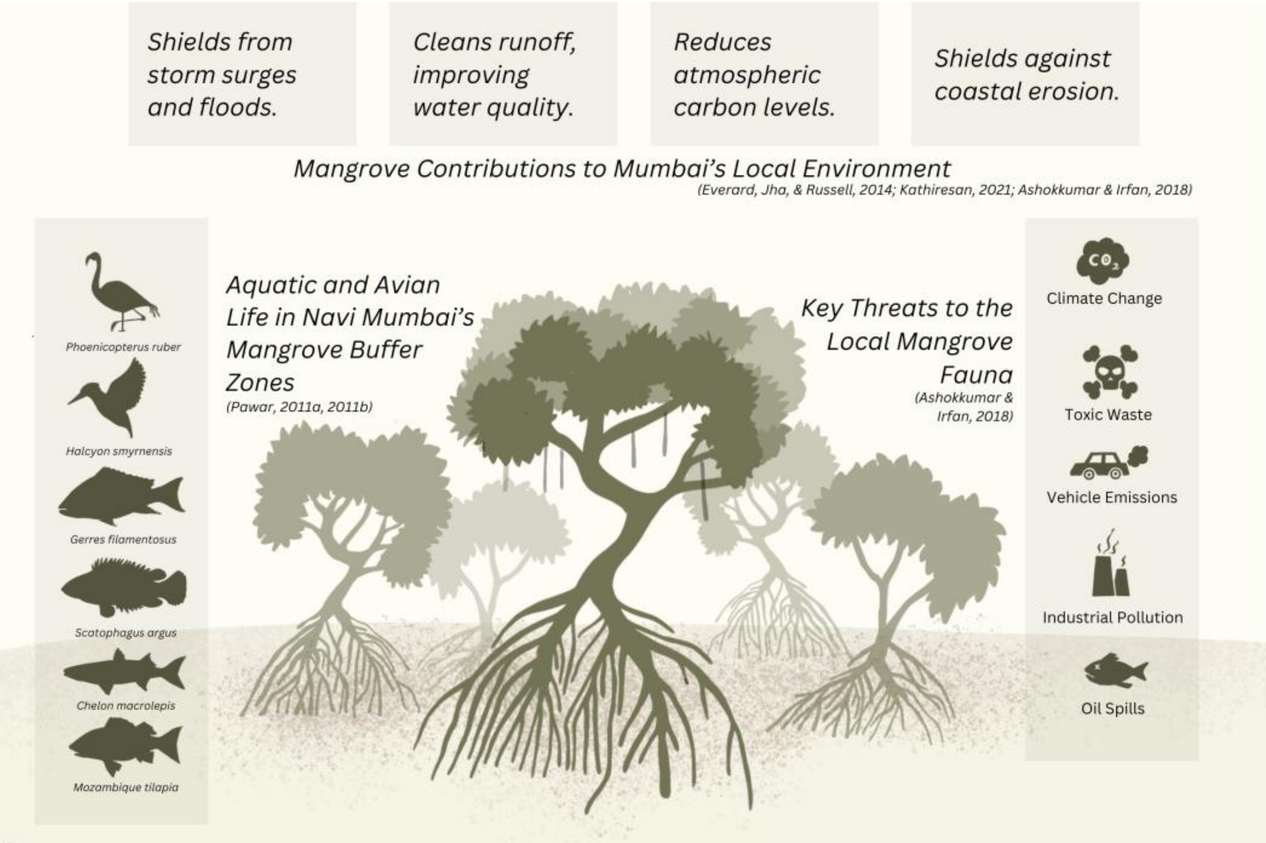

Figure 1. Biodiversity, threats, and ecosystem services of Navi Mumbai's mangroves.

