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Riparian Vegetation as Bioindicator of Heavy Metal Contamination and Soil Nutrient Dynamics in Vamanapuram River, Kerala

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Abstract: This study examines the relationship between riparian vegetation, soil nutrient dynamics, and heavy metal contamination along a 15 km stretch of the Vamanapuram River, Kerala. Six sites representing a gradient of anthropogenic disturbance were assessed through quadrat-based vegetation surveys and comprehensive soil chemical analysis, including macro- and micronutrients (K, Ca, Mg, B, Mn, Cu, Zn) and heavy metals (Hg, Pb, As, Ni, Cd, Cr, Bi, Ga) using ICP-MS. A total of 102 plant species belonging to 45 families were recorded, with Fabaceae and Poaceae dominating across the vegetated sites. Species diversity and abundance were highest at moderately disturbed sites Maveli Nagar (Site 2) and Vamanapuram Bridge (Site 3), which coincided with balanced soil nutrient profiles and lower levels of heavy metals. Conversely, Site 6 (Melattumoozhi), heavily impacted by soil dumping, exhibited minimal vegetation and the highest concentrations of mercury (0.41 mg/kg), arsenic (74.8 mg/kg), and gallium (133 mg/kg). Principal Component Analysis (PCA) revealed that PC1 (45.2% variance) was associated with heavy metal concentrations, while PC2 (27.6%) captured nutrient variability, particularly boron and calcium. Vegetated sites clustered distinctly from polluted sites in the PCA biplot, emphasizing a strong inverse relationship between vegetation cover and metal contamination. The study underscores the role of riparian vegetation as a bioindicator of soil quality and a regulator of contamination. Restoration and conservation of riparian buffers are essential for sustaining soil health and mitigating the ecological impacts of anthropogenic activities along tropical riverine systems.

Keywords: Riparian vegetation, Heavy metals, Soil nutrients, PCA, Vamanapuram River

Riparian zones are ecologically dynamic transition areas located along the margins of rivers, streams, and floodplains. These zones are characterized by unique combinations of vegetation, hydrological regimes, and soil properties that distinguish them from surrounding upland ecosystems (Okeke et al., 2022). This distinctiveness arises from variations in topographical gradients and increased moisture availability, fostering diverse habitats and biological productivity (Mikkelsen and Vesho 2000).

The soils in riparian zones are highly heterogeneous in their chemical composition, influenced by prolonged saturation, periodic inundation, and the bidirectional transfer of nutrients from terrestrial uplands and adjacent aquatic systems (Vidon et al., 2010). Frequent flooding and water level fluctuations slow the accumulation of organic and inorganic materials, often inhibiting the development of structured soil horizons (Mikkelsen and Vesho, 2000; Klemas, 2014). These processes contribute to the fertility and ecological complexity of riparian environments. Riparian zones serve as crucial ecological buffers that enhance water quality, stabilize stream banks, and support a rich diversity of aquatic and terrestrial species. Positioned at the interface between land and water, these zones regulate the flow of nutrients, intercept pollutants, and act as corridors for species migration and habitat connectivity (Liu et al., 2014).

The Vamanapuram River, locally known as “Attingalaru” or “Kollambuzhayaru”, originates from the Chemunji Mottai Hills (1,860 m above MSL) and flows westward through the Thiruvananthapuram district to the Anchuthengu backwaters. It serves as a vital freshwater source for the region. However, the river's catchment area is increasingly affected by anthropogenic activities, including rapid urbanization and agricultural expansion (notably rubber and oil palm plantations). These disturbances have led to growing concerns about heavy metal accumulation in the riparian zone, threatening both plant health and ecological stability.

Heavy metals such as mercury, arsenic, lead, and chromium enter riparian soils primarily through human activities including construction, agricultural runoff, and improper waste disposal (Vidon et al., 2010). These toxic elements impair plant growth, alter species composition, and reduce overall biodiversity. As the soil serves as a biologically active medium essential for supporting life, its contamination poses serious threats to ecological integrity and food security (Singh et al., 2010; Sarwar et al., 2017).

