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Spatial distribution of selected heavy metals and their probable ecological risk in coastal sediments of Tuticorin, southeast coast of India

P. S. Asha^{1*}, R. Lavanya³, A. Usharani², B. Muniswaran Ramar² and Reeta Jayasankar³

¹Regional Centre of ICAR-Central Marine Fisheries Research Institute, Vizhinjam- 695 521, Kerala, India.

²Regional Station of ICAR-Central Marine Fisheries Research Institute, Tuticorin-628 001, Tamil Nadu, India.

³ICAR-Central Marine Fisheries Research Institute, Kochi-682 018, Kerala, India.

*Correspondence e-mail: ashasanil@gamil.com

ORCID: <http://orcid.org/0000-0002-6514-7375>

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Original Article

Abstract

The rise in industrial and urban activities has exacerbated soil contamination with metals, making it a pressing global issue. In this study, eight stations (St.1 to 8) were identified to assess the concentrations of heavy metals such as lead (Pb), cadmium (Cd), nickel (Ni), and mercury (Hg) in the sediments of the Tuticorin coast across four seasons: Monsoon, Post-monsoon, Summer, and Pre-monsoon. The dried, finely ground sediment samples were digested and analysed for heavy metals using standard procedures. Elevated mean concentrations of Cd ($4.95 \pm 0.28 \mu\text{g g}^{-1}$) and Hg ($0.26 \pm 0.06 \mu\text{g g}^{-1}$) were recorded at St.1. At the same time, Ni ($35.59 \pm 4.16 \mu\text{g g}^{-1}$) and Pb ($26.42 \pm 10.1 \mu\text{g g}^{-1}$) showed maximum levels at the St.2. According to the various Sediment Quality Guidelines (SQGs), the study indicated a low probability of adverse effects from Hg, Ni, and Pb along the Tuticorin coast. However, Cd concentrations pose a probable ecological risk with values exceeding the Probable Effect Level (PEL) to Severe Effect Level (SEL) in most stations, indicating potential impact on the benthic ecosystem. A moderate pollution level of Cd (<6) was observed at all stations as per the Environmental Protection Agency (EPA) guidelines. Except for Cd, concentrations of all other metals remained within the PEL thresholds prescribed by the Canadian Environmental Quality guidelines for the protection of aquatic life. The highest pollution index level was noticed at St. 2 and St.1, which reflects the possible anthropogenic impacts. The results of the study emphasise the urgent need for targeted mitigation measures to reduce metal contamination, especially that of Cd, along the Tuticorin coastal belt.

Keywords: Mitigation measures, Probable Effect Level, Sediment Quality Guidelines, Severe Effect Level

Introduction

The high persistence and resistance to natural degradation make heavy metal pollution a significant environmental challenge globally. Heavy metals usually stem from both geogenic and anthropogenic sources in the marine ecosystem (Beier *et al.*, 2022) and serve as a reservoir to release these metals in changing environmental conditions. Usually, these metals pose a threat to the aquatic food chain through bioaccumulation and biomagnification, and ultimately affect human health. Soil contamination by heavy metals arises from sources such as industrial waste, urban effluents, wastewater, mining activities, and prolonged fertiliser application. The intensification of industrial and urban activities has aggravated soil contamination with metals. Non-essential toxic metals, including cadmium (Cd), mercury (Hg), lead (Pb), and nickel (Ni), are particularly harmful, even at low concentrations (Cohen *et al.*, 2001); these are classified as toxic heavy metals.

An industrial town like Tuticorin, in the Gulf of Mannar, has many major and minor industries along its coast. The effluent discharges from various units involved in the production of cotton, staple yarn, caustic soda, PVC resin, fertilisers, soda ash, and liquid carbon dioxide are the primary sources of heavy metal pollution. Earlier studies have identified industrial activities, including fertiliser, chemical, and allied coastal industries, along with urban and port-related inputs, as possible contributors to metal contamination in the Tuticorin coastal environment (Ganesan and Kannan, 1995; Palanichamy

and Rajendran, 2000; Asha *et al.*, 2010; Selvam *et al.*, 2015; Vinothkannan *et al.*, 2022).

