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Soil Geochemistry and Health Assessment Based on Heavy Metal Indexing in Kanyakumari District, Tamil Nadu, India

U.B. Vishnu, A. Aswini, T.M. Vishnu Maya, K Anoop Krishnan and A. Krishnakumar*

National Centre for Earth Science Studies (NCESS), Thiruvananthapuram-695011, Keralam, India
*(*Corresponding Author, E-mail: drakrishnakumar@gmail.com*)

Abstract

Understanding soil characteristics in river basins is crucial, as they directly influence agricultural productivity, ecological health, and the transport of contaminants within watersheds. This study investigates the Tamiraparani River Basin, where 39 soil samples were systematically collected across the region to evaluate physicochemical properties and selected metal concentrations, aiming to assess soil quality and contamination levels. Standard methods were employed to analyse parameters such as pH, electrical conductivity, and elemental concentrations. The degree of contamination ranged from 6.47 to 14.54, with four sites exhibiting low contamination and the remaining sites showing moderate levels. Pollution Load Index values varied between 0.73 and 1.26, with sixteen sites indicating progressive deterioration of soil quality, reflecting increasing anthropogenic pressures. The findings indicate generally low contamination levels, with only marginal enrichment at certain sites, suggesting that precautionary monitoring is needed. Given the critical role of soils in achieving several United Nations Sustainable Development Goals, including Zero Hunger, Climate Action, and Life on Land, the study underscores the importance of sustainable soil management in the context of global environmental changes, climate variability, and accelerating soil degradation. The results not only enhance understanding of regional soil health but also provide a foundation for future research, policy formulation, and sustainable land-use planning.

Keywords: Anthropogenic, Pollution Load Index, Soil Contamination Indices, XRF geochemistry

Introduction

Soil is an essential natural resource that greatly contributes to food security, as it determines the quality and composition of crops and animal feed forming the foundation of the food chain. Soils serve as the basis of all terrestrial ecosystems and play a crucial role in supporting biodiversity and the provision of ecosystem services (Neuenkamp *et al.,* 2024). It also plays an important role in maintaining ecological balance across the planet (Tóth *et al.*, 2016). However, every year, soil is polluted by various harmful substances from industries, agriculture, mining, and household waste (Franco-Uría *et al.*, 2009).

Toxic elements present in soils are particularly concerning. This is because they do not break down naturally, stay in the environment for a long time, and can persist in living organisms (Gowd *et al.*, 2010; Romic and Romic, 2003). These elements accumulate in soil through human activities and can eventually enter crops, leading to contamination of the food chain and posing serious health risks to humans (Antoniadis *et al.*, 2017a, b, 2019; Cheng, 2003; Kelepertzis, 2014). Over time, long-term exposure to high levels of toxic elements—beyond safe limits—can cause harmful effects on human health (Beckers and Rinklebe, 2017; Bolan *et al.*, 2014; Rinklebe *et al.*, 2019). Recent studies have emphasized the importance of geochemical characterization of soils for understanding elemental distribution, contamination levels, and their implications for sustainable land management (Moreno *et al.,* 2026; Wu *et al.,* 2026). Soil geochemistry plays a critical role in identifying both natural and anthropogenic influences on elemental concentrations and helps in establishing baseline values for environmental assessment (Berdie *et al.,* 2026). Health issues such as skin diseases, asthma, cancer, and reproductive problems are commonly reported in the highland regions and may be linked to the heavy use of these agrochemicals (Misra, 2011). Recent research in the southern Western Ghats has highlighted the importance of soil geochemistry in assessing both environmental quality and human health risks. Studies from the Kabini Basin have demonstrated heavy metalloid enrichment and its potential health implications in agricultural soils (Gupta *et al.*, 2025; Gupta *et al.,* 2023). Investigations in the Idukki agroforestry-dominated HRML regions further emphasize how land-use practices influence soil geochemistry and associated health status (Krishnakumar *et al.*, 2024). Complementary work in the Periyar Basin has established baseline reference geochemical values for tropical soils, providing a framework for evaluating contaminant accumulation in the Western Ghats (Krishnakumar *et al.,* 2023). Together, these studies underscore the geochemical variability across river basins and the