Riparian vegetation plays a pivotal role in maintaining river ecosystem health. Dense and fast-growing plant communities along water bodies enhance soil structure, increase porosity, and reduce erosion through their root systems, which anchor soil and buffer streambanks against water flow (Nielsen et al., 2014). Additionally, riparian plants filter surface runoff, intercept sediment, and prevent excessive deposition into watercourses (Fernandes et al., 2016, Hould-Gosselin et al., 2016). However, despite access to perennial groundwater, these plants may also experience water stress during periods of reduced availability or increased evapotranspiration demand (Singer et al., 2013). The objective of this study is to examine the relationship between riparian vegetation structure, soil nutrient dynamics and heavy metal contamination along the Vamanapuram River to underscore the role of riparian plant communities as a bioindicator of soil quality and a regulator of environmental contamination, thereby reinforcing the need for their conservation and restoration.

MATERIAL AND METHODS

Study area: The present study was carried out along the riparian corridor of the Vamanapuram River, situated in Thiruvananthapuram district, Kerala, India. The river originates from the Chemunji Mottai hills and flows westward through Vamanapuram Panchayat. Six sites were selected along 15 km stretch of the river (Table 1), encompassing varying degrees of anthropogenic influence, including agricultural runoff, soil dumping, and urban encroachment. Site 6, characterized by significant disturbance and minimal vegetation, was designated as the control site.

Table 1. Sampling locations

Site	Sampling points	Latitude	Longitude
Site 1	Perunthra	8° 43' 17" N	76° 53' 15"E
Site 2	Maveli Nagar	8° 43' 15" N	76° 53' 35" E
Site 3	Vamanapuram Bridge	8° 43' 35" N	76° 53' 50"E
Site 4	Balikkadavu	8° 43' 28" N	76° 53' 03" E
Site 5	Nedumparambu	8° 43' 20" N	76° 54' 35"E
Site 6	Melattumoozhi	8° 42' 43" N	76° 55' 26" E

Vegetation sampling: Vegetation analysis was conducted using the quadrat method. At each of the five vegetated sites, four quadrats measuring 10 m × 10 m were laid out perpendicular to the river channel, resulting in a total of 20 quadrats. Plant species within each quadrat were taxonomically identified, counted, and recorded. Site 6 lacked sufficient vegetation and was excluded from the floristic survey. Data on species richness, abundance, and family representation were compiled to assess the composition and structure of riparian plant communities.

Soil sampling and laboratory analysis: Soil samples were collected from the top 15 cm of the riverbank at each of the six study sites using standard composite sampling techniques. Five sub samples per site were homogenized, air dried, ground, and sieved (2 mm mesh) to produce one representative sample per location (500 g). Samples were stored in sealed polyethylene bags for chemical analysis (APHA 2005). Soil macro and micronutrients (potassium, calcium, magnesium, boron, manganese, copper, and zinc) as well as heavy metals (mercury, lead, arsenic, nickel, cadmium, chromium, bismuth, and gallium) were analysed using Inductively Coupled Plasma Mass Spectrometry (ICP-MS; iCAP Q, Thermo Fisher Scientific). Calibration was performed using ICP Multielement Standard VI (Merck), and all measurements were reported in mg/kg dry weight.

Data analysis: Data analysis was performed using PAST 4.03 (Paleontological Statistics Software Package) and Microsoft Excel 2019. To identify patterns in soil nutrients and heavy metals to assess their relationship with riparian vegetation structure, Principal Component Analysis (PCA) was conducted using PAST 4.03. The input data matrix included standardized values of soil nutrients and heavy metals from the six sampling sites. PCA was based on a correlation matrix, and components with eigenvalues greater than 1 were retained for interpretation. Biplots were produced to visualize site clustering and variable loadings, thereby highlighting the dominant gradients influencing soil chemical variability.