The objective of the present study is to assess the level of four toxic heavy metals, such as nickel (Ni), cadmium (Cd), lead (Pb) and mercury (Hg) in the surface sediments of eight stations of the Tuticorin coast. The research will establish a benchmark on the impact of anthropogenic activities on the level of four heavy metals and their potential ecological risk along the coastal zone. The findings will, in turn, be helpful in future research on similar aspects and also to formulate appropriate management measures for safeguarding the coastal resources in the region.

Material and methods

Study area

A baseline survey was conducted along the coastal belt of Tuticorin in both northern and southern directions; consequently, eight stations were identified to assess the heavy metal load. Four stations (St. 1, 2, 3, and 4) were selected along the southern coast, while four stations (St.

5, 6, 7, and 8) were identified along the northern coast. The locations of the sampling stations are shown in Fig.1. Station 1 (St.1) was the coastal belt situated north of Hare Island (08°47'039"N; 078°11'136"E), and Station 2 (St.2) was located south of Hare Island (08°45'154"N; 078°11'609"E). Station 3 (St.3) was positioned in proximity to the Muthiahpuram coast (08°43'587"N; 078°09'495"E), and station 4 (St.4) was fixed near the Tiruchendur coast (08°37'610"N; 078°07'624"E). Station 5 (St.5) was located north of the Threspuram coast (08°47'867"N; 078°09'674"E), and station 6 (St.6) was positioned south of Threspuram (08°48'717"N; 078°09'820"E). Station 7 (St.7) was situated along the coastal areas of Siluvaipatti (08°50'596"N; 078°10'025"E), whereas station 8 (St.8) was close to the Pattanamurthur coast (08°54'329"N; 078°10'786"E).

Sample collection, processing and estimation of heavy metals

Samples were collected from selected stations over four seasons: Monsoon (November, December, and January), Post-monsoon (February, March, and April), Summer (May, June, and July), and Pre-monsoon (August, September, and October). In total, 32 sediment samples were collected from the study locations

