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Tables 1 to 3 are available in the Supplementary Files section.

Distribution and Ecological Risk Assessment of Heavy Metals in the Sediments along the Indian Coast

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Abstract

Metal contamination in sediments remains a significant environmental challenge, highlighting the need for comprehensive assessments to evaluate pollution levels and develop effective remediation strategies. Therefore, sediment quality and ecological risk indices were derived from the metal concentrations in the coastal sediments of India. Overall, mean values indicate metal concentrations are higher in the sampling sites on the west coast than on the east coastal sites. Similarly, the organic and inorganic carbon levels are higher on the west coast than on the east coast. Metal concentrations are higher in Goa, Maharashtra, and Kerala compared to, Odisha, and West Bengal. Statistical analyses including correlation, DFA, RDA, and PCA reveal strong associations between sediment metals and carbon, indicating co-deposition mechanisms influenced by organic matter and fine-grained particles. Geographic variation accounts for over 70% of the total multivariate variance, with Cadmium, Lead, and Zinc posing ecological risk, while Copper and Chromium reflect anthropogenic influence. Overall PLI results suggest that most coastal sediments remain unpolluted. Mostly the levels of Manganese, Zinc, and Cobalt found within sediment quality thresholds, although Copper and Chromium observed with elevated levels at few sites. In contrast, toxic metals such as Cadmium and Arsenic reaching concentrations indicative of significant ecological concern exhibiting more frequent and substantial enrichments along with Lead, and Nickel. These patterns demonstrate that certain toxic metals can persist and accumulate in coastal sediments despite natural dispersion. Overall, the findings emphasize the need for coordinated, large-scale monitoring to identify contamination hotspots and support targeted pollution-mitigation strategies.

Keywords: Metals, Coastal sediments, Sediment Carbon, Spatial variability, Environmental Indices, Risk Assessment

1. Introduction

Coastal zones play a pivotal role in ecological functioning and economic development (Costanza et al., 1997; MEA, 2005). However, rapid urbanization and industrial development accelerated on coastal regions that exacerbated the severity of coastal pollution in recent decades. Among various pollutants, metal pollution in coastal environments is greater concern owing to their inherent toxicity, persistence, and bioaccumulative behaviour within aquatic ecosystems (Agah et al., 2025). Coastal environments are receiving substantial inputs of metal pollutants from both natural and anthropogenic sources which constitute a global environmental challenge (Jiwarungrueangkul et al., 2025). Although metal moves into the aquatic environment through atmospheric deposition, the natural weathering of geological formations (Nethaji et al., 2017). Riverine and estuarine inputs are the primary sources of metals, transporting weathered materials, industrial effluents, mining residues, and urban runoff to coastal zones (Krishna et al., 2016; Zhang et al., 2020). Large rivers draining densely populated and industrialized regions significantly enhance metal loading to nearshore sediments. Coastal sediments act as ultimate sink and secondary source of contaminants including metals to the overlying water column.

The accumulation rate of metals in sediments may vary based on the influence of discharge points, load, water flow, depth, and sediment nature (Karthikeyan et al., 2020). Many metals strongly adsorb to fine particles (<63μm), which accumulate in low-energy environments. Organic matter enhances metal retention by forming stable complexes with metal ions, while clay minerals offer additional binding sites through their associated iron and manganese oxides and hydroxides. Key physico-chemical parameters such as pH, temperature, salinity and redox potential strongly influence metal adsorption, desorption, and settling processes in estuarine environments (Brady et al., 2015). Re-suspension and feedback process can remobilize these toxic substances to re-enter into the water column where fine clay particles act as major binding surfaces for metal ions and contributing to one of the most persistent challenges in aquatic environments (Siddiqui & Pandey, 2019). Biological processes such as bioturbation, uptake and excretion by benthic organisms and microbes influence movement and redistribution of metals in surface sediment (Aller, 1980; Kristensen, 2000). Further, they can be transferred into the aquatic food chain via bottom-dwelling organisms, causing harmful effects to the ecosystem (Maranho et al., 2014). Excessive metal enrichment in sediments can alter benthic biogeochemical cycling, enhance metal remobilization under changing redox conditions, thereby impacting coastal productivity and food webs (Burton, 2002). The ecological significance of heavy metals becomes more pronounced when they accumulate in

sediments, it regulates trophic conditions, modulates ecological cycling, and supports detritus-based food webs within aquatic ecosystems.

Globally, the increased metal concentration in the coastal environment causes ecological and human health impacts (Garofalo et al., 2025). Bioaccumulation and toxicity to marine organisms at cellular to population levels which leads to reduced biodiversity (Oros, 2025). Subsequently, metal pollution is impairing ecosystem services from fisheries, seagrass/reef health and causing chronic human-health risks through seafood exposure. Similarly, the coastal pollution by metals is causing significant concern in India. The coastline of India in the mainland (excluding islands) extends roughly 7,870.5 km, while the total including islands is about 11,098.8 km (TRW, 2025). Nearly 14% of the Indian population is supported by the economic activities in the coastal zones. The extensive coastline is currently experiencing major pollution challenges that impact marine ecosystems, human populations, and coastal economies. Along this stretch, pollutants are reaching coastal waters from various human activities and natural processes through estuaries, creeks, and canals etc (Vudamala et al., 2025). Approximately 390 million tonnes of industrial effluents are released into India's coastal waters annually, either directly or indirectly through riverine discharge. Additionally, the escalating use of fertilisers and pesticides to enhance agricultural yields contributes to nutrient and chemical runoff, further contaminating coastal environments. Aquaculture operations, tourism activities, and waste disposal from fishing vessels and small ships also serve as significant pollutant sources. Collectively, these inputs intensify the anthropogenic pressure on ecologically sensitive and economically significant coastal ecosystems (MoSPI, 2019). In addition, nearly 5,133 million litres per day (MLD) of treated industrial effluents and 5343 (MLD) untreated effluents are discharged into India's coastal waters from over 48,000 industries across ten coastal states and union territories (CPCB, 2023). Further, the Indian coastline also bears an estimated 0.98 metric tons of marine litter per kilometre, further aggravating coastal pollution (Centre for Science and Environment (CSE), 2023).

Hydrodynamic and depositional patterns in the nearshore coastal environments are different from those in the estuaries, lakes, and creeks (Pradhan et al., 2024). The nearshore environments, such as the inner shelf, surf, and breaker zones, are highly influenced by wave action, littoral drift, and coastal currents. Therefore, analysis of metals in the nearshore sediments is important to understand the amount of accumulation, dispersal, transformation and source contribution as well as to estimate the total coastal metal flux budget (M. Liu et al., 2019; Srinivas et al., 2017). Moreover, the determination of sediment quality indices such as

the geoaccumulation index, enrichment factor, and pollution load index for coastal sediments provide robust tools for evaluating contamination levels, identifying pollution hotspots, and assessing ecological risks. Despite most of the studies on metal contamination in Indian coastal waters are region-specific and largely focused on emphasizing local anthropogenic inputs such as urban drains, tourism activities, and port operations.

Currently, there is no peer-reviewed study that reports an original, empirical metal risk assessment covering the entire Indian coastline (Naik et al., 2023; Saravanan et al., 2024). Most available studies focused on the isolated regions such as the Chennai-Puducherry coast, Gulf of Kutch, southern Kerala, and individual estuaries like Ennore, but none have reported comprehensive, unified sampling and risk quantification across the entire coastline as one coordinated effort (Dudiya et al., 2025a; R. S et al., 2012; Rajendiran et al., 2025). Consequently, nearshore sediment systems remain understudied, despite their critical role in coastal metal cycling and ecological risk propagation. Therefore, the present study aims (1) to determine the concentration of metals in sediments along the Indian coastal nearshore region (2) to evaluate the relationships between metal distribution, sediment organic carbon, and grain-size characteristics (3) to examine spatial distribution patterns and regional variability of sediment-bound metals and (4) to assess sediment quality and ecological risks using established contamination indices and guidelines.

2. Materials and Methods

2.1. Study Area

India lies in the south-central peninsula of the Asian continent. The mainland of India, surrounded by coastline from the Rann of Kutch on the west coast and the Sundarban Delta on the east coast, has a length of 11,098.81 km, which hosts many estuaries, rivers, harbours, and fishing villages. Around 9 coastal states and 4 union territories covered the entire east and west coasts (Fig.1). Major harbours, fisheries, and industrial developments along the coast play a vital role in supporting the Indian economy. Conversely, these activities contribute to the deterioration of coastal ecosystem health through the build-up of pollutants, particularly heavy metals. The present study covered a total of 8 states (East Coast - West Bengal, Odisha, and Andhra Pradesh - and the West Coast - Gujarat, Maharashtra, Goa, Karnataka, and Kerala). The specific locations are Fraserganj in West Bengal, Paradeep in Odisha, Visakhapatnam in Andhra Pradesh, Kochi in Kerala, Mangalore in Karnataka, Mandovi in Goa, Mumbai in Maharashtra, Hazira in Gujarat. The sampling locations were fixed based on the land-based

pollutants received from anthropogenic and natural sources, estuaries, creeks, canals, rivers, harbour operations, fishing activities, tourism and industrial discharges. Based on this data, for each location, three transects covering nine sampling stations (each transect contain three stations), and sediment samples were collected in triplicate manner for the heavy metals risk assessment. The Gujarat sector included eight sampling stations due to site-specific constraints. All sediment samples were obtained during low tide to ensure consistent exposure and sampling conditions.

2.2. Sampling and analysis of sediment chemistry

A total of 213 surface sediment samples were collected from 8 locations (East Coast: West Bengal, Orissa, and Andhra Pradesh; and West Coast: Gujarat, Maharashtra, Goa, Karnataka, and Kerala) along the Indian coast during the dry season (December 2023 to April 2024) using a van Veen grab (0.01 m^2). Polythene containers were filled with sediment samples, transported to the laboratory by using an icebox, and stored at -20°C in a deep freezer for further analysis. A part of the sediments was dried at 65°C for 24 hr in a hot-air oven for sediment total organic carbon, and metals analysis.

2.3. Sediment particle size analysis

Particle size is analysed by laser diffraction measurement method. Approximately 2 gram of wet sediment was transferred onto a clean watch glass and placed into a hot-air oven to dry it overnight at 60°C to remove moisture. The dried sediment sample was subsequently treated with 2 N hydrochloric acid (HCl) for 24 hours, with 2-3 times successive acid washes to eliminate carbonates and acid-soluble impurities. After acid treatment, the residue was thoroughly rinsed 2–3 times with distilled water to remove excess acid. The decarbonated sediment was then oxidized with hydrogen peroxide (H_2O_2), added 2-3 times until effervescence ceased, to remove organic matter from the sample. Following oxidation, the sample was again washed 2–3 times with distilled water to ensure the removal of residual reagents. The cleaned sediment was subsequently dispersed in distilled water and analysed for particle size distribution using a Mastersizer laser diffraction analyzer (Malvern Instruments, UK) (Schulte et al., 2016).