RESULTS AND DISCUSSION

A total of 102 plant species were recorded across the riparian study sites, with species diversity increasing in the order: Site 1 (Perunthra) < Site 4 (Balikkadavu) < Site 5 (Nedumparambu) < Site 2 (Maveli Nagar) < Site 3 (Vamanapuram Bridge). The highest species density and abundance were observed in Sites 2 and 3, while Sites 1 and 4 exhibited the lowest. Fabaceae family was the most dominant, indicating its adaptability and ecological importance in riparian environments. The structure and composition of plant communities appeared to be closely linked to soil conditions, with nutrient-rich sites supporting a greater diversity of vegetation. The growth and health of riparian plants were influenced by the concentration and balance of essential nutrients such as nitrogen, phosphorus, and potassium, which play key roles in physiological processes like cell division, root development, and photosynthesis. Sites with well-balanced nutrient profiles exhibited more robust and diverse plant growth, while areas with nutrient imbalances showed reduced vegetation and signs of ecological stress (Liu et al., 2014, Hale et al., 2018)

Vegetation analysis: A total of 102 riparian plant species belonging to 45 families were recorded along the Vamanapuram River. The flora comprised a diverse mix of herbs, shrubs, trees, and climbers, with a predominance of herbaceous taxa. The most represented families were Fabaceae, Asteraceae, Poaceae, and Lamiaceae, highlighting their adaptability to riparian conditions. Frequently occurring species across the sites included *Mimosa pudica*, *Phragmites karka*, *Melastoma malabathrium*, *Hyptis suaveolens*, *Glyricidia sepium*, *Caryota urens*, *Tridax procumbens*, *Synedrella nodiflora*, and *Adiantum raddianum*, indicating wide ecological tolerance.

Site wise analysis revealed substantial variation in species composition influenced by anthropogenic pressure. Site 1, with 43 species from 22 families, showed reduced vegetation, dominated by grasses and a few woody plants due to disturbances such as grazing and bathing. Site 2, least disturbed, hosted 61 species from 32 families, including abundant riparian taxa like *Pandanus odoratissimus* and *Hyptis capitata*. Site 3 was the most floristically rich, with 64 species from 31 families and a high density of bamboos and ferns, notably *Bambusa bambos* and *Adiantum raddianum*. Site 4, under greater human impact, recorded only 44 species, dominated by disturbance-tolerant plants such as *Amaranthus spinosus* and *Hyptis capitata*. Site 5 supported 58 species across 28 families, marked by abundant grasses and bamboos (*Bambusa vulgaris*, *Phragmites karka*). Site 6, used as a control, was devoid of vegetation due to recent soil disturbances and hence excluded from vegetative analysis.

Analysis of the presence - absence matrix emphasized species specific spatial patterns. Certain species were restricted to single sites, such as *Barringtonia racemosa* and *Spondias pinnata*, suggesting localized habitat preferences (Table 2). In contrast, several taxa were consistently present across multiple sites, serving as indicators of general riparian adaptability. The vegetation structure and diversity were closely linked to underlying soil conditions and disturbance intensity, reinforcing the role of riparian zones as biodiversity hotspots and sensitive indicators of environmental change.

Soil nutrient analysis: The analysis of soil nutrients across the six sites along the Vamanapuram River demonstrated substantial variability in both macro- and micronutrient concentrations, which showed a strong correlation with the density and diversity of riparian vegetation. Potassium (K) levels were high across all sites, ranged from 12,721 mg/kg in Site 2 to 17,063 mg/kg in Site 1, indicating either naturally elevated levels or enrichment from agricultural runoff. Even the sparsely vegetated Site 6 recorded a high potassium concentration of 15,141 mg/kg. Calcium (Ca) levels varied more significantly, with the highest concentration observed in Site 6 (1,642 mg/kg), which had minimal vegetation, while Sites 2 and 3 characterized by rich plant diversity, recorded lower calcium levels of 389 mg/kg and 711 mg/kg, respectively. This suggests that excessive calcium may hinder plant nutrient uptake and root development, thereby restricting vegetation growth, whereas moderate calcium availability appears to support healthier and more diverse riparian plant communities. Radar chart (Fig. 1) illustrates the normalized average concentrations of soil nutrients across the study sites, highlighting major contributors like potassium**,** magnesium, and manganese, which dominate the soil nutrient profile.