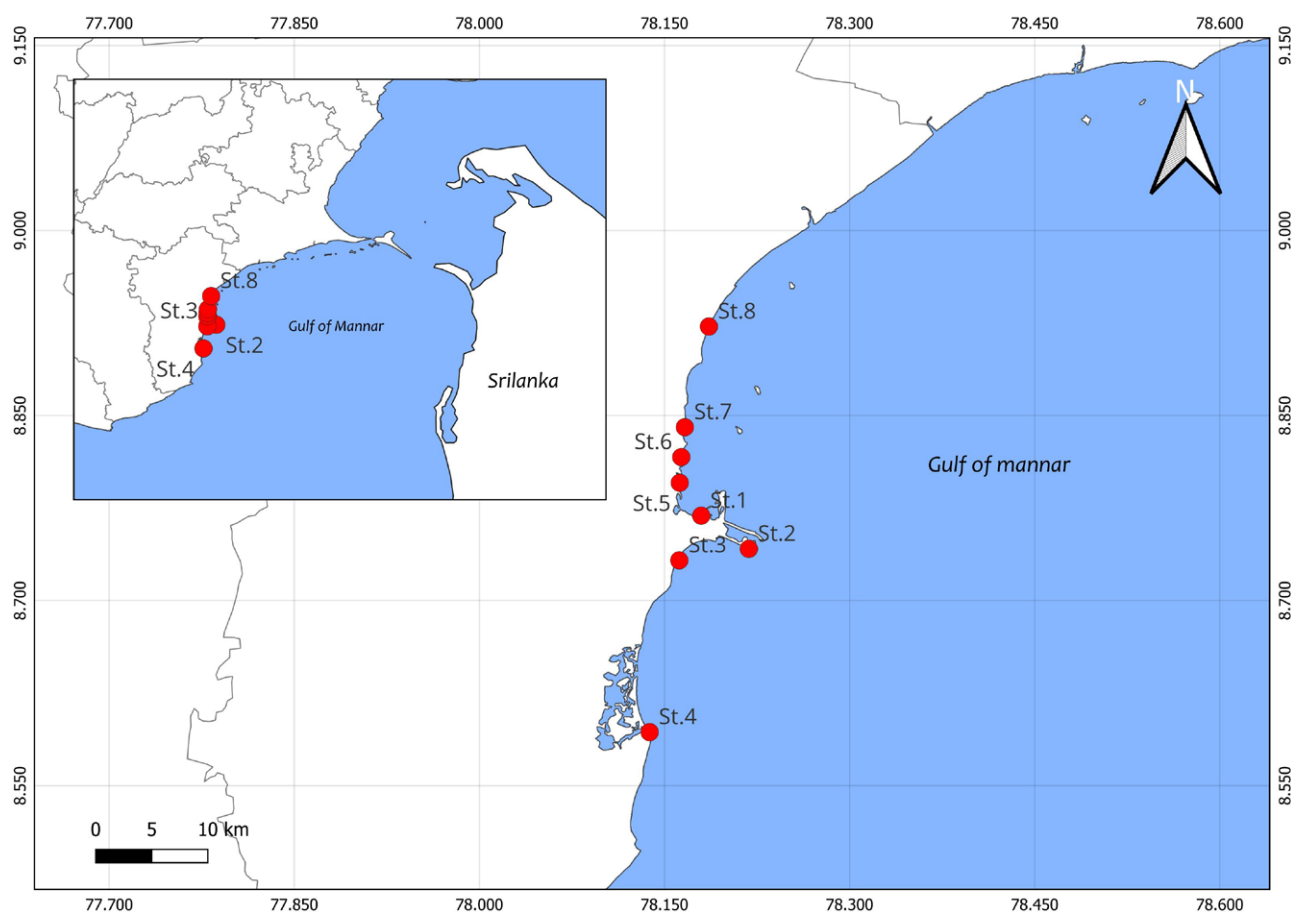


Fig. 1. Location of the sampling stations

across these four seasons. Surface sediment samples were obtained from the top two cm of the intertidal zones using 3.5-inch outer diameter PVC pipes. The collected sediment samples were dried at room temperature, ground to a fine powder using an agate mortar and pestle, and then sieved through a 63- μm sieve. One gram of the sieved sample was acid-digested (Dalziel and Baker, 1984) and filtered with Whatman Grade 542 filter paper to remove residual contaminants. The filtered samples were made up to 100 ml and analysed in triplicate using an atomic absorption spectrophotometer (AAS) Thermo Fisher Scientific–AAS ICE – 3300 AA SPECTRO, by Flame analysis and Hg by cold vapour technique using the vapour generator –VP 100, which is attached to the AAS. The accuracy of the analytical procedure was estimated using the Standard Reference Material for sediment, SIGMA-ALDRICH (USA) SQC001-30G. The analysis precision was within 10%, and the metal recovery from the samples was >90%. All reagents used in the procedures were prepared with metal-free, double-distilled water and analytical grade chemicals. Additionally, the instrument was rinsed with double-distilled water after each use.

Statistical analysis and ecological risk assessment

The estimated mean metal concentrations were used to interpret the results. The significant differences in heavy metal concentrations among sampling sites at the 0.05 level were determined by one-way ANOVA using SPSS software (version 22; Chicago, USA). Different sets of international Sediment Quality Guidelines (SQGs) for marine and estuarine ecosystems were used to evaluate the potential risks posed by heavy metal concentrations in sediments (Long and Morgan 1990; Macdonald *et al.*, 1996; Engler *et al.*, 2005). The

SQGs of the Threshold Effect Level (TEL), Probable Effect Level (PEL), and Severe Effect Level (SEL), which indicate the various ranges of these guidelines (Long *et al.*, 2023), were compared with the estimated concentrations of various heavy metals at all sampling stations. Pollution Load Index (PLI) was used to assess the level of sediment deterioration and to determine whether the target heavy metals originated from natural or anthropogenic sources (Angulo, 1996). The PLI can be calculated by the following formula.

Where n is the number of metals, CF is the contamination factor, which is the ratio of measured concentrations of target metals in the sediment and their original background (geochemical) concentrations. Standard pre-industrial reference levels of target metals in sediment (in mg/kg) are 6.8 for Ni, 1.0 for Cd, 70 for Pb and 0.3 for Hg. The following classes of PLI (Kowalska *et al.*, 2018) were used for interpretation: $1 > \text{PLI}$ – no contamination, $\text{PLI} = 1$ – only baseline levels of contamination, $1 < \text{PLI}$ – deterioration of site quality.