2.4. Analysis of metals in the sediment samples

The sediment metals were analysed by using the acid digestion method (Tessier et al., 1979). From the preserved sediment stored at -20°C in a deep freezer, a 10 gram of sediment

sample was air-dried and then finely ground using a mortar and pestle, sieved by 63 µm size, and stored. 0.2 gram of powdered sediment samples were digested at 195°C in a microwave digester for 90 minutes with a 1:4:1 ratio of H_2O_2, Nitric acid (HNO_3), and HCl. After the digestion, the samples were filtered using Whatman No. 1 filter paper and made up to 10 ml with Milli-Q water. The extract was measured by inductively coupled plasma optical emission spectrometry (ICP-OES, make: Agilent; 5110 VDV). The instrument was calibrated before the sample analysis by using a trace metal mix (Agilent Technologies) standard. To validate the heavy metal analysis, a certified reference material (CRMs) was used for the marine sediment (PACS-3, Lot G 4169010, NRC, Canada). A similar method was followed for the sediments for CRM analysis (Naik et al., 2023; Neethu et al., 2024).

2.5. Total carbon, Inorganic carbon and Total organic carbon of Sediment

Total carbon (TC), Inorganic carbon (IC) and Total organic carbon (TOC) in surface sediments was analysed by the Combustion oxidation method.

From the sediment sample, preserved at -20 °C in a deep freezer, a 10 gram subsample was oven-dried at 65 °C for 24 h prior to analysis and homogenized by mortar and pestle then passed through 0.5mm sieve to ensure uniformity. For TC measurement, an aliquot of each sample was combusted at 900°C temperature in an oxygen-rich environment, and the resulting CO_2 was quantified by an infrared detector of total organic carbon analyzer (SSM-5000A). IC was determined by acidifying an aliquot of each sample with 5ml of orthophosphoric acid followed by combustion at 200°C temperature in an oxygen-rich environment to release carbonate and bicarbonate-derived CO_2, which was measured under the same detection system. TOC was calculated as the difference between TC and IC. Instrument calibration was performed using Glucose anhydrous and Sodium bicarbonate for TC and IC respectively, and all measurements were conducted in triplicate to ensure analytical precision (J. Wang et al., 2012).

2.6. Derivation of environmental quality indices

The environmental quality indices are used to assess the source and level of pollutants that reveal the environmental quality of the sampling locations. Several authors have tried several methods, but the most referred methods are the geoaccumulation index (Igeo), enrichment factor (EF), contamination factor (CF), ecological risk assessment (ERA), pollution load index (PLI), and potential ecological risk index (PERI). The average metal concentration of the present study was compared with the background values (shale value) (Turekian &

Wedepohl, 1961a)is considered the standard value for reliable interpretation of the geochemical data.

2.6.1. Geo-accumulation index

The geo-accumulation index (Igeo) is used to calculate the degree of pollution in the sediments. Based on (Muller, 1969), the following formula was used to derive the Igeo values.

$$\text{Geo} - \text{Accumulation Index}(I_{geo}) = \log_2\left(\frac{C_n}{1.5 \times B_n}\right)$$

Where B_n is the background concentration for metal, C_n is the concentration of metal in the sediments, and factor 1.5 is used to account for any variation in the background concentration due to the lithological variances.

2.6.2. Enrichment Factor

The enrichment factor (EF) is derived by the (Sinex & Helz, 1981) formula to assess the anthropogenic impact of heavy metals in surface sediments.

$$Enrichment\ Factor\ (EF) = \frac{\left(\frac{C_x}{C_{AI}}\right) Sample}{\left(\frac{C_x}{C_{AI}}\right) Background}$$

Where C_x sample and C_x background represent the average concentration of the selected metals in the sediments. C_x / C_{AI} background is the ratio of the background values of AI.

2.6.3. Contamination Factor

Specific metal contamination in the surface sediments of study sites was assessed by using contamination factor (CF) followed by (Hakanson, 1980). The formula used to derive the contamination factor is

$$Contamination\ factor\ (CF) = \frac{C_{metal\ contamination\ in\ sediment}}{C_{background\ value\ of\ metal}}$$

2.6.4. Pollution Load Index

The pollution load index (PLI) is used to derive the total toxicity and status of pollution in the specific site or zone (Tomlinson et al., 1980). The following formula is employed to derive the total toxicity:

$$Pollution\ load\ index\ (PLI) = (CF1 \times CF2 \times CF3 \times \ldots\ldots\ldots\ldots CFn)\ 1/n$$

Where n denotes the total number of metals, CF indicates the contamination factor. Value 1 is baseline, and values above 1 show increasing deterioration.

2.6.5. Ecological Risk Index

According to (Hakanson, 1980), the overall ecological impact of metal contamination is evaluated by using the ecological risk index (ERI).

$$Ecological\ risk\ index\ (ERI) = \sum Ef^i$$

$$Ef^i = Tf^i \times Cf^i$$

Where Tf is the toxic response factor for certain metals, Cf is for contamination of chosen metals, and Ef is the ecological risk of particular metals.

2.6.6. Potential Ecological Risk Index (PERI)

The environmental behaviour and characteristics of metals in the surface sediments were derived by using the potential ecological risk index (PERI). Previously, (Hakanson, 1980) proposed the formula used to assess the contamination-causing agents present in the sample. Where the risk index (RI) denotes the summation of all risk factors to detect the metal contamination in the sediments. The following formula is used to calculate the risk index (RI).

$$C_r^i = \frac{C^n}{C_n^i}$$

$$E_r^i = T_r^i \times C_r^i$$

$$Risk\ index\ (RI) = \sum_{i=1}^{n} T_r^i \times C_r^i = \sum_{i=1}^{n} T^i\ C^i/C_n^i$$

Here, RI denotes the total potential ecological risk of the individual metal: E_r^i is the potential ecological risk of individual metal; T_r^i is the toxic response factor (toxicity of particular metal); According to (Hakanson, 1980), the standardized toxic response factor for Copper (Cu), Zinc (Zn), Chromium (Cr), Nickel (Ni), Lead (Pb), and Cadmium (Cd) is 5, 1, 2, 5, 5, and 30. C^i is the measured metal concentration in sediment samples; C_n^i is the standard value of metal 'n' in the sediments.

2.7. Statistical analysis

Totally 53 parameters consisting of 11289 individual values (triplicated) were used as variables for statistical analysis. The statistical tools such as Linear Discriminant Analysis (LDA), Hierarchical Cluster Analysis (HCA), Correlation co-efficient analysis, redundancy analysis (RDA), Principal Component Analysis (PCA), and Multivariate ANOVA used to determine the relationships among the sediment quality parameters and metals. The 53 parameters consist of sediment carbons (3), texture (3), concentration of metals (9), indice values of individual metals such as geo-accumulation index (9), enrichment factor (9), contamination factor (9), and toxic risk index (9), and cumulative indices like pollution load index (1) and potential ecological risk index (1). Statistical analysis such as correlation, heatmap, principal component analysis, HCA, RDA, LDA, PCA, ANOVA, and PERMANOVA were performed using R Studio (Version 2024.12.0+467). Correlation and redundancy analysis (RDA) are performed to investigate the relationships between sediment metal concentrations (Cr, Cu, Cd, Pb, Zn, Ni, Manganese (Mn), Arsenic (As), and Cobalt (Co)) and sediment physicochemical parameters total carbon (TC), inorganic carbon (IC), total organic carbon (TOC), sand, silt, and clay **(Fig. 2)**. Spatial mapping and visualization were carried out using ArcGIS software (version 10.8).

3. Results and Discussion

The emerging population density in coastal areas emphasizes the land-cover changes, urbanization, industrialization, and a range of anthropogenic processes that collectively introduce substantial quantities of pollutants including heavy metals to the Indian coastal environment (Siddiqui & Pandey, 2019). Metals are of high concern due to the fact that, they are persistent, bioaccumulative, and toxic to marine organisms. This study focuses on analysing the degree of metal pollution and its risk along with sediment texture, and carbon in coastal sediments of densely populated major cities along the Indian coastline (**Table 1, Fig. 2 & 3**). Essential and non-essential major elements of environmental concern such as chromium (Cr), copper (Cu), cadmium (Cd), lead (Pb), zinc (Zn), nickel (Ni), manganese (Mn), arsenic (As), and cobalt (Co) are measured for ecological risk assessment (**Fig. 3)**. The spatial distribution of metals along the coast is analysed along with their relationship with sediment texture and sediment carbons. Extent of pollution by individual metal and their combined ecological risk is categorized using the indices. The geochemical based risk indices such as geoaccumulation index, enrichment factor, contamination factor, and pollution load index along with ecological risk index exhibited moderate risk to considerable risk due to high Cd concentrations. Relevant

277 statistical tools adopted to examine and extract influencing, sediment characteristic parameter,
278 metals, and to identify metal of concern. The LDA analysis used to discriminate the most
279 functional parameters (Ganugapenta et al., 2018a). Further LDA segregates the clusters based
280 on influence of parameters. Among the 71 sampling sites across the Indian coast, three major
281 clusters of sampling sites are separated by LDA and HCA. Cluster 1 consists of 28 sites
282 including all 9 sampling sites each from Goa and Maharashtra, 8 sites from Gujarat, and 1 site
283 each from West Bengal and Odisha. Four sampling stations from Kerala formed as cluster 2.
284 Similarly, cluster 3 includes a total of 39 sampling sites from east and west coasts. The
285 distribution of sampling sites in the separated clusters and isolation of northern west coast sites
286 indicate the similarity and dissimilarity of metal distribution along the Indian coast. Principal
287 Component Analysis (PCA) was conducted to identify more influential metals and classify the
288 sources based on relationship among metals and sediment characteristics. Comparison of
289 thresholds with observed levels of metals, distribution and range of concentrations would carry
290 meaningful information to environmental managers and are presented in **Table 1**. The metal
291 concentrations are compared with the sediment quality guidelines such as Australian Interim
292 Sediment Quality Guidelines (ISQGs), Effect Range Low (ERL), Effect Range Medium
293 (ERM), Toxic Reference Value (TRV), World Surface Rock Average (WSA), Threshold Effect
294 Level (TEL), and Probable Effect Level (PEL) (Bai et al., 2011; Caritat, 2011; Long et al.,
295 1995; MacDonald et al., 2000; J.-M. Martin & Meybeck, 1979; Mohiuddin et al., 2011).