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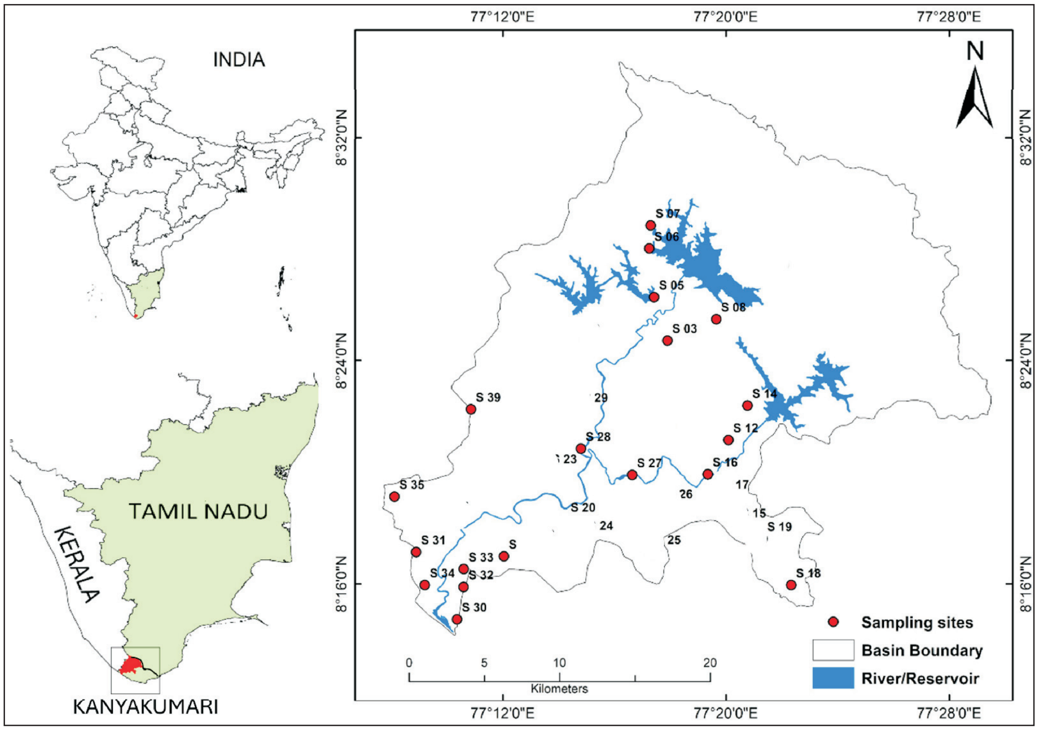

Fig. 1. Location map showing the stations in Tamiraparani River Basin, Kanyakumari District

emerging concerns related to elemental contamination in soils of the Western Ghats.

Research on the sources and magnitude of pollution in the agricultural soils of the TRB remains limited. Therefore, this study focuses on measuring the concentration of elements in the soil, identifying relationships between different elements using geochemical methods. Understanding how much of these metals are available to plants is critical because it affects soil quality and food safety. Hence, this research aims to shed light on soil conditions in the TRB's agricultural systems, helping inform future policies to limit their buildup, ensure safe food production, and protect human health (Gowd *et al*., 2010).

While scientific knowledge and proven technologies exist, a major challenge lies in translating this knowledge into practice through inclusive governance, policy interventions, and community-based engagement. In this context, examining the soil geochemistry of the Tamiraparani River Basin in Tamil Nadu's Kanyakumari district is especially significant. Evaluating the physicochemical traits and contamination status of soils in this area provides valuable insights into the relationship between soil quality, agricultural productivity, and environmental sustainability. Such region-specific analyses not only support local land and water management strategies but also align with global efforts to meet SDG targets through informed, science-based interventions.

Materials and Methods

Study Area

Kanyakumari district, located at the southernmost tip of India in Tamil Nadu, holds unique geographical and cultural significance as the confluence of the Arabian Sea, Bay of Bengal, and the Indian Ocean. Historically part of the erstwhile Travancore kingdom, the district lies between 8°13′ N to 8°34′ N latitude and 77°5′ E to 77°31′ E longitude (Krishnakumar *et al*., 2025). The region is characterized by a subtropical climate and a predominantly agrarian landscape, shaped by its peninsular setting. Unlike most parts of Tamil Nadu, Kanyakumari benefits from both the southwest and northeast monsoons, receiving annual rainfall ranging from 80.06 to 241 mm, with average temperatures between 23°C and 27°C (Kaliraj *et al.*, 2015), which supports extensive agricultural activity covering nearly 66% of the land, including coconut plantations, paddy fields, and forested tracts (Kaliraj *et al.,* 2015). The Tamiraparani River (locally known as Kuzhithuraiar) forms the principal drainage system of the district and is vital for its agrarian economy; it originates in the Western Ghats and extends for about 42.78 km, formed at Moovattumugam by the confluence of the Kodayar and Paraliyar rivers before draining into the Arabian Sea at Thengapattanam (Krishnakumar *et al.,* 2025). The Tamiraparani river basin covers approximately 745 km², accounting for nearly 45% of the total geographical area of Kanyakumari district, underscoring its hydrological and socio-economic importance (Krishnakumar *et al*., 2025).