Results

Spatial variation of heavy metal concentration

Notably, there was a considerable fluctuation in Nickel (Ni) concentrations among the stations. The Ni concentrations were relatively higher at Sts. 1, 2, and 3 during the post-monsoon period and lower at St. 5, 6, 7 and 8 (Table 3). The Ni concentrations varied from 20.04 to 39.83 $\mu\text{g g}^{-1}$ at St. 1, 29.45 to 47.87 $\mu\text{g g}^{-1}$ at St.2, and 18.05 to 56.01 $\mu\text{g g}^{-1}$ at St.3. The highest mean value, recorded at St.2, was $35.59 \pm 4.16 \mu\text{g g}^{-1}$ (Fig. 2 a), followed by $34.28 \pm 8.59 \mu\text{g g}^{-1}$ at St.3.

Table 1. Seasonal variation in the heavy metal concentrations in the sediments of the Tuticorin coast

Stations	Heavy metal concentrations ($\mu\text{g g}^{-1}$) during different seasons															
	Ni				Cd				Pb				Hg			
	MON	POM	SUM	PRM	MON	POM	SUM	PRM	MON	POM	SUM	PRM	MON	POM	SUM	PRM
1	20.04	39.83	21.04	36.75	4.88	5.32	5.42	4.18	30.42	10.51	21.88	27.84	0.11	0.22	0.35	0.35
2	32.57	32.48	47.87	29.45	4.56	4.92	4.37	5.49	26.43	3.79	22.62	52.82	0.09	0.11	0.08	0.09
3	23.34	56.01	18.05	39.70	4.82	4.15	4.27	4.71	0.00	0.00	16.19	0.00	0.07	0.06	0.06	0.07
4	28.92	19.76	28.85	25.63	4.54	4.39	4.44	3.86	28.96	1.00	5.38	34.12	0.03	0.05	0.05	0.05
5	18.99	13.85	10.12	16.34	4.54	4.71	4.14	4.24	6.95	10.03	12.80	1.00	0.05	0.05	0.04	0.05
6	10.84	12.63	15.05	18.76	4.46	4.39	4.90	5.06	1.46	2.80	3.04	5.81	0.04	0.05	0.04	0.04
7	22.97	9.64	19.80	16.12	4.88	2.99	4.72	4.07	1.39	0.74	1.22	0.96	0.04	0.04	0.04	0.05
8	0.00	18.93	17.26	18.44	4.76	4.54	4.39	4.54	0.00	0.00	0.00	0.00	0.04	0.04	0.04	0.04