296 **3.1. Relationship among sediment characteristics and metals**

297 Sediment texture is classified based on the percentage of sand, silt and clay particles.
298 Total carbon, total organic carbon, and inorganic carbon are analysed in the sediment samples.
299 RDA and correlation revealed significant relationships between soil properties and trace metals
300 **(Fig.4 & 5)**. Total carbon (TC), inorganic carbon (IC), and total organic carbon (TOC) were
301 positively correlated with each other ($r > 0.60$). Soil texture fractions showed strong
302 interrelationships, with sand negatively correlated with silt and clay, while silt and clay were
303 positively associated. Since the proportion of coarser particles increases, finer fractions tend to
304 decrease and vice versa, reflecting the inherent compositional constraints of sediment particle
305 size distributions (Fungo et al., 2010). The positive correlation among inorganic, organic, and
306 total carbon in coastal sediments along the Indian coast suggests co-deposition influenced by
307 common sources and processes, such as high primary productivity, sinput, and carbonate
308 biogenesis, reflecting coupled carbon cycling in nearshore environments. Trace metals

exhibited strong positive correlations among themselves, particularly between Cr-Cu (r > 0.70), Cd-Pb (r > 0.65), and Zn-Ni-Co (r > 0.70). Arsenic (As) was positively correlated with Co ($r \approx 0.70$), Mn ($r \approx 0.65$), Ni ($r \approx 0.60$), and Zn ($r \approx 0.55$), suggesting that these elements share common accumulation pathways. These associations are characteristic of anthropogenic inputs where multiple metals are released simultaneously and transported together into coastal systems (Dou et al., 2013; Paul et al., 2024). Metals such as Cr and Cu are frequently linked to industrial discharges and antifouling paints, while Cd and Pb often co-occur due to fossil-fuel combustion, vehicular emissions, and sewage inputs, explaining their strong mutual correlations (L. Liu et al., 2015; N. Singh & Turner, 2009). Negative correlations were observed between sand content and several metals, indicating that finer-textured soils (silt/clay) favour trace metal retention. These results highlight that soil organic carbon and fine particle fractions (silt, clay) are major drivers of trace metal and metalloid distribution, while sandy soils act as poor reservoirs for metal retention (Trifuoggi et al., 2022) **(Fig. 5)**. Similarly, Nair and Ramachandran observed greater relation of metal with silt and clay of estuarine sediment but the association of metals with silt is moderate in marine sediment at Southwest coast of India (Nair & Ramachandran, 2002).

Redundancy analysis **(Fig.4)** indicated that sediment properties explained 42.44% of the total variation in metal concentrations. The first two axes accounted for 26.4% (RDA1) and 12.5% (RDA2) of the total variance, respectively. Together, these axes explained 38.9% of the overall variance and represented 91.7% of the sediment-constrained variance. This demonstrates that the primary environmental gradients influence metal distributions which are well represented by the first two canonical axes. The RDA biplot suggests that metals such as Cr, Ni, and Co have a strong affinity for finer-grained sediments like clay and silt vectors. In contrast, Pb, Zn, and Cu aligned more closely with TOC and TC, indicating possible complexation with organic matter. The Mn and As vectors were positioned intermediately, implying broader distribution patterns possibly governed by both mineral and organic associations. In contrast, sand fractions exhibited negative relation to most metals, reflecting its physical properties like pore size and mixing. Sampling stations (blue points) clustered along these environmental gradients, showing spatial differentiation likely driven by sediment texture and carbon content **(Fig. 4)**. Clay minerals and oxide phase act as major metal-retaining components in sediments due to their high specific surface areas. Oxide adsorb metals onto their surface sites whereas clay minerals such as montmorillonite, illite, and kaolinite can incorporate metal ions into their interlayer spaces through ion-exchange processes (Mary Ugwu

342 & Anthony Igbokwe, 2019). Fe-oxides were shown to retain Pb nearly as effectively as clay
343 minerals. Under alkaline conditions, carbonates can increase the overall uptake of metals, and
344 combining clay minerals with Fe-oxides further improves metal adsorption (Sipos et al., 2008).
345 Again, kaolinite and mica exhibited strong retention for Cd, while vermiculite showed the
346 highest affinity for Cu and Zn. Iron oxide and Mn-oxide were most effective in retaining Pb.
347 Kaolinite displayed low retention for Cu, whereas vermiculite and Mn-oxide demonstrated the
348 greatest overall ability to hold metals among the minerals examined (Vega et al., 2007). Nickel
349 (Ni) and cobalt (Co) commonly occur as positively charged ions in sedimentary environments
350 (Davison et al., 1991), allowing them to interact strongly with the negatively charged surfaces
351 of clay minerals (Mohammed et al., 2022). Chromium (Cr), however, is often present in more
352 stable and less mobile forms under typical sediment conditions (Barnhart, 1997; Magar et al.,
353 2008), yet it may be able to associate with fine-grained sediments through surface
354 complexation or incorporation into mineral phases. The high surface area and cation-exchange
355 capacity of clay minerals further enhance the retention of these metals.

356 On the other hand, the organic component of sediments, particularly humic substances,
357 also plays an important role in metal retention. Trace elements bound to humic matter are
358 generally less mobile, and this stability is mainly controlled by functional groups such as
359 carboxylic (-COOH), phenolic (-OH), and amino-based groups (amine, amide, and sulphur-
360 containing groups). These groups readily form strong complexes with many metals, although
361 the strength of this binding can vary with changes in pH and ionic strength (Baran et al., 2019).
362 Such mechanisms support the close association of Pb, Zn, and Cu with TOC in the present
363 study, as these metals have a high tendency to complex with the reactive functional groups
364 present in organic matter. Arsenic adsorption onto clay minerals is strongly influenced by pH
365 and arsenic speciation. As(V) exhibits the greatest affinity for clays such as kaolinite,
366 montmorillonite, illite, halloysite, and chlorite near neutral pH, with adsorption decreasing
367 under more alkaline conditions. In contrast, As(III) shows weak retention at low pH but
368 increases in adsorption as pH rises. Below pH 7, As(V) is preferentially adsorbed, whereas at
369 higher pH the adsorption of As(V) and As(III) becomes comparable, and As(III) may even
370 dominate. These interactions occur mainly at aluminum-associated edge OH groups capable of
371 forming inner-sphere complexes (Nikolopoulos D, 2015). In addition to clay minerals, arsenic
372 interacts strongly with Fe-Mn oxides, which can immobilize arsenic under oxidizing
373 conditions. However, microbially driven reduction of Mn oxides can release previously
374 adsorbed arsenic, while organic matter influences this redox cycling and arsenic mobility, these

combined mineral–organic controls likely contribute to the intermediate positioning of Mn and As (Cai et al., 2022). Sand fractions are usually dominated by quartz and other inert minerals with minimal binding affinity for trace metals, whereas finer sediments are enriched in clay minerals, organic matter, and Fe–Mn oxyhydroxides, which act as major metal scavengers. Consequently, increasing sand content dilutes metal concentrations and weakens metal–sediment associations (Sundaray et al., 2011a).

3.2. Distribution of metals along Indian coastal sediments

Mn (394.67 µg/g) was observed at high concentration in both east and west coasts of India. Overall, the west coast exhibits markedly higher concentrations of metals compared to the east coast. Cr, Mn, and As were recorded highest levels in Goa and lowest in Karnataka, whereas in the east coast these metals were high in Odisha and are less in Andhra Pradesh. The remaining metals such as Cu, Ni, and Co exhibit high concentrations in Maharashtra and low in Karnataka on the west coast, while on the east coast they are most enriched in West Bengal. In Andhra Pradesh and Odisha recorded lowest levels of Co, Ni and Cu and at the same time most dangerous metals such as Cd and Pb was recorded high in Kerala coast. In the northern region of the west coast these metals showed lowest concentration. Compared to the west coast, the highest levels of Cd (Andhra Pradesh) and Pb (Odisha) were observed in the East coast. Zn was recorded at maximum in Gujarat region at west coast and West Bengal in east coastal region.

In general, the reported concentrations of metals in the estuaries, creeks, lakes and rivers are considerably lower than the coastal sediments. The reported metal concentrations in the sediments of Gangasagar estuary, and Ganga river in West Bengal, Mandovi estuary in Goa, Thane Creek in Mumbai, Hazira Tapti estuary in Gujarat, Dhamara in Odisha, Visakhapatnam coast, Vembanad Lake in Kerala, Mangalore coast in Karnataka were compared with the results of respective coastal sediments (Antizar-Ladislao et al., 2015; Cyriac et al., 2021; Dudiya et al., 2025b; Fernandes & Nayak, 2014; Gaonkar et al., 2021; Gosai & Mankodi, 2024; Joseph & Gandhi, 2025; Lonkar et al., 2022; Mohammad et al., 2021; Sahoo & Swain, 2023; Sarkar et al., 2017; Selvam et al., 2012; Shah et al., 2013; Siddiqui & Pandey, 2019; Swain et al., 2021; Trifuoggi et al., 2022; Veerasingam et al., 2015). The Cu concentrations measured in this study from 11.9 µg/g to 23.2 µg/g is comparable to the Cu found in the Gangasagar estuary in the range of 6.7 µg/g - 109 µg/g, Ganga river from 2.1 µg/g - 73.9 µg/g, and Gangasagar Phuldubi (6.9 µg/g - 34.8 µg/g) (Antizar-Ladislao et al., 2015;

Sarkar et al., 2017; Siddiqui & Pandey, 2019; Trifuoggi et al., 2022). Likewise, the concentrations of Co, Mn, Cd, Zn, and Cr are consistent with the results of present study. However, nearly 10 folds of high levels of Ni and As were reported. Similarly, the PLI of 8.28 in Ganga River was reported is considerably high than the Gangasagar with PLI of 0.32 and West Bengal coast with an average PLI of 0.51 (Antizar-Ladislao et al., 2015; Siddiqui & Pandey, 2019). Cr, Cu, Mn, Zn, Pb, and Co concentrations have reported in the Mandovi estuary during 2015 (Gaonkar et al., 2021; Veerasingam et al., 2015). In addition to these metals, this study measured the Cd, As, and Ni concentrations despite there are no reports on metals in the Goa coastal sediments. The increased concentrations of Cr, Pb and Zn within the Mandovi estuary is observed over a period of 6 years between 2015 to 2021 reports. Most of the metal concentrations are found at lesser concentrations in the Goa coastal sediments in comparison to the Mandovi estuary. This study observed significantly low concentrations of metals like Pb at 4 folds, Zn at 2-3 folds, Co at 2 folds, and Cu at 1.5 folds in the coastal sediments of Goa. The decrease in metal concentration in the coastal sediments than the upstream of estuaries, creek, and river sediments can be explained by the dispersal of metals. Sediment displacement by the coastal physical forces like wave, tidal run-offs, water currents, and upwelling attributed to the dispersal of metals in the coastal sediments.