2. Material and Methods

2.1. Site Description

The study site (19°04'19.7" N and 72°58'53.0" E) is located in the Vashi sector of Navi Mumbai, along the highly urbanized Thane Creek, adjacent to the Mumbai-Satara highway. This low-lying coastal landscape is characterized by a network of tidal channels and mudflats, with the mangrove cover predominantly consisting of the *Avicennia marina* (Figure 2). It faces pollution risks from the APMC market runoff, untreated sewage, and industrial discharge from nearby MIDC zones. The mangrove ecosystem here is under constant pressure from this rapid urbanization, making it a critical site for studying the mangroves in highly disturbed environments. The study was conducted across three distinct study sites of Navi Mumbai coastline—Sagar Vihar Public Park (SVPP), Mumbai-Satara Highway (MSH), and Tata Power Camp (TPC)—with samples collected from three locations spaced 1 meter apart within each site, totaling multiple collection sites.

Figure 2. (a) Coastal habitat of Thane-Vashi Creek featuring the growth of mangroves with prop roots and plastic debris in the muddy intertidal zone. (b) Flocks of Black-headed Gulls (*Chroicocephalus ridibundus*) foraging in Thane-Vashi Creek waters. Captured from the camera featuring a 12 MP sensor with an f/1.6 aperture and dual-camera system.

2.2. Estimation of Mangrove Density

Three quadrats of 2 m² each were randomly established in each study site to assess mangrove density and structural parameters. Within each quadrat, all *Avicennia marina* individuals were enumerated. The height of the tallest branch per tree was measured using a calibrated pole, and canopy spread was determined by measuring the maximum lateral extent of the crown using a tape measure. Data were collected to evaluate inter-regional variation in mangrove density and morphological characteristics. The following formulae were used to determine crown volume and relative crown spread.

$$\text{Crown Volume } (\text{m}^3) = \frac{\pi}{6} \times (\text{Crown Diameter})^2 \times (\text{Plumage Height})$$

$$\text{Relative Crown Spread } (\%) = \frac{\text{Crown Diameter}}{\text{Plumage Height}} \times 100$$

2.3. Sample Collection

Triplicate samples were obtained at approximately 1-meter intervals across each of these three distinct locations: SVPP, MSH, and TPC (Figure 3). Stratified sampling was implemented by selecting these regions within the study area to ensure a comprehensive representation of spatial variations. Water samples were collected from each region using pre-cleaned polyethylene bottles, submerged 15 cm below the surface, and immediately sealed. Soil samples were obtained from a depth of 20–30 cm using a stainless-steel auger, stored in airtight polyethylene bags, and transported in cool, insulated containers. Plant material was harvested from mangroves, stored in sterile breathable bags, and kept under shaded conditions. All samples were clearly labeled with location coordinates, sample type, and date of collection, and transported to the lab under refrigerated conditions (4°C) for subsequent physicochemical and heavy metal analyses. The sampling approach may not have fully captured temporal variations, as it focused on a single time point, which may have had limited insights into seasonal fluctuations in pollution levels.

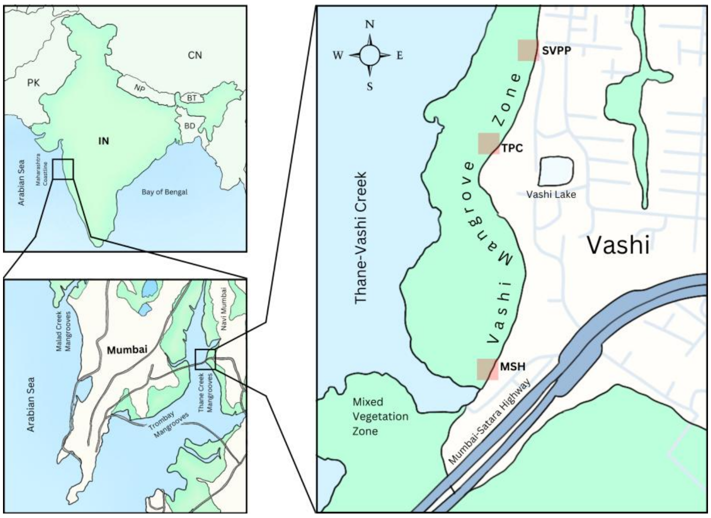

Figure 3. Geospatial depiction of study sites: SVPP, MSH, and TPC within Navi Mumbai's mangrove ecosystem.