MON-Monsoon, POM-Post Monsoon, SUM-Summer, PRM –Pre Monsoon

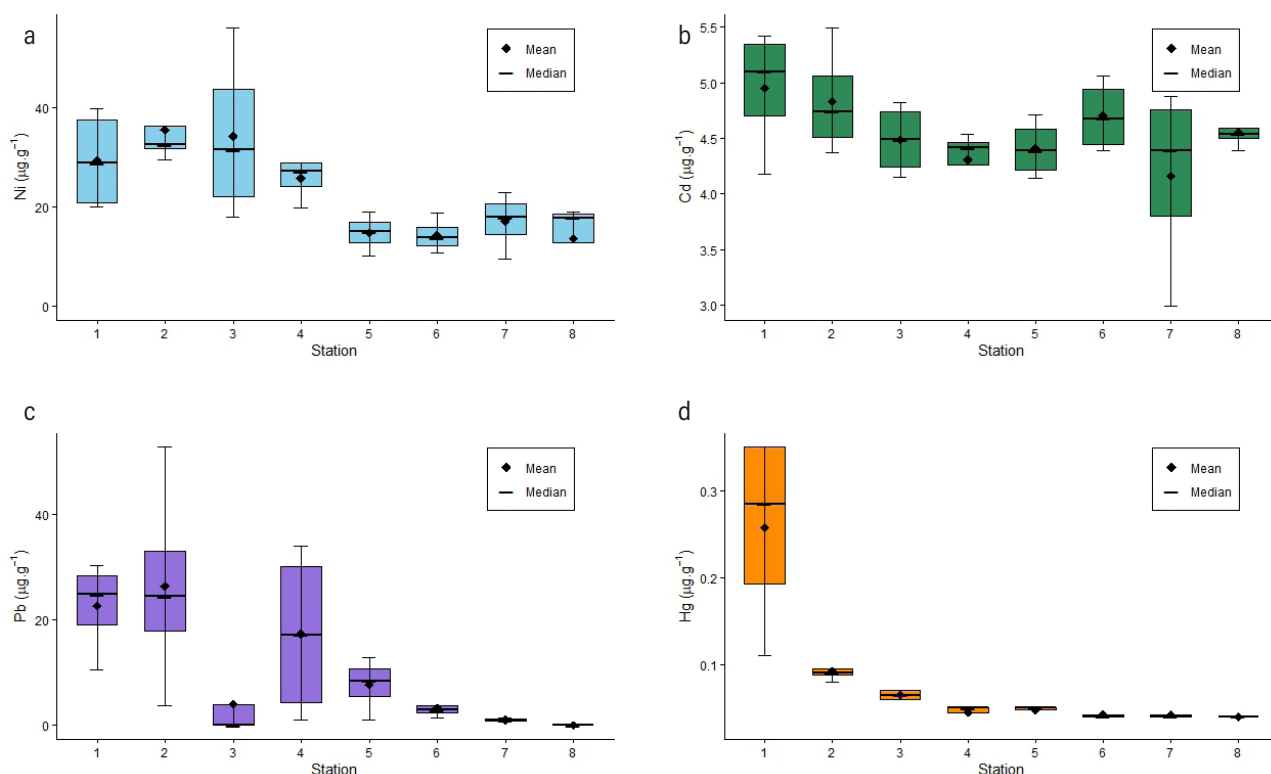


Fig. 2. Concentrations (mean±SE) of heavy metals (a. Ni; b. Cd; c. Pb; and d. Hg) in the coastal sediments of Tuticorin across eight sampling stations

Regarding Cadmium (Cd) concentrations, fluctuations were minimal between stations, with values ranging from a low of $2.99 \mu\text{g g}^{-1}$ at St.7 during the post-monsoon period to a high of $5.498 \mu\text{g g}^{-1}$ at St.2 in the Summer (Table 1). The highest mean concentration was $4.84 \pm 0.25 \mu\text{g g}^{-1}$ at St.1, while the lowest was $4.17 \pm 0.43 \mu\text{g g}^{-1}$ at St.7 (Fig. 2 b).

Lead concentrations were notably higher at St.1 and 2, below the detectable limits at St.8 for all seasons, and could only be detected during the Summer at St.4. The lead levels varied between 10.51 and $30.42 \mu\text{g g}^{-1}$ at St.1, 3.79 and $52.82 \mu\text{g g}^{-1}$ at St.2, and 1 to $34.12 \mu\text{g g}^{-1}$ at St.4. The maximum mean concentration of $26.4 \pm 10.1 \mu\text{g g}^{-1}$ was observed at St. 2 (Fig. 2 c).

With regard to mercury concentrations, fluctuations among St.4, 5, 6, 7, and 8 were not significant, and levels were exceptionally higher at St.1, where the Hg concentrations ranged from 0.11 to $0.35 \mu\text{g g}^{-1}$, with the highest mean concentration being $0.26 \pm 0.06 \mu\text{g g}^{-1}$ (Fig. 2 d).

Ecological risk assessment based on Sediment Quality Guidelines (SQGs)

The levels of heavy metals in the sediments according to the Sediment Quality guidelines are given in Table 2. Accordingly, most stations showed Ni concentrations causing minor

adverse effects as the levels were within the range of TEL to PEL (Fig. 3 a). At the same time, significant negative impact levels were anticipated only at St.2 and 3 during the summer and post-monsoon seasons. Cd concentration causing a significant negative impact on the benthic ecosystem (PEL to SEL) was observed in most stations, including Sts. 1, 2, 3, 4, 5, 6, and 8 (Fig. 3 b). The maximum impact was observed at St.2 and 8. Among the stations, the seasonal variations in Pb levels were significantly high at St.2 and 4 and moderate at Sts. 1 and 5. It was below the threshold effect level (TEL), causing no harm to the benthic fauna at all the remaining stations. during the rest of the season (Fig. 3 c). Minor adverse level effects of Hg were reported at St.1 during the post-monsoon, summer, and pre-monsoon seasons. For all the other stations, Hg was below the threshold effect level (Fig. 3 d). Thus, the study indicated a low probability of adverse

Table 2. Heavy metal levels according to the Sediment Quality Guidelines (SQG) for sediment samples

Metals	Not polluted	Minor adverse effect	Significant negative impact	Heavily polluted
Ni	<5.90	5.90-42.8	42.8-75	>75
Cd	<0.68	0.68-4.21	4.21-10	>10
Pb	<30.20	30.2-112.20	112.2-250	>250
Hg	<0.174	0.174-0.486	0.486-2	>2