Dissimilar distribution patterns of metals respectively, like Mn>Cr>Zn>Cu>Ni>Co>Pb>As>Cd, and Mn>Cr>Zn>Ni>Cu>Pb>Co>As>Cd were observed for average concentrations of metals in the west and east coasts. Interestingly, the overall average of metal concentrations followed the pattern of west coast Mn>Cr>Zn>Cu>Ni>Co>Pb>As>Cd. This difference is caused due to higher variation in the concentrations of Cu, Ni, Co, and Pb among the sampling locations in the east and west coasts, but their concentrations were high in the west coast. The function of Cu, Ni, Co, Pb and Cd to the distribution pattern and influence on sediment quality is complimented by the Linear Discriminant Analysis (LDA), and Hierarchical cluster analysis (HCA) **(Fig. 6a&b)**. The LDA and HCA grouped all the 71 sampling sites along the coastline into three clusters. In LDA, the first discriminant axis (LD1) explained 83.3% of the variance, primarily reflecting Co, As, and Cd, while the second axis (LD2) explained 16.7% and was influenced by Co, Cd, and Ni. The results confirm that specific metals are responsible for the distinct regional groupings observed in the HCA dendrogram. Cluster I was characterized by moderate background concentrations of most metals, Cluster II by elevated Cu, Zn, Mn, and Co levels, while Cluster III was distinguished by high Cr, Ni, and Mn concentrations. This is attributed by the dissimilarity of

sources, geographical features and sediment characteristics (Ganugapenta et al., 2018b; Taghinia Hejabi et al., 2011).

Principal Component Analysis (PCA) was conducted to identify the dominant factors controlling the spatial variability of heavy metals across the eight coastal regions, namely Andhra Pradesh (AP), Goa (GA), Gujarat (GJ), Karnataka (KA), Kerala (KL), Maharashtra (MH), Odisha (OD), and West Bengal (WB). The first three principal components (PC1, PC2, and PC3) together explained 81.8% of the total variance, with contributions of 46.4%, 22.2%, and 13.2%, respectively **(Fig. 7)**. PC1 was primarily associated with Cr (0.397) and Cu (0.424), whereas PC2 exhibited strong negative loadings for Cd (-0.610) and Pb (-0.623). PC3 was characterized by a positive loading of Zn (0.497) and a moderate contribution from Cu (0.317). The loading patterns may suggest that PC1, strong loading on Cu and Cr is mainly associated with broad compositional variability related to geogenic background and metal-bearing mineral phases. Cu in the environment may originates from several anthropogenic and natural sources. Major human-related inputs include agrochemical industries, industrial effluents, and agricultural land use (Dey et al., 2021; Islam et al., 2015). Copper levels may also be elevated due to natural geological processes such as rock weathering and soil erosion, along with human activities like copper mining and smelting operations (Giri et al., 2013; Huang et al., 2020), again Cr concentrations in the environment may originate from natural geological processes such as the weathering of chromium-bearing rocks, as well as from various industrial discharges (Sundararajan & Natesan, 2010).

In contrast PC2, strong loading on Cd and Pb; and PC3, strong loading on Zn, and Cu, reflect anthropogenic enrichment linked to industrial such as and urban activities such as vehicle emission, burning of leaded and unleaded automobile fuel, (Botle et al., 2025). Samples from Goa (GA) and Maharashtra (MH) formed compact and isolated clusters along distinct regions of the negative PC1 and PC2 plane, indicating relatively consistent yet compositionally distinct contamination profiles, likely influenced by industrial activities, mining runoff, and urban emissions, while also being modulated by local lithological characteristics (Botle et al., 2025; Gaonkar et al., 2021; Renjan et al., 2017). Samples from Gujarat (GJ) and Karnataka (KA) exhibited moderate dispersion along the positive PC1 and PC2 axes, suggesting a predominance of geogenic or lithogenic controls associated with the natural enrichment of Cr and Cu bearing minerals (Cyriac et al., 2021; Shah et al., 2013). In contrast, samples from Kerala (KL), Odisha (OD), and West Bengal (WB) showed partial overlap along PC2 and PC3,

indicating mixed influences from both natural and anthropogenic sources, including urban runoff, agricultural inputs, and estuarine processes (Antizar-Ladislao et al., 2015; Swain et al., 2021). As PCA is an exploratory multivariate technique, these interpretations are indicative rather than definitive and should be considered in conjunction with regional environmental characteristics.

3.3. Risk assessment of metals through geochemical and ecological risk indices

3.3.1. Geoaccumulation Index

The Geoaccumulation Index (Igeo) values for nine heavy metals displayed clear spatial and elemental variability across the eight sampling locations **(Fig. S1)**. This is emphasizing heterogeneity in metal accumulation in the sediment along the coast. Overall, Igeo values ranged from approximately -6.26 to +3.89, representing a contamination spectrum from unpolluted to moderately polluted conditions according to classification of Igeo described by (Muller, 1969). Among all metals, Cd consistently exhibited the higher Igeo values, reaching up to +3.89 in several locations, indicating moderate to strong enrichment. High Igeo values of Cd underscores the influence of anthropogenic inputs. Such high Igeo values for Cd are reported in coastal sediments due to discharges of industrial effluents, urban sewage, and port-related activities, as well as its high mobility and low natural background concentrations (Raju et al., 2011; Seifi et al., 2019). Whereas, moderate Igeo values of Zn, Pb, Cr and Cu observed in selected sites suggest localized anthropogenic activities. Similar enrichment of these metals are reported in the previous studies along both the east and west coasts of India (Chakraborty et al., 2014; Gaonkar et al., 2021). Negative Igeo values for Co, Mn, As, and Ni signifying natural background levels attributing to contribution of geogenic sources. This is common for these metals due to their abundance in the earth crust (Miranda-Avilés et al., 2012; Mostafa et al., 2023; Tijani & Onodera, 2009). Igeo identified Gujarat, Maharashtra, Kerala, and Goa for high accumulation of Cd, Zn, Pb, Cu, and Cr. Major ports, industrial corridors, mining zones, refineries, and densely urbanized coastal belts in these regions caused high accumulation of metals in nearshore sediments through estuarine runoff (Balachandran et al., 2006; Gosai & Mankodi, 2024; Sheela et al., 2012; Veerasingam et al., 2015). Conversely, Odisha, Andhra Pradesh, West Bengal, and Karnataka exhibited predominantly negative Igeo values for nearly all metals, reflecting unpolluted to background conditions and emphasizing the dominance of natural sedimentary inputs and lower anthropogenic pressure in these regions. The Igeo-based assessment effectively captures both the intensity and spatial variability of metal

contamination, supporting its continued application as a reliable index for evaluating sediment quality in complex coastal environments (Müller, 1969). The overall pattern confirms a marked spatial heterogeneity in metal enrichment, consistent with the statistical evidence from ANOVA and PERMANOVA that indicated significant ($p < 0.001$) differences in multivariate metal composition among locations.

3.3.2. Enrichment Factor

The Enrichment Factor (EF) values of the analyzed heavy metals demonstrated pronounced spatial and elemental variability across the eight sampling locations **(Fig. S2)**. Across all samples, EF values ranged from < 0.5 to > 20, encompassing contamination categories from deficiency to very high enrichment. The highest EF values were consistently observed for Cd, with maximum values >20 in certain locations notably Kerala, thereby classifying these sites under the very high enrichment category, >16 in Andhra Pradesh and >12 in Maharashtra, classifying these sites under the significant enrichment category. Zn, and Cr also exhibited moderate enrichment (EF ≈ 2 to >4) in several locations, indicating partial anthropogenic contribution (E. Liu et al., 2010), whereas Co, As, Cu, Ni, and Mn generally showed EF values close to unity, reflecting predominantly lithogenic origin and minimal external input (Dragović et al., 2008). Spatially, the western coastal states (Kerala, Gujarat, Maharashtra) recorded the highest mean EF values, consistent with intense industrialization and maritime activities. In Goa, chromium (Cr) exhibited enrichment factor (EF) values >2, indicating moderate enrichment relative to the natural background level. In contrast, Odisha, West Bengal and Andhra Pradesh displayed EF values close to background levels (EF < 2) for nearly all metals, indicating limited anthropogenic influence and stronger control by natural sedimentary processes (Alagarsamy & Zhang, 2010; G. D. Martin et al., 2012). The median EF trend across the entire study area followed the order Cd > Cr > As > Mn > Co > Zn > Cu > Pb > Ni, reflecting the dominance of Cd and Cr as the principal enriched elements. The large interquartile ranges observed for Cd and Cr in certain locations denote substantial intra-site variability, implying heterogeneous contamination sources or variable deposition intensities within those regions. The strong spatial heterogeneity in EF values aligns with the results of the ANOVA and PERMANOVA analyses that have revealed highly significant ($p < 0.001$) location-based differences in multivariate metal composition. Collectively, these findings suggest that metal enrichment in the study area is neither uniform nor random but is spatially

structured according to the degree of anthropogenic activity and sediment geochemical characteristics.

3.3.3. Contamination factor

The spatial distribution of contamination factor (CF) values for different metals across the eight coastal locations is illustrated in Figure **(Fig. S3)**. Overall, CF values exhibited pronounced variability among metals and regions, indicating heterogeneous contamination patterns along the studied coastline. Cadmium (Cd) consistently showed the highest CF values across most locations, particularly in Kerala, Andhra Pradesh, Maharashtra, and Karnataka, where CF values frequently >6 and reached maxima >20 at certain stations. Such elevated CF values classify Cd as a metal of considerable contamination concern, suggesting strong anthropogenic inputs, potentially from industrial discharges, agricultural runoff, and urban effluents (Mookan et al., 2023). In contrast, metals such as As, Co, Cr, Cu, Mn, Ni, Pb, and Zn generally displayed CF values <2.5 across most locations, indicating low to moderate contamination levels. Though the Cd is observed at lower levels in sediments than other metals, the CF exhibits high values. This is due to the earth crust values of metals used to derive CF as background concentrations. Less CF values of major elements like Mn and Zn with their higher concentrations at many fold than Cd is explained by the low earth shell concentration of Cd than other metals (Turekian & Wedepohl, 1961b). Among these, Cu and Cr showed slightly elevated CF values in Maharashtra and Goa, reflecting localized enrichment possibly linked to port activities, industrial operations, or sedimentary geochemical controls. Likewise, the Cu and Cr with high enrichment is reported in Qianzhen Fishing Port (Taiwan) due to strong anthropogenic contamination linked to port activities such as ship operations and antifouling paints (Lim et al., 2022). Similar observation in the southeast coast of India demonstrates the high CF of Cu and Cr from anthropogenic influence on metal distributions, and suggested shared common sources affecting spatial patterns of contamination (Veluchamy et al., 2025). Zn and Pb exhibited relatively uniform and low CF values across regions, suggesting limited anthropogenic accumulation and a stronger influence of natural background levels (K et al., 2025). The expanded lower CF range (0 to 2.5) highlights subtle but meaningful spatial variations among stations within each location, emphasizing the importance of site-specific assessment rather than regional generalization. The presence of multiple stations within each location showing consistent CF trends further supports the robustness of the observed patterns. Overall, the dominance of Cd contamination coupled with generally low CF values for other

metals suggests that targeted mitigation strategies should prioritize Cd sources, while continued monitoring is essential to prevent future accumulation of other trace metals in coastal sediments. Further, the high CF values of Cd reflect in the pollution load index values classifying the pollution level in the sediments.