Heavy metal analysis: Heavy metals like mercury, arsenic, lead, nickel, bismuth, gallium, cadmium, and chromium were analysed in this study. Heavy metals in the environment are problematic and pose a threat to human health, the heavy metals are increasing in the order mercury <cadmium <bismuth <lead <arsenic <gallium <nickel <chromium (Table 4).

The heavy metal analysis of soil samples from the riparian zones along the Vamanapuram River revealed significant spatial differences, largely driven by varying levels of human disturbance at each site. Site 6, which was most affected by activities such as soil dumping and construction, exhibited the highest concentrations of nearly all heavy metals measured. Specifically, mercury was recorded at 0.41 mg/kg, lead at 49.7 mg/kg, arsenic at 74.8 mg/kg, chromium at 319 mg/kg, and gallium at 133 mg/kg. These values were substantially higher than those at other sites and far exceeded typical background levels for uncontaminated soils. In contrast, Sites 2 and 3, which had richer vegetation and less disturbance, showed comparatively lower levels of these metals. The study indicate that anthropogenic pressures significantly contribute to heavy metal accumulation in riparian soils, with the highest contamination observed in areas lacking vegetative cover. Radar chart displayed the normalized average concentrations of heavy metals across the six study sites showing chromium, nickel, and gallium in the highest level (Fig. 2).