Fig. 3. Variation in the Sediment Quality Guidelines concentration of heavy metals (a. Ni, b. Cd, c. Pb and d. Hg) at sampling stations

effects from heavy metals such as mercury (Hg), nickel (Ni), and lead (Pb). Specifically, the analysis revealed a very low risk for Hg, with only 9.4% of samples exceeding the permissible environmental levels (PEL); for Ni, only 6.3% surpassed the PEL; and for Pb, again, 9.4% exceeded the PEL. In stark contrast, the risks associated with cadmium (Cd) were notably high, as 93.8% of the analysed samples surpassed the PEL.

The pollution load index was derived from the contamination factor for each metal (Fig. 4 a, b, c and d) and from the estimation of the pollution index level (PLI). It was found that the PLI was maximum for St.1, followed by St.2, and the least was noticed for St.8 (Fig. 4 e). Consequently, the present evaluation indicated that there was no significant contamination level, except for Cd in the coastal sediment along the Tuticorin coast.

Comparison with regulatory standards

The estimated levels of heavy metal concentrations at sampling stations were compared with Environment Protection Agency (US EPA, 2008) guidelines, as shown in Table 3. The Ni concentration was within the range of moderate pollution (20-50 ppm) at St.1, 2, 3 and 4. Notably, it was in a highly polluted state (>50 ppm) at St.3 during the post-monsoon season, whereas

the unpolluted range of Ni status was reported at St.5, 6, 7, and 8. Cd concentration was notable at all the sampling Stations, which reported a moderate pollution level with Cd (<6) at all the stations. Accordingly, the Pb pollution was not so severe at Tuticorin, as in most of the stations, it was below 40 ppm; it can be considered as unpolluted and a moderately polluted condition was noticed only at St.2 during the pre-monsoon season, which reported a value between 40 – 60 ppm. Mercury levels at all the sampling stations were the lowest as they were not polluted at ≥ 1.0 ppm throughout. All other metal concentrations, except Cd, fell within the levels prescribed by the Canadian Environmental Quality guidelines aimed at protecting aquatic life. An ANOVA test revealed significant differences in the levels of Ni ($p > 0.05$) and Hg ($p > 0.000$) between the sampling stations. However, none of the samples exhibited significant variations across different seasons.

Table 3. Heavy metal levels according to the EPA guidelines for coastal sediment

Metals	Not polluted	Moderately polluted	Heavily polluted	Average In the present study
Pb	<40	40-60	>60	27.98
Cd	-	<6	>6	4.60
Ni	<20	20-50	>50	15.64
Hg	\geq	-	>1.0	0.10