2.4. Estimation of pH

The pH of water, soil, and plant samples was analyzed using Laboratory pH Testing Paper (Trikamlal and Sons®). The pH strips were introduced into the prepared samples, which included aliquots of water samples, the supernatant from the soil sample mixed with distilled water, and the filtrate from homogenized plant tissue samples. The pH was subsequently determined by matching the color changes to a reference chart for accurate assessment.

2.5. Estimation of Soil Moisture

The moisture content of the soil samples was determined by weighing a dry crucible (W1), adding the soil sample to obtain the combined weight (W2), and then drying the sample in an oven at 110 ± 5°C for 16 to 24 hours. After cooling in a desiccator, the final weight (W3) was recorded. The moisture content was calculated as the percentage of water lost during drying relative to the mass of the dried soil using the following formula:

$$\text{Moisture Content} = \frac{(W_2 - W_3)}{(W_3 - W_1)} \times 100$$

2.6. Estimation of Organic Carbon

Weighed 10 g of each soil sample was placed in 50 mL glass test tubes. 10 mL of Carbochem-A and 10 mL of Carbochem-B (from B.A.R.C.® Organic Carbon Detection Solution Mix) were added to the soil samples. The mixtures were vortexed for 30 seconds and allowed to stand for 15 minutes. The supernatants were filtered using Whatman No. 42 filter paper, and the filtrates were compared to a reference color chart provided in the B.A.R.C Organic Carbon Detection manual.

2.7. Estimation of Electrical Conductance

Electrical conductivity was determined using an MW301 Pro-EC meter (Milwaukee®) with an accuracy of ±2%. The instrument was calibrated using 0.01 M KCl solution to ensure accuracy. Water samples were pre-filtered using 0.45 µm membrane filters and allowed to equilibrate at room temperature (25°C) before measurement. The electrode was immersed in the sample, and the conductivity (in µS/cm) was recorded after the stabilization of the reading.

2.8. Estimation of Total Dissolved Solids (TDS)

A 100 mL aliquot of each water sample was transferred into pre-weighed porcelain evaporating dishes. The samples were evaporated to dryness in a hot air oven at 105°C±5°C until constant weight was achieved. The dishes were then cooled in a desiccator and weighed on an analytical balance. TDS concentrations were calculated using the formula:

$$\text{TDS} = \frac{W_2 - W_1}{V} \times 1000$$

Where W1 is the initial weight of the empty dish, W2 is the final weight with dried residue, and V is the volume of the water sample.

2.9. Estimation of Water Hardness

In a conical flask, 50 mL of the water sample was combined with 1 mL of ammonia buffer (pH 10) and 5 drops of Eriochrome Black T indicator. The solution was titrated with 0.01 M EDTA solution from a burette until the color shifted from wine red to blue, indicating the endpoint. The titration was repeated three times for each sample, and the total hardness was calculated based on the EDTA volume used (Yappert and DuPre, 1997).

2.10. Estimation of Salinity

Chloride concentration in water samples was determined via argentometric titration. A standardized 0.1 N $AgNO_3$ solution was used to titrate 10 mL of water sample in the presence of 3 drops of potassium chromate (K_2CrO_4) as an indicator. The endpoint was reached when the solution changed from yellow to buff red (Mohr, 1856).

2.11. Estimation of Dissolved Oxygen

For the estimation of dissolved oxygen, 200 mL samples were taken from the collected water samples without bubbling. In a glass tube, 2 mL of manganese sulfate solution and 2 mL of alkali-iodide-azide reagent were added, allowing the solution to react with dissolved oxygen. After thorough mixing, a 50 mL aliquot was taken for immediate titration with sodium thiosulfate, using a starch indicator to detect the color change from blue to colorless (Carvalho et al., 2021).