3.3.4. Pollution Load Index

The Pollution Load Index (PLI) values exhibited clear spatial variation among the eight coastal regions **(Fig. 8)**, reflecting differences in anthropogenic pressure and sediment quality. Overall, PLI values ranged between 0.15 and 1.05, indicating conditions from unpolluted to moderately polluted sediments. The highest PLI values were observed along the Maharashtra coast, where near Sunk rock lighthouse (Station 2) exceeded a PLI value of 1.0, indicating localized degradation of sediment quality. This elevated value signifies the influence of industrial discharges, port operations, and urban runoff concentrated around specific estuarine or harbour zones. Similar studies using PLI in Maharashtra coastal and estuarine sediments confirm high pollution due to intense coastal urbanization and industrial clustering (Sundaray et al., 2011b; Vudamala et al., 2025). Similarly, in Kerala, most stations displayed moderate PLI values (0.4–0.8), but Bolgatty Ferry (Station 7) recorded a PLI > 1.0, suggesting significant localized contamination and deterioration of sediment quality. This may be linked to port activities and discharge from densely urbanized coastal belts. Moderate PLI values were also recorded in Goa (≈ 0.85) and Gujarat (≈ 0.80), representing slightly polluted sediments likely influenced by tourism, urban drainage, and industrial emissions. In contrast, the eastern coastal states Odisha, Andhra Pradesh, and West Bengal exhibited consistently low PLI values (0.25 - 0.55), confirming unpolluted conditions and the dominance of natural geogenic sources over anthropogenic contributions. Karnataka showed the lowest mean PLI (~0.2), classifying it as unpolluted, corresponding to its low industrial intensity and lithogenic sediment composition. Comparable localized exceedances of PLI thresholds have been reported in other Indian port-influenced coasts, emphasizing the patchy nature of sediment contamination even within otherwise moderately impacted regions (V. K. Singh et al., 2005; Vudamala et al., 2025). Overall, the spatial distribution of PLI values demonstrate the site-specific anthropogenic activities rather than uniform regional contamination. The presence of elevated PLI values in major estuarine and harbour environments supports recent national-scale syntheses reporting considerably high PLI values in heavily industrialized estuaries along both

598 the east and west coasts of India (Vudamala et al., 2025), emphasizing the need for targeted,
599 site-specific management strategies than broad regional generalizations.

600 **3.3.5. Potential Ecological Risk Index (PERI)**

601 The Potential Ecological Risk Index (PERI) values varied substantially across the eight
602 coastal regions **(Fig. 9)**, revealing distinct spatial trends in ecological risk intensity associated
603 with heavy metal contamination. PERI values ranged from approximately 53 to over 403,
604 spanning from low to considerable ecological risk categories(Hakanson, 1980). Among all
605 regions, Kerala recorded the highest PERI values, with one station near Bolgatty Ferry (Station
606 7) exceeding 400, indicating considerable ecological risk. This elevated risk is primarily driven
607 by the high concentration and toxicity of cadmium (Cd), coupled with moderate enrichment of
608 Pb and Zn. Kerala's overall mean PERI (>243) signifies substantial ecological stress and
609 highlights localized areas of heavy anthropogenic impact (Selvam et al., 2012). Maharashtra
610 exhibited moderate ecological risk, with PERI values ranging between 156 and 241, indicating
611 the influence of industrial discharge, urban effluents, and maritime activities (Botle et al.,
612 2025). Andhra Pradesh, most stations reflected low ecological risk (<150); however, two
613 stations exhibited elevated PERI values - near Rock beach view point (S2) with a moderate
614 risk (259) and another with a considerable risk (301), approx. 3km from coast towards open
615 ocean (S3) indicating localized ecological impairment likely driven by industrial effluents or
616 port and tourism-related sources in confined coastal sectors (Mohammad et al., 2021).
617 Similarly, Karnataka showed two stations with PERI values between 150 (near Ullal delta (S4))
618 and 174 (Ullal end point (S9)), categorizing them as moderate ecological risk zones, while the
619 remaining sites remained within the low-risk threshold. These moderately impacted sites may
620 reflect localized metal accumulation from urban wastewater and minor industrial discharges
621 (Cyriac et al., 2021). In Gujarat, overall ecological risk remained moderate (PERI ~120),
622 though a station 3Km from Dumas Beach towards open ocean exhibited a PERI value of 159,
623 indicating localized moderate ecological risk. Such variation suggests site-specific
624 contamination from port-based activities and industrial effluent inputs (Shah et al., 2013).
625 Conversely, Goa recorded low to moderate risk levels (PERI ≈ 86–105), while Odisha and
626 West Bengal exhibited the lowest PERI values (<150), classifying them under low ecological
627 risk, dominated by natural background metal levels with minimal anthropogenic impact.
628 Odisha and West Bengal coastal sediments are displayed with lesser PERI values indicating
629 safe levels of metals.

3.4. Relationships among risk indices and metals

The interrelationships among heavy metal concentrations and their associated pollution indices analysed using the correlation heatmap **(Fig. 10)**. The heatmap of correlation clearly distinguished anthropogenically influenced metals (Cd, Pb, Zn, Cu, Cr) from those of natural geogenic origin (Mn, Co, Ni, As) (Rivera-Rivera et al., 2020). Additionally, the correlation structure indicates that most metals and indices are interdependent. The correlation coefficients range from –1 to +1, where positive values indicate co-occurrence or shared behavior among metals/indices, and negative values represent inverse relationships. The correlation heatmap reveals a strong pattern of positive correlations across most metals and indices, indicating that variations in heavy metal concentrations are closely reflected in the derived pollution indices. Specifically, EF, Igeo, PERI, and PLI exhibit strong positive associations with most heavy metals, suggesting that these indices effectively capture the variability of elemental enrichment and ecological risk levels within the study area (A. Kumar et al., 2020). Among the metals, Cd, Pb, and Zn show the strongest positive correlations with PERI and PLI, implying that these elements are major contributors to overall ecological risk and pollution intensity. Similarly, Cu and Cr display significant correlations with EF and Igeo, reflecting their sensitivity to anthropogenic enrichment processes. Moderate to high correlations are observed between EF and Igeo for individual metals, confirming their consistency in assessing contamination intensity. The PERI and PLI indices, both composite measures, demonstrate strong internal correlations, further supporting their reliability as integrative indicators of ecological hazard (Castro et al., 2018; Manoj & Padhy, 2014) . In contrast, weaker or near-zero correlations (green to yellow shades) are seen between certain metals (e.g., Mn and Co) and indices such as PERI or PLI. The weaker correlation of PERI with Mn and Co is attributed to the least toxicity. Similarly, lesser relationship with PLI explained by the predominant lithogenic origin of Mn and Co.

3.5. Spatial distribution and variations among risk indices

A one-way ANOVA was performed to examine spatial differences in the concentration of heavy metals and related indices among the eight sampling regions. The results revealed that all analyzed elements (Cr, Cu, Cd, Pb, Zn, Ni, Mn, As, and Co) exhibited highly significant variation among locations ($p < 0.001$). Tukey's HSD post-hoc analysis identified distinct groupings, with Gujarat (GA) and Maharashtra (MH) generally showing the highest mean concentrations for most metals, whereas Kerala (KL), Odisha (OD), and West Bengal (WB)

exhibited comparatively lower values. For example, Cr levels were markedly higher in Gujarat than in Andhra Pradesh, Kerala, or Odisha ($p < 0.001$), and Cu concentrations were substantially elevated in Maharashtra and Gujarat relative to other regions. Similarly, Cd and Pb were significantly enriched in Kerala compared to most other locations, while Ni and Mn showed maximum accumulation in Gujarat and Maharashtra. The consistent significance across metals (ANOVA $p < 0.001$ for all) indicates pronounced spatial heterogeneity in sediment metal distribution, suggesting localized sources of contamination and varying geochemical or anthropogenic influences among sites (Díaz-de Alba et al., 2011).

Similarly, the PERMANOVA test was conducted to assess spatial differences in the overall heavy metal and risk index composition among the eight sampling locations. The analysis revealed a highly significant effect of location ($F = 70.49$, $p = 0.001$, $R^2 = 0.706$), indicating that approximately 70.6% of the total variance in the multivariate dataset was explained by geographic variation. This demonstrates that the overall metal and risk profiles differed markedly among the studied sites. The test for homogeneity of multivariate dispersion (beta dispersion) was also significant ($F = 11.97$, $p = 0.001$), suggesting that some locations exhibited greater internal variability than others. This likely reflects differences in local contamination intensity or multiple pollution sources within certain regions. Despite this variability, the significant PERMANOVA results confirm that compositional dissimilarities among locations are strong and systematic rather than random. Pairwise PERMANOVA comparisons further supported these findings, revealing that most inter-location contrasts were significant after false-discovery correction (adjusted $p < 0.05$). Locations such as Gujarat, Maharashtra, and Kerala exhibited distinct metal and risk signatures, whereas a few sites (e.g., Odisha and West Bengal) showed relatively similar profiles. Overall, these results indicate pronounced spatial heterogeneity in metal contamination patterns and ecological risk indices across the study area (Díaz-de Alba et al., 2011).