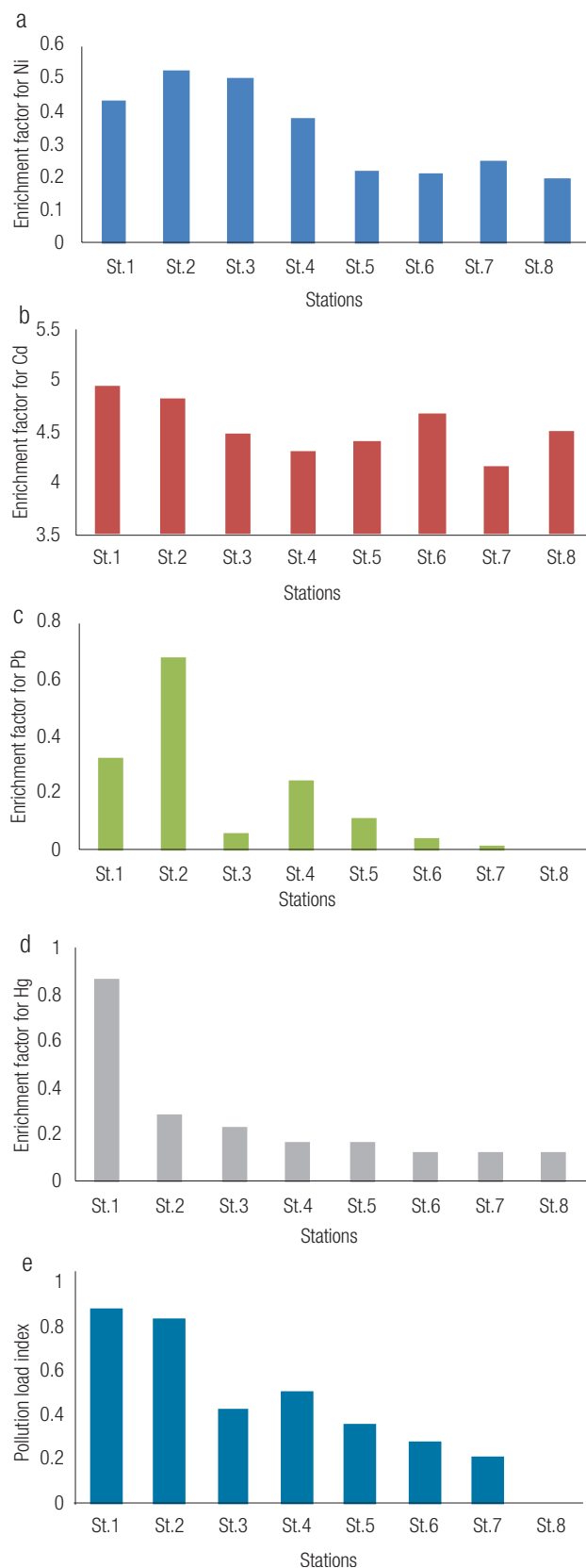


Fig. 4. Enrichment factor for heavy metals (a. Ni, b. Cd, c. Pb and d. Hg) and e. Pollution load index at sampling stations

Discussion

The present study highlighted the presence of four heavy metals in the coastal sediment of eight stations along the Tuticorin industrial zone. The concentration of Ni was found to vary significantly across stations, with the highest mean values observed at St. 2 and 3. Comparable values of Ni in coastal sediments have been noted along the coast of Eastern Tamil Nadu (Harikrishnan *et al.*, 2017), the Gulf of Mannar (Jonathan *et al.*, 2006), and the Palk Strait (Kasilingam *et al.*, 2016). In the present study, exceptionally high concentrations of Ni (56.01ppm) at St.3 during the post-monsoon season clearly indicated the monsoon effect on metal transportation and accumulation in this region, as reported by Wang *et al.* (2013) and El Nemr *et al.* (2016).

The concentration of Cadmium (Cd) in the sediment samples of the study locations was distinctively higher, as 93.8% of them exceeded the Probable Effect Level (PEL), which warns of the probability of negative biological impact. Higher concentrations of Cd in the coastal sediment of Tuticorin and the Gulf of Mannar were earlier reported by many researchers (Asha *et al.*, 2010; Magesh *et al.*, 2013; Selvam *et al.*, 2015; Harikrishnan *et al.*, 2017). High Cd concentrations at multiple sampling points indicate the possible influence of surrounding industries but require source-specific confirmation. In the present study, the maximum concentration of Cd was observed at St. 1, indicating the crucial role of anthropogenic impact. Similar findings of a significant source of Cd pollution in the coastal sediments of the Indian coast have been reported previously (Agrawal *et al.*, 2010; Patel *et al.*, 2017; Gavhane and Pagar, 2025; Mandal and Raj, 2025). Cd is also considered a common impurity in phosphate fertilisers and effluents from fertiliser industries and other anthropogenic discharges, which have been reported to cause significant damage to coastal ecosystems (Robin *et al.*, 2012; Naik *et al.*, 2023; Veluchamy *et al.*, 2024; Nagarajan *et al.*, 2024).

The Lead (Pb) concentrations were below the Threshold Effect Level (TEL) in the majority of the stations; however, significantly higher levels were noticed at Sts. 1, 2, and 4, particularly during the monsoon and pre-monsoon periods. These increases may be attributed to the anthropogenic influences and remobilisation from polluted stations (Dassenakis *et al.*, 1997). The Pb concentration reported in the present study is comparable with that observed by Kasilingam *et al.* (2016) in the Palk Strait sediment. Mercury (Hg) concentration was comparatively higher at St.1, especially during the summer and pre-monsoon season. The increased Hg values at St.1 may be attributed to anthropogenic inputs. Comparable results of Hg concentrations were reported by Veluchamy *et al.* (2024) along south-eastern India and Naik *et al.* (2023) along south-western Bay of Bengal. Although at

the majority of the stations, the mercury level was very low and below the Threshold Effect Level (TEL), hence ongoing monitoring is still required owing to its persistent nature and the capacity for bio-magnification (UNEP, 2013).