2.12. Manganese Estimation

For manganese estimation, 5 mL of the sample was treated with 1 mL of concentrated nitric acid and heated until dryness. The residue was dissolved in 10 mL of 0.1 N sulfuric acid and 2 mL of potassium periodate (0.1 M) was added. The mixture was heated at 90°C for 15 minutes to oxidize manganese to permanganate. After cooling, the absorbance was measured at 545 nm. Manganese levels were determined from a standard curve using manganese sulfate standards (0.05-5 µg/mL) (Single, 1957).

2.13. Copper Estimation

For copper estimation, 5 mL of the sample was digested with 5 mL of concentrated nitric acid and 2 mL of 30% hydrogen peroxide at 80°C until a clear solution was obtained. After cooling, 10 mL of 1% neocuproine in ethanol was added, followed by 5 mL of 1 M acetate buffer (pH 5). The resulting copper(I)-neocuproine complex was extracted into 10 mL of chloroform by vigorous shaking for 2 minutes. The absorbance of the organic phase was measured at 450 nm. Copper concentrations were determined from a standard curve prepared with copper sulfate solutions (0.1-10 µg/mL) (Gahler, 1954).

2.14. Lead Estimation

To estimate lead concentration, a test tube for the samples was prepared by mixing 4 mL deionized water, 2.5 mL of the samples, 0.1 mL ammonium solution, and 0.09 mL sulfide solution. A blank was prepared with the same excluding sulphide. For the standard, 2.5 mL of deionized water and 2.5 mL of the working standard were combined with ammonium solution. After standing for 10 minutes until a brown color developed, the optical density (O.D.) was measured at 430 nm (Budden and Hardy, 1894).

2.15. Zinc Estimation

Zinc was estimated by dithiozone extraction. A standard solution was prepared by dissolving 2.099 g zinc chloride in 1 L water. Acetate buffer was made from 68 g sodium acetate in 250 mL water (pH 4.8), and sodium thiosulphate at 25 g in 100 mL. Dithiozone solution (100 mg in 1 L chloroform) was diluted 1:9. Following the preparation of these solutions, 10 mL of the water sample was added to a separating funnel, along with 5 mL of acetate buffer, 1 mL of sodium thiosulphate, and 10 mL of diluted dithizone. The organic phase of the bottom layer was subsequently collected, and its absorbance was measured at 555 nm (Song et al., 1976). These metals—manganese, copper, lead, and zinc—were selected due to their known environmental persistence, toxicity to marine ecosystems, and relevance to mangrove health.

2.16. Statistical Analysis

The data were analyzed for mean and standard deviation (SD) using GraphPad Prism (Version 9) to summarize the central tendency and variability of each parameter across regions. All analyses were performed on data normalized for potential skewness or outliers, ensuring the robustness and reliability of statistical interpretations. For analyzing the relationships between metal concentrations (Zn, Cu, Pb, Mn) and morphological traits (height and crown dimensions), Pearson's correlation analysis was employed to assess the strength and direction of the linear relationships. Pearson's correlation coefficient (r) was calculated for each pair of variables. To determine the significance of these correlations, pp-values were obtained, with a threshold for significance at p<0.05p<0.05. Correlations with a pp-value less than 0.05 were considered statistically significant, indicating a meaningful association between the variables. The correlation analysis was performed using statistical software—R (Version 4.2.0). Specifically, in R, the "cor()" function with the method parameter set to "Pearson" was utilized to calculate Pearson's correlation coefficient, while the "cor.test()" function was used to determine the p-value for the significance of each correlation.

3. Results

3.1. Water and Soil Quality

The water samples collected from the three regions exhibited slightly acidic pH levels, with mean values of 6.03±0.17 for SVPP, 5.97±0.05 for MSH, and 5.8±0.10 for TPC, resulting in an overall average pH of 5.93 ± 0.12. Soil samples showed a mean pH of 5.38 ± 0.15, with SVPP at 5.47±0.15, MSH at 5.2±0.20, and TPC at 5.47±0.05. Additionally, moisture content measurements indicated high levels, with SVPP averaging 64.17 ± 2.36%, MSH at 67.56 ± 1.47%, and TPC at 64.32 ± 0.45%. These findings suggest that the mangrove ecosystems are well-suited to retain moisture, which is critical for their health (Tables 1 and 2).