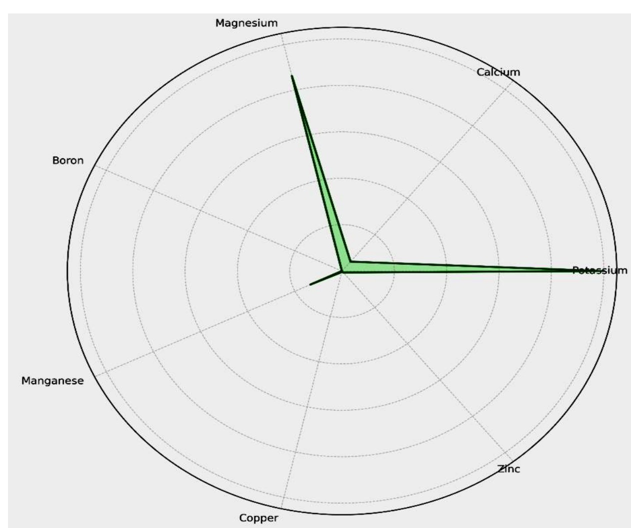

Fig. 1. Radar chart of soil nutrients

Table 2. Riparian plants along Vamanapuram River

Botanical name	Local name	Site 1	Site 2	Site 3	Site 4	Site 5
Adiantum raddianum	Maiden hair	√	√	√	√	√
Acacia caesia	Inja	√		√	√	
Adenanthera pavonina	Manjadi		√	√	√	√
Alstonia scholaris	Ezhilam paala		√			√
Anacardium occidentale	Kashumaavu		√			√
Orthosiphon aristatus	Poochameesa		√	√	√	
Curcuma amada	Mangayinji			√	√	
Areca catechu	Kavungu			√		
Artocarpus hetrophyllus	Plaavu	√			√	
A. hirsutus	Ayani maram		√		√	√
Argyreia hirsuta	Samudrappacha		√	√		
Synedrella nodiflora	Mudiyan pacha	√	√	√	√	√
Bambusa bambos	Mula	√		√	√	√
B. vulgaris	Manja mula	√			√	√
Bauhinia malabarica	Vellamandaram		√	√		
Tridax procumbens	Chiravanaakku	√	√	√	√	√
Biancaea sappan	Pathimukham		√			
Calophyllum calaba	Cherupunna				√	
Caryota urens	Olatti	√	√	√	√	√
Cinnamomum malabatrum	Vazhana	√				√
C. riparium	Aattuvayana	√	√			
Clerodendron infortunatum	Peringalam		√	√		√
Cassia fistula	Konnamaram		√	√		
Cyclea peltata	Paadathali		√	√		√
Acmella ciliata	Palluvedana chedi		√	√	√	√
Blumea axillaris	Kukkura		√	√		√
Cyanthillium cinereum	Poovamkurunila		√	√		
Emilia sonchifolia	Muyal cheviyan		√	√	√	√
Ficus hispida	Therakam	√				
Garcinia gummi-gutta	Kodampuli			√		
Stachytarpheta indica	Seemakongini		√	√		√
Glyrricedia maculata	Seemakkonna	√	√	√	√	√
Glycosmis pentaphylla	Kurumpannal			√		√
Heliconia rostrata	Vazhachedi		√			√
Hibiscus tiliaceus	Thaipparuthi			√		√
Holigarna arnottiana	Chaaru		√	√		
Amaranthus spinosus	Mullan cheera				√	√
Carica papaya	Papaya		√	√		
Humboldita vahliana	Aattuvanchi	√	√			√
Urena lobata	Uthiram		√		√	√
Hydnocarpus pentandra	Marotti			√		
Hyptis suaveolens	Naattappoochedi	√	√	√	√	√
Ixora coccinea	Vella Thetti		√	√		√
Justicia adhatoda	Aadalodakam	√	√	√		
Ludwigia perennis	Neerkarayambu	√			√	√
Lagerstroemia speciosa	Manimaruth			√		
Lawsenia inermis	Mylanchi		√			

Cont...

Table 2. Riparian plants along Vamanapuram River

Botanical name	Local name	Site 1	Site 2	Site 3	Site 4	Site 5
Leea indica	Choriyanthali	√				
Tragia involucrata	Kodithoova		√	√		√
Madhuca neriifolia	Aattilippa	√	√			
Pilea microphylla	Mathilppacha		√	√		
Desmodium triflorum	Nilamparanda	√	√	√		√
Clitoria ternata	Shankhupushpam		√	√		√
Melastoma malabathrium	Kalambatty	√	√	√	√	√
Mikania micrantha	Drutharashtrappacha	√		√	√	√
Mollotus philippensis var. philippensis	Kumkumam		√	√		
Mussaenda frondosa	Musanda		√	√		√
Myristica beddomei	Jaathi		√			
Crotalaria angulata	Kilukilukki			√	√	
Ochlandra travancoria	Eetta	√			√	
Ochlandra wightri	Eera	√			√	√
Senna alata	Aana thakara	√				√
Tinospora cordifolia	Chittamruth			√	√	
Palms	Pana		√	√		
Pandanus odoratissimus	Kaitha		√		√	√
Pennisetum polystachion	Poochavalan pullu	√			√	√
Persea macrantha	Uuraavu	√		√		√
Phragmites karka	Pullu	√	√	√	√	√
Piper nigrum	Kurumulaku		√			
Polycarpae corymbosa	Akkaramkolli			√		
Polyalthia longiflora	Aranamaram	√	√			√
Cynodon dactylon	Karuka					√
Crateva magna	Neermathalam			√		
Ricinus communis	Aavanakk	√		√	√	
Saccharum officinarum	Karimb				√	
Senna tora	Pon thakara		√	√	√	
Barringtonia racemosa	Samudrakkaya					√
Syzigium cumini	Njaval	√				√
Tiliacora acuminata	Valli kanjiram	√	√	√		
Solanum torvum	Chunda	√	√	√	√	
Spondias pinnata	Ambazham					√
Saccharum spontaneum	Choottapullu	√			√	√
Tabernaemontana divaricata	Paala	√	√	√		
Tamarindus indica	Pulimaram	√		√		
Pothos scandens	Paruvakkodi		√	√		√
Tectona grandis	Thekk		√	√		√
Terminalia bellinica	Thaanni					√
Tetracera akara	Nannalvalli			√		
Thespesia populnea	Cheelanthi	√				
Trema orientalis	Aamathaali		√	√	√	√
Trewia nudiflora	Thavalamaram			√		
Eclipta prostrata	Kayyonni	√	√	√		√
Colocasia esculenta	Thaalu		√	√	√	√
Panicum maximum	Kuthirappullu	√	√		√	√
Ziziphus oenopolia	Thodali		√	√	√	√
Terminalia catappa	Badaam	√	√		√	√
Sphagneticola calendulaceae	Manjakkanjunni	√		√	√	√
Memecylon umbellatum	Kaashaavu		√			
Mimosa diplotricha	Aanathottavadi	√		√	√	
Mimosa pudica	Thottavaadi	√	√	√	√	√
Lantana camara	Kongini	√	√			√
Hyptis capitata	Mittayi chedi		√	√	√	√