Only a few studies have reported metal levels in coastal sediments compared with the relatively larger number of investigations in estuarine and riverine systems. Although some regional assessments exist, a comprehensive evaluation of metal contamination in coastal sediments is still lacking. Reviews on estuarine and riverine sediments clearly emphasize the sparsity of comparable coastal data and highlight the need for focused, broad-scale monitoring (V. Kumar et al., 2020; Vudamala et al., 2025). A recent study on comparative assessment of metal pollution trends in estuarine sediments report moderate to severe pollution from 62

published records (Vudamala et al., 2025). The study highlights the high temporal average PLI (TAPLI) attributed to uncontrolled effluent discharges. Also, containment of effluent discharges through management practices improved the sediment quality by considerable decline in TAPLI. A significant reduction in the PLI in Mandovi estuary evidenced after implementation of the mining ban (Vudamala et al., 2025). This signifies the importance of monitoring and risk assessment of metals in support of regulatory measures. The limited attention to coastal sediments may partly stem from the presumption that metals become widely dispersed in the open coastal environment, resulting in reduced perceived ecological impact or risk (P. Wang et al., 2025). The present study provides evidence supporting this assumption for certain biologically essential elements. Similar to the observation in the nutrient dispersion in the nearshore and offshore coastal waters from the river mouth (Sarma et al., 2020). Estuaries and nearshore zones act as initial receptors and retention areas for nutrients and contaminants delivered by rivers, urban runoff, and industrial discharges, whereas offshore waters experience substantial dilution due to higher water volumes, stronger circulation, and enhanced mixing. As a result, concentrations of nutrients, trace metals, and other pollutants generally decrease seaward, unless counteracted by processes such as upwelling or atmospheric deposition. Physical mixing, hydrodynamic dispersion, and coastal circulation in regulating the fate of nutrients and pollutants in Indian coastal waters. It emphasizes the role of estuaries and nearshore zones as critical interfaces where anthropogenic impacts are most strongly expressed.

Measured concentrations of Mn, Zn, and Co, and to some extent Cu and Cr, generally fall within established sediment quality guidelines. While minimum and mean Cu and Cr concentrations align with the ISQG range of 6.3–55.6 µg/g, the maximum Cr concentration of 78.3 µg/g on the west coast exceeds ISQG limits. Cu also exceeds the Toxic Reference Value (TRV) at many west-coast sites and a few east-coast locations, and surpasses the Effect Range Low (ERL) at selected sites. Of greater concern, however, are the toxic metals Cd, As, Pb, and Ni, which exceed one or more sediment quality thresholds across several locations. All the range of Cd concentrations, even the lowest levels exceeded the ISQGs. Overall maximum concentration of 6.7 µg/g is exceeding all the sediment quality thresholds such as ERL, ERM, TRV, WSA, TEL, and PEL. Similarly, the maximum As concentrations 9.85 µg/g on the west coast and 10.98 µg/g on the east coast surpass the ISQG limit of 5.7 µg/g (Caritat, 2011) and also exceed other benchmark values including TRV and TEL (MacDonald et al., 2000;

Mohiuddin et al., 2011). These exceedances underscore that, despite assumptions of dispersion, certain toxic metals can accumulate in coastal sediments to ecologically significant levels.

Conclusion

The levels of metals in nearshore sediments in anthropogenically influenced eight coastal states are determined with texture and carbon distribution. Spatial composition of sediment is significantly varied with the distribution pattern of metals. The west coast is mostly observed with a higher range of metals than in the sediments of the east coast. The statistical tools such as PCA, DFA, and RDA differentiated the sources of metal enrichment through their inter-compositional relationships among and within the metals and sediment properties. The application of geochemical indices, including Igeo, EF, and CF, demonstrated that significant anthropogenic enrichment of Cd, Pb, and Cr as they are scarce in the earth crust. Among, the metals Cd is posing moderate to considerable ecological risk in few sediments in the west coast due to localized accumulations. State wise, high metal concentrations are found in Kochi in Kerala, Mumbai in Maharashtra, and Hazira in Gujarat. Exceedances of sediment quality guidelines, therefore this study reinforces the need for systematic, spatially extensive monitoring of metal concentrations in coastal sediments, with particular emphasis on regions receiving industrial effluents, sewage outfalls, and urban discharges. Further studies focusing determination of contaminants across the coast are essential for reliable risk assessment, early detection of contamination hotspots, and the development of effective mitigation and management strategies.

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Declarations

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Conflict of Interest

The authors declare no competing interest.

Ethical approval

All authors have read, understood, and complied, as applicable, with the statement on "Ethical Responsibilities of Authors" as outlined in the Instructions for Authors of the EMAS journal.

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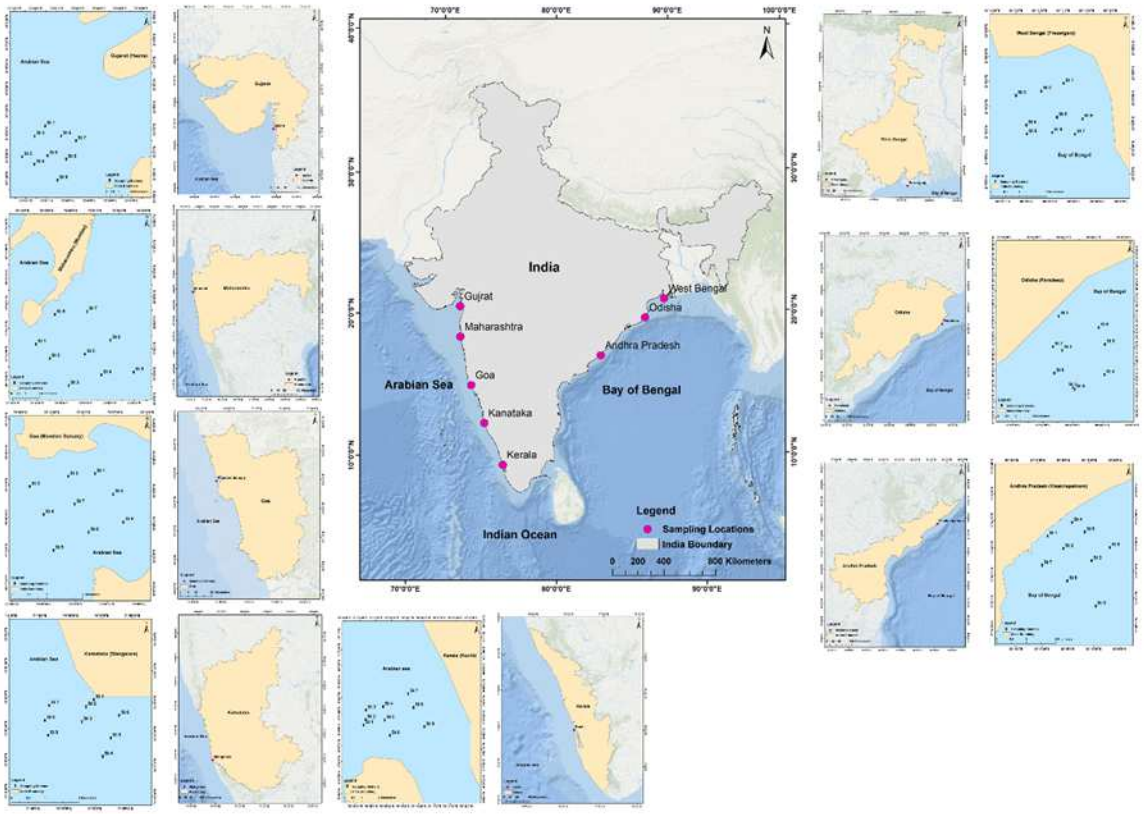
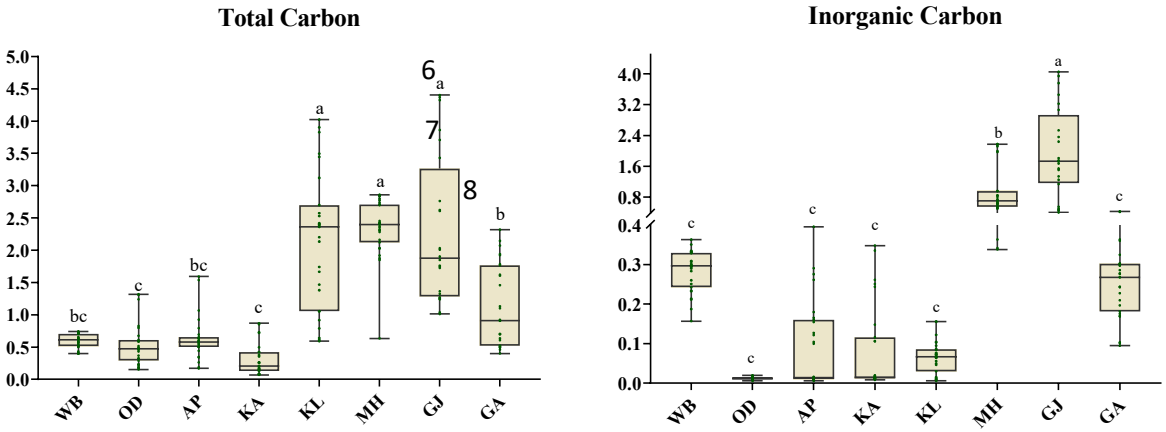


Fig.1. Geographic representation of the study area illustrating the sampling locations along the eastern and western coastal regions of India



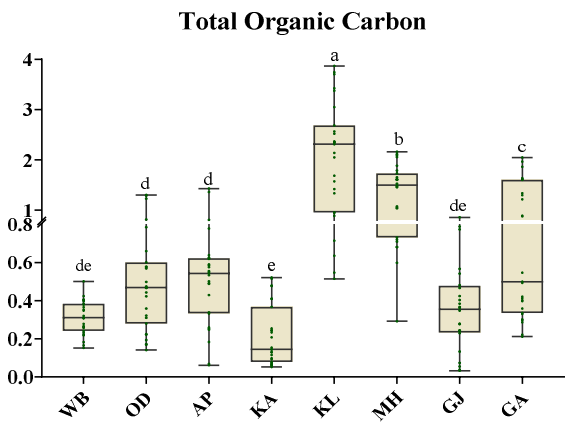


Fig.2. Distribution of total organic carbon along the Indian coastal sediments. Multivariate ANOVA indicated with alphabets on the individual boxes of the box plot. Boxes with different alphabets are significantly different ($p \leq 0.05$).