Table 1. pH of different sample types from study sites.

Sample Type	SVPP (Mean ± SD)	MSH (Mean ± SD)	TPC (Mean ± SD)	Grand Mean (± SD)
Water Samples	6.03 ± 0.17	5.97 ± 0.05	5.8 ± 0.10	5.93 ± 0.13
Soil Samples	5.47 ± 0.15	5.20 ± 0.20	5.47 ± 0.05	5.38 ± 0.12
Plant Samples	6.10 ± 0.10	6.03 ± 0.05	6.00 ± 0.00	6.04 ± 0.03

Values in each row represent the mean (± SD) for each study site. SVPP = Study Site 1, MSH = Study Site 2, TPC = Study Site 3.

Table 2. Comparative analysis of water quality parameters by study site.

Study Site	TDS (mg/L)	Conductance (µS/cm)	Salinity (%)	Hardness (mg/L)	Dissolved Oxygen (mg/L)	Soil Moisture (%)
SVPP	360.00 ± 5.00	525.00 ± 5.00	22.00 ± 1.00	18.50 ± 0.50	0.15 ± 0.015	64.17 ± 2.36
MSH	365.00 ± 12.58	543.33 ± 21.08	20.00 ± 1.00	17.00 ± 0.50	0.17 ± 0.010	67.56 ± 1.47
TPC	373.33 ± 30.55	521.67 ± 15.28	23.67 ± 2.52	19.00 ± 0.50	0.11 ± 0.010	64.32 ± 0.45
Grand Mean (± SD)	366.11 ± 17.89	530.00 ± 14.09	21.89 ± 1.6	18.17 ± 0.50	0.14 ± 0.01	65.35 ± 1.35

Values in each row represent the mean (± SD) for each study site.

Table 3. Regional variations in metal concentrations (Zn, Cu, Pb, Mn).

Study Site	Zn (µg/L)	Cu (µg/L)	Pb (µg/L)	Mn (µg/L)
SVPP	136.67 ± 1.53	200.00 ± 10.00	16.20 ± 0.26	183.33 ± 5.77
MSH	140.00 ± 1.00	200.00 ± 8.16	16.60 ± 0.20	196.67 ± 5.77
TPC	145.00 ± 1.00	223.33 ± 12.47	17.07 ± 0.15	220.00 ± 10.00
Grand Mean (± SD)	140.56 ± 4.67	207.78 ± 11.47	16.66 ± 0.48	200.00 ± 11.55

Values in each row represent the mean (± SD) for each study site.

Table 4. Mangrove growth and morphology parameters through study sites.

Study Site	Plumage Height (m)	Crown Diameter (m)	Crown Volume (m^3)	Relative Crown Spread (%)
SVPP	2.70 ± 0.10	2.43 ± 0.49	8.30 ± 2.80	90.60 ± 21.10
MSH	2.80 ± 0.10	2.20 ± 0.25	7.20 ± 1.80	78.70 ± 10.20
TPC	2.37 ± 0.15	2.07 ± 0.12	5.00 ± 0.90	83.40 ± 3.40
Grand Mean (± SD)	2.65 ± 0.24	2.23 ± 0.18	6.83 ± 1.78	84.30 ± 6.37

Values in each row represent the mean (± SD) for each study site.

3.2. Heavy Metal Concentrations

Analysis of heavy metal concentrations revealed that zinc (Zn) averaged 140.56 ± 1.25 µg/L, copper (Cu) at 207.78±10.25 µg/L, lead (Pb) at 16.62±0.21 µg/L, and manganese (Mn) at 200±7.22 µg/L across the study sites (Table

3). TPC showed the highest levels of zinc (145 µg/L) and manganese (220 µg/L), suggesting higher contamination in this region, which could impact mangrove health. Elevated concentrations of zinc, copper, lead, and manganese suggest pollution stress, especially at TPC. These levels are concerning for mangrove health as they can interfere with nutrient uptake and metabolic processes, relating to the study's objective of assessing contamination impact.