Principal component analysis: The first principal component (PC_1) accounted for 45.2% of the total variance and was strongly influenced by elevated concentrations of heavy metals, particularly mercury (0.82), arsenic (0.78), copper (0.75), and gallium (0.74), with zinc (0.65) contributing moderately. This axis reflects the pollution gradient among the sites. The second component (PC_2) contributed 27.6% of the variance and was driven predominantly by boron (0.88) and calcium (0.85), representing nutrient related variation. Zinc (0.48) also loaded moderately on PC_2, suggesting its overlapping association with both nutrient and pollution profiles. Combined, PC_1 and PC_2 explained 72.8% of the total variance, while PC_3 contributed an additional 12.1%, yielding a cumulative explanation of 84.9%.

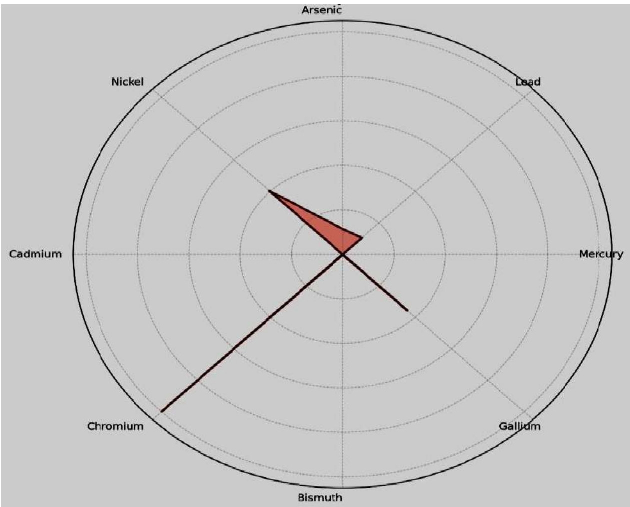

Fig. 2. Radar chart of heavy metals

The PCA biplot effectively separated the study sites based on their underlying soil chemistry (Fig. 3). Site 6 showed the highest score on PC_1, indicating pronounced heavy metal presence. Site 2 aligned positively with PC_2, corresponding to nutrient richness. Sites 3 and 5 formed a central cluster, reflecting balanced nutrient metal conditions, whereas Site 1 was positioned with low scores on both axes. The variable vectors revealed strong influences of gallium, manganese, and arsenic in differentiating the sites, emphasizing their role in driving spatial heterogeneity in riparian soil chemistry.

The findings from this study provide a comprehensive understanding of the interactions between riparian