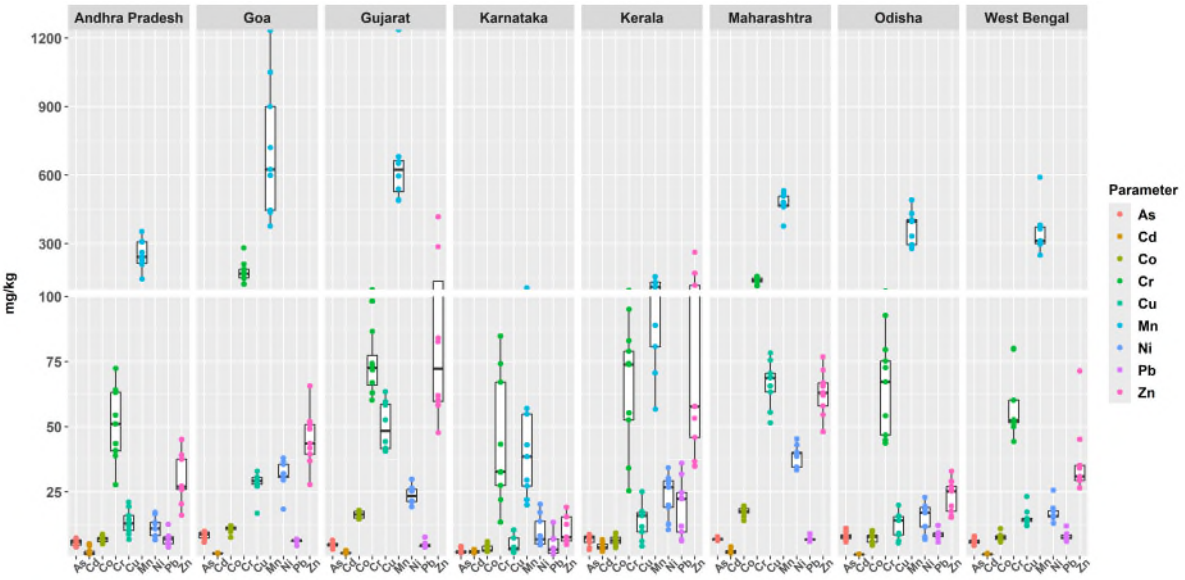
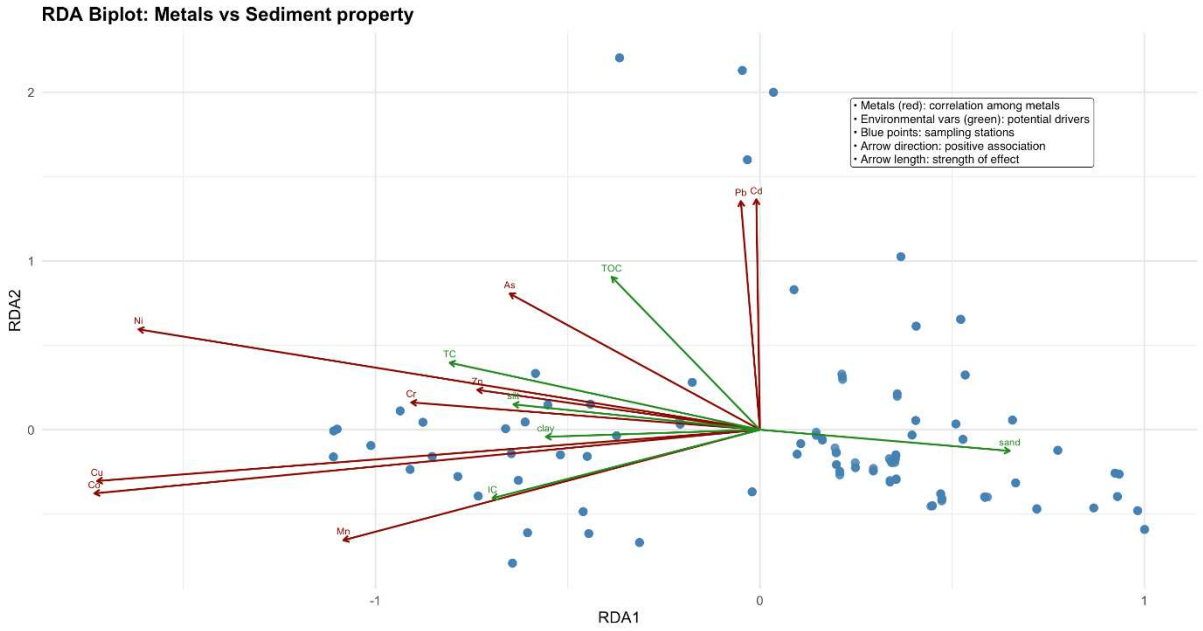


Fig.3. Distribution of metal concentrations in coastal samples from the eastern and western regions of India.

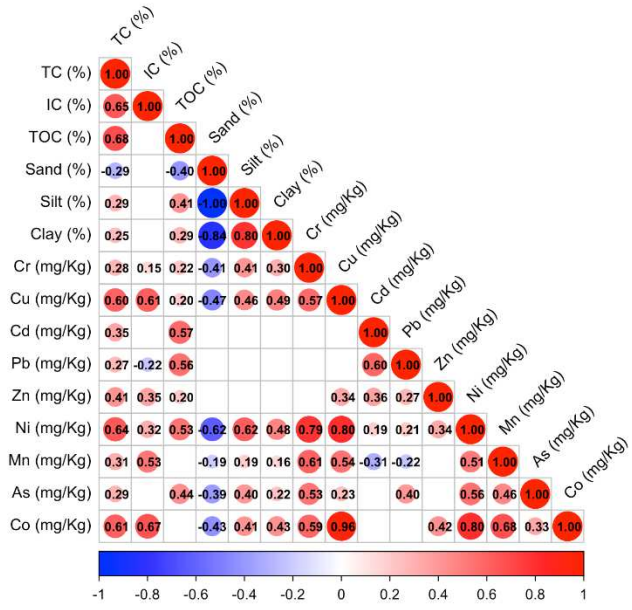


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31 **Fig.4.** RDA biplot showing the multivariate relationships between sediment metal

32 concentrations and associated sediment characteristics.

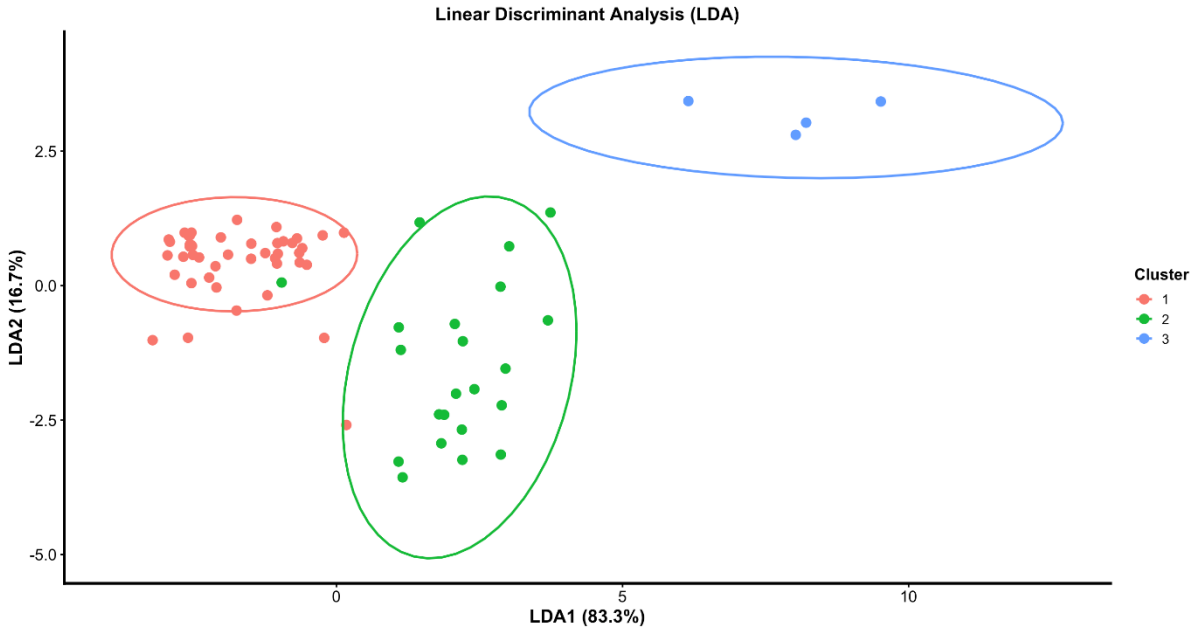


33 Correlation coefficients (Pearson r). Blue = negative, Red = positive

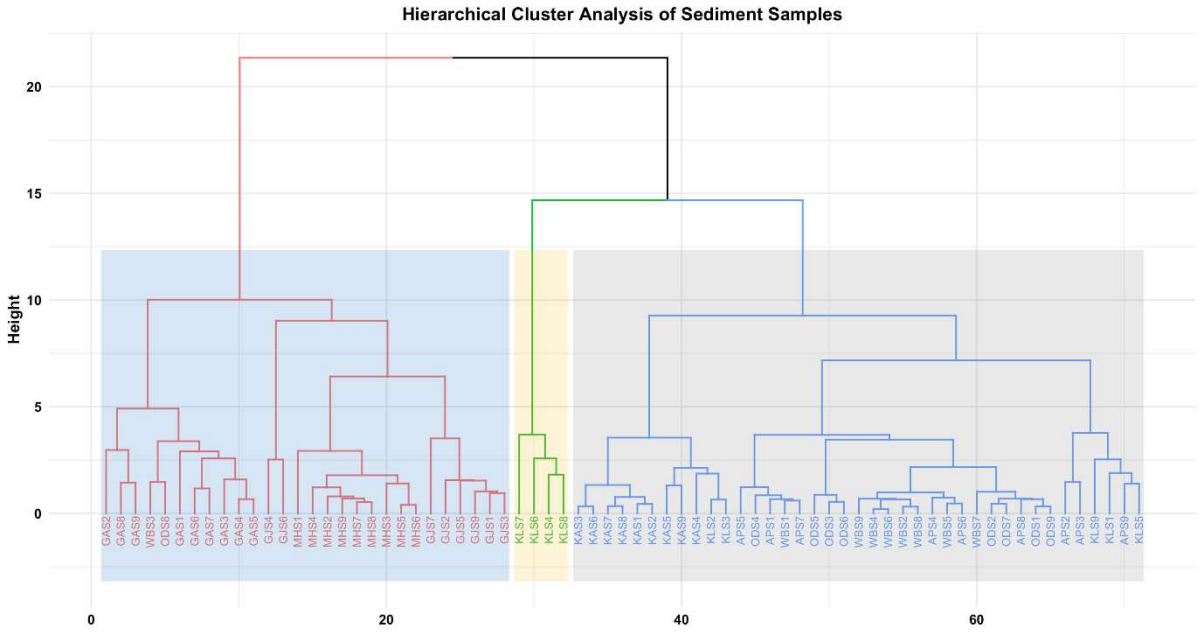
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35 **Fig.5.** Correlation plot with R values explain the degree of relationship among the sediment

36 physiochemical characteristics and sediment metals concentration.



(a) LDA



(b)HCA

Fig.6. (a) Linear Discriminant Analysis (LDA), and (b) Dendrogram of hierarchical clusters demonstrate the distribution of metal concentration and their influences on the sediment quality along the coastal sediments in India.