3.3. Mangrove Growth Metrics

Mangrove height measurements indicated robust growth, with averages of 2.7 ± 0.10 m for SVPP, 2.8 ± 0.10 m for MSH, and 2.37 ± 0.15 m for TPC. The overall mean height across study sites was 2.65 ± 0.24 m (Table 4). Additionally, crown diameter measurements averaged 2.43 ± 0.49 m in SVPP, 2.2 ± 0.25 m in MSH, and 2.23 ± 0.18 m in TPC (Table 4). The growth metrics indicate that mangrove populations are currently stable, showing neither significant improvement nor high decline despite the pollution risks. In conclusion, the study revealed that TPC had the highest concentrations of heavy metals, with zinc at 145 µg/L and manganese at 220 µg/L, indicating potential localized pollution stress. MSH exhibited the highest moisture content (67.56%), while the lowest pH was observed in water samples from TPC (5.8) and soil from MSH (5.2). Mangrove growth was generally robust, with the tallest trees at MSH (2.8 m) and the largest crown volume at SVPP (8.3 m^3). However, the data suggest that the higher pollution levels at TPC may limit mangrove adaptation and growth, highlighting the interaction between pollution and environmental factors.

4. Discussion

The mangrove systems at SVPP, MSH, and TPC provide a perspective on the compounded anthropogenic pressures these ecosystems endure, arising from a multitude of local and regional factors. The pH values in water, soil, and plant samples indicate slightly acidic conditions across all study sites, with a consistent mean water pH of 5.93 (Table 1). Acidic environments enhance metal solubility, allowing for greater uptake by plants and posing potential toxicity risks (McBride and Blasiak, 1979). Such acidic conditions often lead to detrimental effects, including oyster kills, fish disease, and loss of native vegetation (Sammut et al., 1996). This acidification possibly because of the pollutants from traffic emissions from Mumbai-Satara Highway, APMC market, Turbhe MIDC, and other nearby sources could signify an increased susceptibility to stress and hindered growth for mangrove fauna. The water samples from this region also displayed high salinity, which amplifies the impact of acidic pH by increasing ion exchange and, consequently, the mobility of metals. Similar findings are seen in urbanized zones where acidity-amplifying pollutants, including street solids and sewer-deposited materials, were linked to environmental degradation and reduced vegetation health (Field et al., 1982; Novotny and Olm, 1994; Bang et al., 1997) This study is, therefore, among the first to demonstrate that the pollutants from Mumbai-Satara Highway, Turbhe MIDC and other regions in Vashi, Navi Mumbai, not only acidify mangrove habitats but also synergistically amplify overall pollution, providing a perspective on how localized urban stressors threaten mangrove resilience.

The accumulation of Cu, Zn, Pb, and Mn was examined in this study, as these are frequently detected in estuarine environments due to urban and industrial pollutants, particularly from urban runoff (Mills, 1995; Peters et al., 1997). Sources such as street solids and sewer-deposited material are major contributors to metal pollutants in urban runoff, intensifying the influx of contaminants into estuarine systems (Houhou et al., 2009). Such metal pollutants that are primarily accumulated in root tissues likely weaken pneumatophore structures, which are essential for oxygen exchange in waterlogged soils (Peters et al., 1997; Kryger and Lee, 1996). For instance, Cu and Zn demonstrated notable correlations with reduced plant height (-0.727, $p < 0.01$ and -0.884, $p < 0.001$, respectively) (Figure 3a and Table 5), suggesting that metal pollutants contribute to growth impairment in mangrove species.