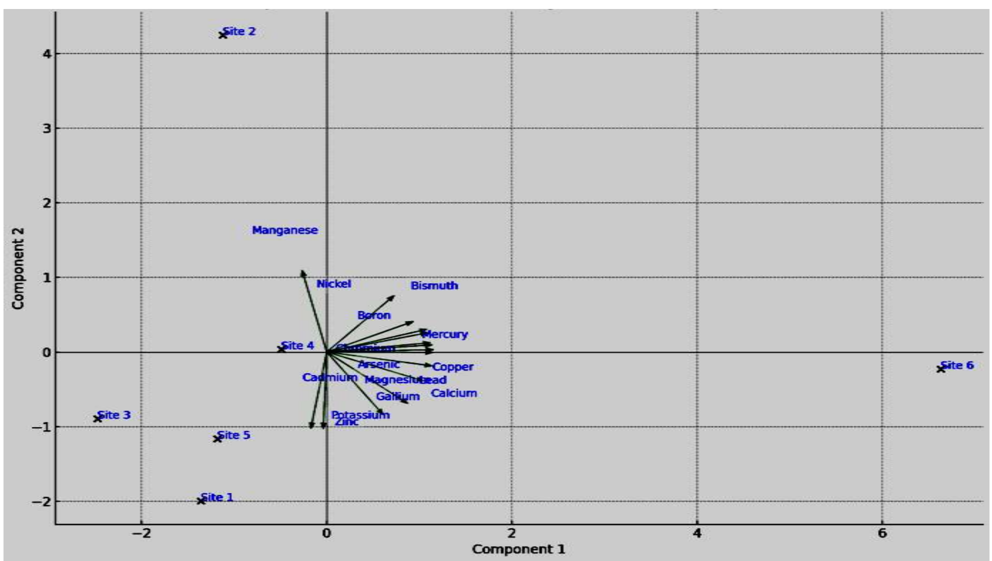

Fig. 3. Principal component analysis biplot of soil nutrients and heavy metals

Table 3. Status of soil nutrients

Nutrients (mg kg^{-1})	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6
Potassium	17063	12721	14783	14312	17052	15141
Calcium	849	389	711	616	514	1642
Magnesium	14929	9364	10754	13969	14151	15370
Boron	9.62	11.3	8.51	12.1	9.54	15.3
Manganese	1597	3610	1931	1630	1710	1636
Copper	64.1	67.9	61.9	62	62.4	97.0
Zinc	124.1	101	121	132	123	148

vegetation, soil nutrient dynamics, and heavy metal contamination along the Vamanapuram River. Sites with rich riparian vegetation, notably Sites 2 and 3, exhibited high species diversity and plant abundance, particularly from families such as Fabaceae and Poaceae, indicating their resilience and ecological adaptability (Baptista et al., 2020). These sites also showed comparatively lower concentrations of toxic heavy metals, suggesting that vegetation plays a vital regulatory role by acting as a natural buffer that reduces pollutant inflow and enhances soil health. In contrast, Site 6, which had minimal vegetation due to soil dumping and developmental disturbances, recorded the highest levels of heavy metals, including mercury (0.41 mg/kg), lead (49.7 mg/kg), arsenic (74.8 mg/kg), chromium (319 mg/kg), and gallium (133 mg/kg). This pattern indicates that in the absence of riparian plant cover, the soil becomes increasingly vulnerable to contamination, lacking the biological filtration and root systems that would otherwise intercept and stabilize pollutants (Sharma et al., 2018; Tchounwou et al., 2012).

Riparian plants also contribute to phytoremediation, a process through which certain species absorb and immobilize heavy metals, thereby improving soil conditions over time (Brdar et al., 2020). However, when concentrations of heavy metals exceed physiological thresholds, they become toxic to plants, inhibiting growth, altering species composition, and in severe cases, leading to mortality (Alloway 2013). This creates a feedback loop in which vegetation loss worsens contamination, while contamination itself further limits vegetation, ultimately degrading the ecological stability of the riparian zone.

Micronutrient patterns also correlated with vegetation health. Boron (B) levels, although below toxic thresholds, were highest in Site 6 (15.3 mg/kg) and lowest in Site 3 (8.51 mg/kg), suggesting accumulation in disturbed soils (Nable et al., 1997). Manganese (Mn) peaked in Site 2 (3,610 mg/kg), likely due to organic matter decomposition enhancing Mn solubility under acidic conditions. Despite these high levels, lush vegetation persisted in Site 2, possibly due to the presence of Mn tolerant species. Copper (Cu) and zinc (Zn) concentrations were notably high in Site 6 (97.0 mg/kg and 148 mg/kg, respectively), exceeding WHO's permissible limits. These elevated values suggest anthropogenic inputs such as construction debris and landfill materials as potential contamination sources.