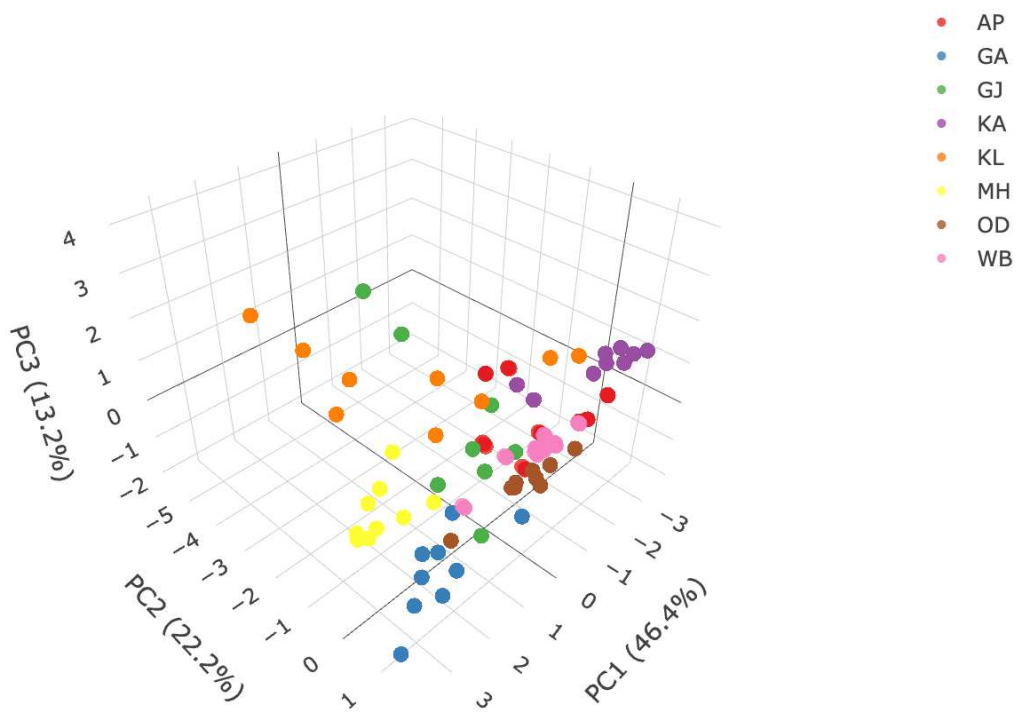


Fig.7. Principal component analysis (PCA) illustrating the potential sources and spatial variability of heavy metals across the eight study regions.

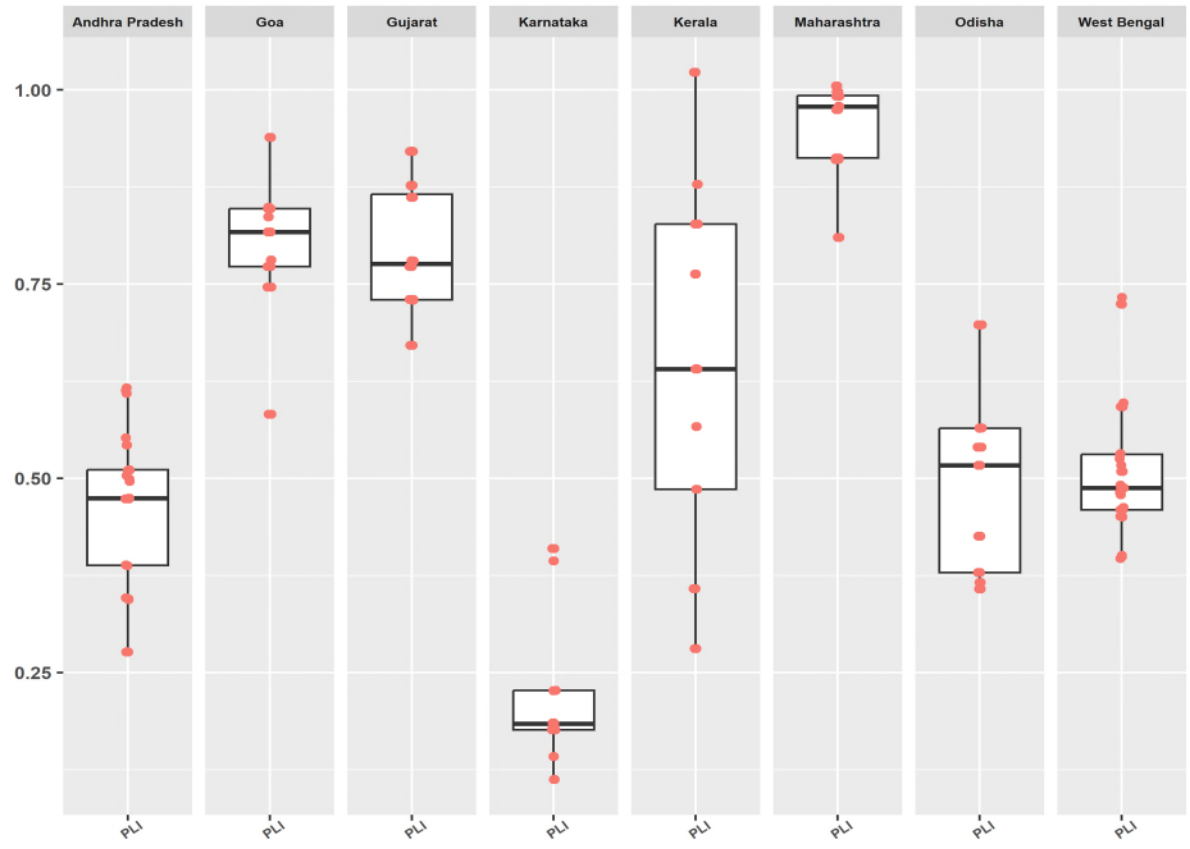


Fig.8. Box-and-whisker plot showing the distribution of Pollution Load Index (PLI) in coastal sediments.

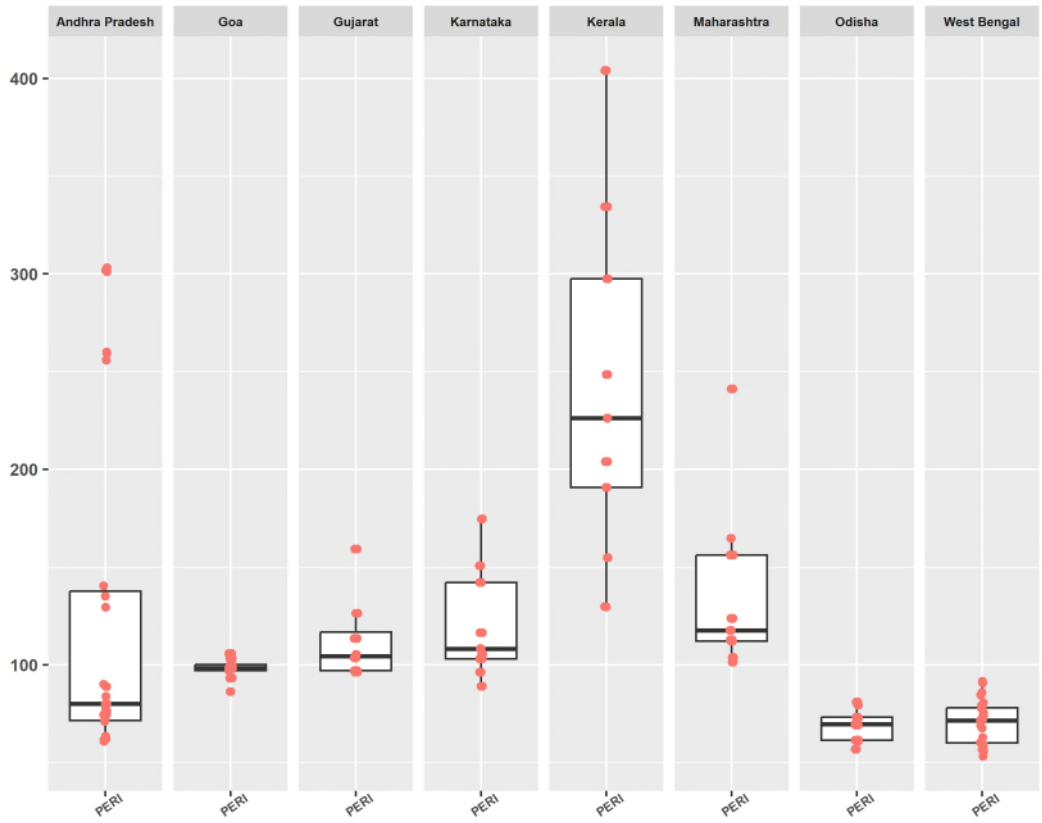


Fig.9. Spatial variation in the Potential Ecological Risk Index (PERI) among coastal states represented using box-and-whisker plots.

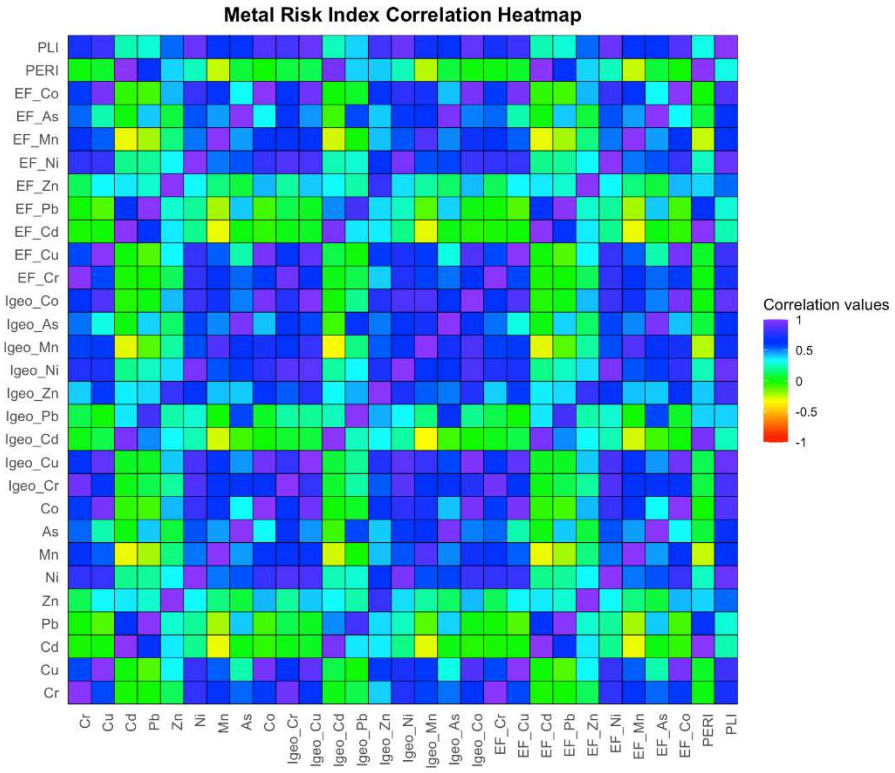


Fig.10. Correlation heatmap demonstrates the interrelationships among heavy metal concentrations and their associated pollution indices

Supplementary Files

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