In general, the studies reiterated the possible role of anthropogenic sources in the metal pollution of Tuticorin coastal sediments. Relatively lower metal values were noted at stations north of Tuticorin (St. 5, 6, 7, and 8), and the least detected station was St.8, as evidenced by the below-detectable-limit values of Pb during all seasons and Ni during the monsoon period, probably due to less anthropogenic impact, minimising ecological damage.

The studies conducted on similar aspects in the region (Ganesan and Kannan, 1995; Magesh *et al.*, 2013; Selvam *et al.*, 2015; Vinothkannan *et al.*, 2022) also identified that industrial, port-related activities, untreated sewage, and urban runoff are significant sources of heavy metal contamination along the Tuticorin coast. From different parts of the World, other industrialised coastal belts, such as the Pearl River Delta (Zhang *et al.*, 2010), the Red Sea (El-Said *et al.*, 2014), and Mumbai's Thane Creek (Pekey *et al.*, 2006), have reported similar spatial trends.

In this study, slight seasonal variations, especially in Ni concentrations during the post-monsoon period, were observed; ANOVA tests did not reveal significant seasonal variations in metal concentrations. These variations might be due to the redistribution of pollutants along the shore and the drift of coastal currents and monsoonal runoff. The impact of hydrodynamics and sediment transport on the distribution of heavy metal contaminants has been reported earlier (Palanichamy and Rajendran, 2000). Except for Cd, the study showed that the concentrations of other metals, such as Pb, Ni, and Hg, were within the limits prescribed by the Canadian Environmental Quality Guidelines (CEQG) for sediment quality. According to the Sediment Quality Guidelines (SQGs), Cadmium (Cd) was identified as the most concerning pollutant in this ecosystem. At the same time, nickel (Ni), lead (Pb), and mercury (Hg) presented moderate risks. This pattern is consistent with findings from other Indian coastal sediments (Chatterjee *et al.*, 2009; Sahoo and Swain, 2023).

Based on the estimated mean Probable Effect Level (PEL), metals such as Hg, Ni, and Pb exhibited low ecological risk along the Tuticorin coast, whereas Cd levels indicated a comparatively higher potential for ecological concern. The contamination factor (CF) and the Pollution Load Index (PLI) estimate further support these observations, indicating the need for continuous monitoring and appropriate remediation efforts across the region.

This study underscores the spatial differences in the presence of metals in sediments along the southern and northern coastal areas of Tuticorin. These findings indicate possible anthropogenic influences as a source of heavy metal accumulation in this area. High levels of Cd, Pb, and Hg at St.1; elevated levels of Ni, Pb, and Cd at St.2; and a notable increase in Ni at St. 3 highlight the possible role of anthropogenic disturbances in these areas. The consistently high Cd levels across all stations also emphasise the need for remedial actions to mitigate the potential hazards. In contrast, the northern coastal sediments exhibited comparatively lower metal concentrations, suggesting limited anthropogenic influence pressure in this region compared to that in the southern coastal sediments.

Overall, the findings provide a valuable scientific baseline for future environmental monitoring, ecological risk assessment, and policy formulation aimed at sustainable coastal zone management. Continuous monitoring, stricter effluent management, and implementation of environmentally sustainable industrial practices are essential to prevent further accumulation of toxic metals and safeguard the ecological health of the Tuticorin coastal ecosystem. Additionally, the use of appropriate bioremediation strategies (Eggleton and Thomas, 2004; Li *et al.*, 2015) and supplementary ecotoxicological research involving local biota is advised. Given the impact of coastal currents and sediment movement, this study also emphasises the necessity for enhanced surveillance measures and community awareness programs along the Tuticorin coastline.

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Author contributions

Conceptualisation: PSA, JR; Methodology: PSA, DP, LR, JR; Data Collection: PSA, AU, MR, LR; Data Analysis: PSA; Writing Original Draft: PSA; Supervision: KSS, JR, DP.

Data availability

The data are available and can be requested from the corresponding author.

Conflicts of interest

The authors declare that they have no conflict of financial or non-financial interests that could have influenced the outcome or interpretation of the results.

Ethical statement

No ethical approval is required as the study does not include activities that require ethical approval or involve protected organisms/ human subjects/ collection of sensitive samples/ protected environments.

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