The overall nutrient profile revealed that sites with moderate and balanced concentrations of macro and micronutrients (Sites 2 and 3) supported higher species richness and healthier plant communities. In contrast, nutrient imbalances and extreme values, especially in Site 6, correlated with reduced vegetation (Hale et al., 2018). This underscores the importance of maintaining nutrient equilibrium in riparian soils for sustaining vegetation structure and ecosystem services. The analysis of riparian soils revealed elevated concentrations of heavy metals particularly Pb, Cd, Cr, and Ni, indicative of pronounced anthropogenic influence stemming from agricultural inputs and unregulated waste discharge. Site-specific variations, such as the high Pb and Cr levels, highlight localized zones of contamination that can significantly disrupt riparian plant communities. These metals are known to impair physiological processes in plants, influencing growth, reproduction, and overall species composition. Notably, the elevated Ni concentration at Site 2 (130 mg/kg) did not correspond with reduced vegetation cover, suggesting a degree of metal tolerance or adaptive resilience among native flora, especially within the Fabaceae family. This points to their potential utility in phytoremediation strategies (Brdar et al., 2020).

Trace elements like Cu and Zn, while essential for plant metabolism, can exert toxic effects when present in excess, leading to enzymatic inhibition and photosynthetic disruption (Alloway 2013). The observed pattern of higher metal accumulation in sparsely vegetated zones and lower levels in areas with dense vegetation cover underscores a reciprocal relationship between metal pollution and plant community health. In this context, vegetation degradation appears not only as a consequence of contamination but also as a contributing factor, given the loss of natural buffering capacity. These dynamics emphasize the dual role of riparian vegetation in both mitigating and reflecting environmental stress, reinforcing the urgency of conservation-based

Table 4. Status of soil heavy metals

Heavy metals (mg kg^{-1})	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6
Mercury	0.04	0.07	0.04	0.05	0.04	0.41
Lead	21.8	28.8	27.1	27.7	28.2	49.7
Arsenic	23.9	15.2	15.6	35.4	22.8	74.8
Nickel	111	130	99.3	118	116	129
Cadmium	0.20	0.09	0.21	0.12	0.19	0.16
Chromium	289	294	272	287	281	319
Bismuth	0.36	0.74	0.43	0.41	0.71	1.03
Gallium	95.2	97.8	97.2	96.2	96.5	133

management (Liu et al., 2019, Selvi et al., 2019, Prodipto et al., 2024). Riparian vegetation provides vital ecological functions including riverbank stabilization, erosion control, runoff filtration, and habitat support. The dense root networks reduce sediment displacement and buffer pollutants, thus improving water quality and soil structure (Hould-Gosselin et al., 2016, Fernandes et al., 2016). In the context of the Vamanapuram River, areas with robust riparian vegetation were consistently associated with improved soil quality and reduced metal toxicity, reinforcing their importance in maintaining ecological balance and buffering against anthropogenic disturbances.

CONCLUSION

This study reveals an intricate link between riparian vegetation, soil chemistry, and contamination along the Vamanapuram River. Spatial analysis showed that sites with intact vegetation had more balanced nutrient profiles and lower concentrations of toxic heavy metals, while highly disturbed zones exhibited severe contamination and vegetation loss. Principal component analysis (PCA) successfully distinguished pollution-dominated sites Melattumoozhi (Site 6) from nutrient-rich, vegetated sites Maveli Nagar and Vamanapuram Bridge (Site 2 , 3), reinforcing the sensitivity of riparian zones to anthropogenic pressures. These findings underscore the necessity of conserving riparian buffers as ecological safeguards to mitigate contamination risks and ensure the long-term stability of tropical riverine ecosystems.

AUTHOR'S CONTRIBUTIONS

Sruthy Krishna M R was responsible for the core research activities, including field investigation, data collection, statistical analysis, and the initial drafting of the manuscript. Dr. Alexander T, as the corresponding author, provided the overall conceptualization of the study, supervised the project, and was responsible for the final manuscript review and submission. Dr. Anila George contributed by providing methodological guidance, aiding in data interpretation, and assisting with the manuscript review and editing processes**.**

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