The elevated concentrations of Zn, Cu, Pb, and Mn not only reflect the influence of urban runoff but also underscore the physiological and biochemical disruptions that occur in response to metal accumulation within the rhizosphere and aboveground tissues (Chaudhuri et al., 2014). Given the pronounced negative correlations observed between Cu and Zn and reduced plant height (Table 5), it is plausible to hypothesize that these metals, while biologically requisite in trace amounts, elicit deleterious effects through oxidative stress pathways (Machado et al., 2005; Marchand et al., 2011). This oxidative imbalance may interfere with growth-regulatory pathways, indicating a threshold beyond which metal assimilation transitions from a defensive to a cytotoxic mechanism (Kosiorek and Wyszkowski, 2020). While adaptive traits like metal sequestration are seen in mangroves, prolonged exposure to high concentrations of Cu, Zn, Pb, and Mn might, therefore, lead to sublethal effects on reproductive success and hinder the regeneration potential, and could be a critical area for future research.

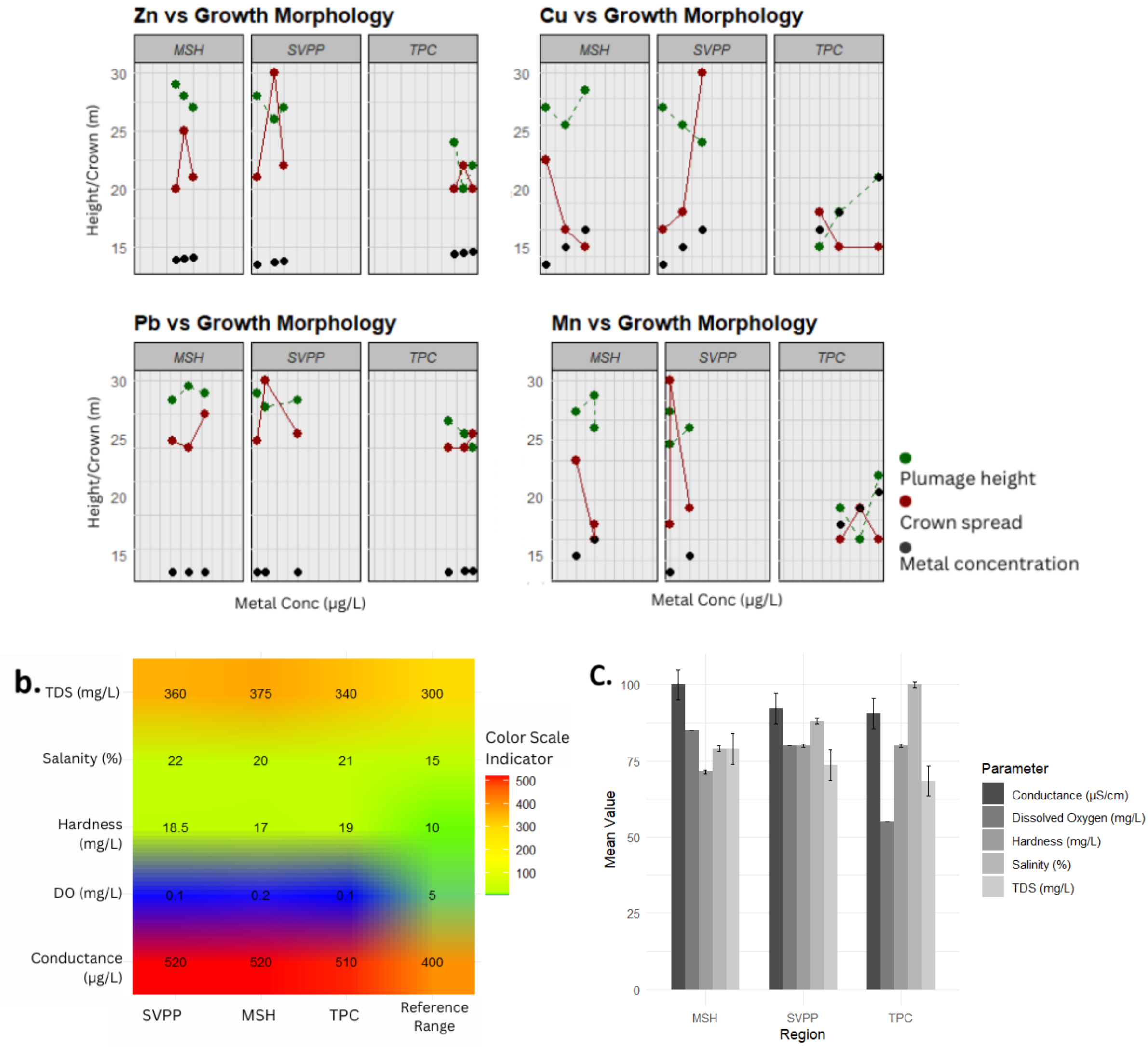

Figure 4. (a.) Relationship between Plumage Height and Crown Diameter vs. Concentrations of (i) Zn, (ii) Cu, (iii) Pb, (iv) Mn. This shows negative correlations between metal levels and height, strongest for Zn ($r = -0.88$, $p < 0.001$), indicating metal toxicity likely inhibits growth. (b.) Heatmap of TDS, Salinity, Hardness, DO, and Conductance across MSH, SVPP, and TPC compared to approximate reference range derived from a synthesis of available literature and online sources for contextual relevance. High variability is noted in TDS and salinity, with DO consistently lower than the reference range. (c.) Bar graph illustrating mean values for Conductance, DO, Hardness, Salinity, and TDS across study sites. Data were normalized to ensure comparability across scales

Table 5. Statistical relationships between heavy metals and mangrove growth and morphology metrics.

Variable	Height Correlation (r)		Crown Correlation (r)	P-Value (Height)	P-Value (Crown)
Zn	-0.8846621	***	-0.24407825	< 0.001	0.301
Cu	-0.7272871	**	-0.07576539	< 0.01	0.854
Pb	-0.701945	*	-0.08103345	< 0.05	0.83
Mn	-0.7593264	**	-0.13189734	< 0.01	0.617

* = Moderately Significant ($p < 0.05$); ** = Significant ($p < 0.01$); *** = Highly Significant ($p < 0.001$).

The recently built establishments nearby like the Turbhe MIDC industrial complex, Navi Mumbai Special Economic Zone (SEZ), and Mumbai-Satara Highway (NH 66), might have largely contributed to the aforementioned observations in this region. Historical events, such as the 2005 Mumbai floods, may have also played a pivotal role, as these floods resulted from intense rainfall and poor urban planning, leading to substantial sediment runoff and pollution in coastal areas of interest. The degradation of mangrove ecosystems, compounded by such events and nearby industrial developments, aligns with global trends of mangrove decline, where forested areas have dwindled from an estimated 225,000 km² in the 1970s to approximately 137,000 km² by 2014 (Friess et al., 2019). In response, several countries have committed to restoring coastal wetlands, including mangroves through, for example, their Nationally Determined Contributions (NDCs), aiming to support climate adaptation and mitigation (Ministry of Environment, Forest and Climate Change, 2022). Efforts like these alongside practices like seed dispersal, supply of nutrient-rich soil, stormwater filtration systems at the Vashi railway station, Metal-tolerant mangrove nurseries near Vashi industrial complexes, buffer zones between mangrove ecosystems and nearby residential settlements, updated urban development policies in the Navi Mumbai special economic zones (SEZ) may also prove effective.

5. Conclusion

The findings from this study reveal significant environmental stressors impacting mangrove ecosystems at SVPP, MSH, and TPC. The observed correlations between heavy metals and growth metrics underscore the potential biochemical disruptions, likely through oxidative stress pathways, affecting plant health. To build on these findings, further research is needed to investigate long-term resilience mechanisms, including biochemical and physiological pathways, that enable mangroves to tolerate heavy metal stress and acidic conditions. While mangroves demonstrate resilience, the ecosystem's vulnerability is heightened by urban and industrial pressures. Restoration initiatives—such as establishing protective buffer zones, nutrient enhancement, and replanting—are essential to mitigate degradation. By adopting these measures, we can support mangrove resilience, contributing to broader climate adaptation and local biodiversity preservation efforts.

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