Soil Sampling, Sample Preparation and Laboratory Analysis

During this study, a total of 39 soil samples were collected from different sites across the TRB in April 2023 (Fig. 1) at depths ranging from 5–20 cm, corresponding to the soil "A" horizon. The sampling locations were selected based on land-use categories, including built-up areas, urban soils, residential zones, forested regions, proximity to industrial areas, and riverine alluvium. This approach ensured spatial representativeness across different land-use types. The sampling points were located and recorded using GPS. Samples were placed in self-sealing polythene bags and transported to the laboratory for analysis. The samples were oven-dried at 60°C for 48 hours, after which dry weight was determined and moisture content calculated using the gravimetric method. The dried soils were ground with an agate mortar and pestle, sieved through a 230-mesh (US standard), and homogenized with boric acid crystals as a binder. Pellets were then prepared using a hydraulic press in collapsible aluminum cups. Metal ion concentrations were analyzed with an X-ray fluorescence spectrometer (S8 Tiger and S4 Pioneer, Bruker Scientific Pvt. Ltd., India), with detection limits as low as 1 ppm.

Quality Assurance and Quality Control (QA/QC)

Strict quality assurance and quality control (QA/QC) protocols were followed to ensure the accuracy and reliability of both analytical and instrumental results. All measurements were conducted in triplicate to maintain precision, and accuracy was verified using standard calibration curves along with certified reference materials. Additionally, major and trace element analyses carried out using X-ray fluorescence (XRF) spectroscopy were validated with the sediment reference material MAG-1 procured from the United States Geological Survey (USGS), which also served in the preparation of calibration curves.

Analytical precision was evaluated using the Relative Standard Deviation (RSD) derived from triplicate analyses of the MAG-1 reference material. The RSD values for all analyzed elements were below 10%, demonstrating a high level of precision. Accuracy was further assessed by comparing the measured concentrations with certified reference values, with relative errors consistently remaining under 10%. These results collectively confirm the reliability and robustness of the analytical methods applied in this study.

Evaluation of Contamination Indices

Establishing geochemical baselines is essential for distinguishing between natural background levels and anthropogenic contamination in soils (Kafle *et al*., 2026). Several recent investigations have highlighted that land-use practices significantly influence elemental enrichment, depletion, and overall soil quality (Sun *et al*., 2026; Li *et al.*, 2026). The level of contamination in soils by various metallic elements was assessed using:

Contamination Factor (Cf)

The contamination factor is a dimensionless parameter calculated by dividing the concentration of each element in the study area by its corresponding natural background or baseline value, typically derived from uncontaminated (pristine) soils.The equation is given as:

$$CF = C/B$$

Where C is the element concentration in the soil sample (ppm), B represents the background concentration of that element in the sample (ppm). In the present study, the baseline reference geochemical values suggested by Krishnakumar *et al.* (2023) were used as background values for comparison. Hakanson (1980) used four categories for contamination factor based on the range of values as:

$C_f < 1$ low contamination factor;
$1 \leq C_f < 3$ moderate contamination factor;
$3 \leq C_f < 6$ considerable contamination factor;
$C_f \geq 6$ high contamination factor

Degree of Contamination (C_d)

The sum of Contamination Factors (C_f)s of all the elements tell us the degree of contamination (C_d) of the area and the four classes are:

$C_d < 8$ low degree of contamination;
$8 \leq C_d \leq 16$ moderate degree of contamination;
$16 \leq C_d < 32$ considerable degree of contamination;
$C_d \geq 32$ very high degree of contamination.

Pollution Load Index (PLI)

The method proposed by Tomlinson *et al*. (1980) was used to find the level of pollution in the TRB. It is calculated as:

$$PLI = (C_{f1} * C_{f2} * C_{f3} \; .....* C_{fn})^{1/n}$$

Here, C_f represents contamination factors for different elements 1,2,3 …n at a given site, 'n' represents the number of elements taken into consideration for that particular site. The various classes of PLI includes:

PLI = 0 (perfection);
PLI up to 1 (baseline level of pollution present);
PLI > 1 (progressive deterioration of site).

Geo-accumulation Index (I_{geo})

The geo-accumulation index was applied to assess the present environmental condition and the extent of metal contamination in comparison to natural background levels. This method uses chemical data to estimate the degree of pollution. Müller (1969) proposed the following equation for calculating Igeo values.

$$I_{geo} = \log_2 C / (1.5 * B)$$

In this context, C represents the concentration of the element in the soil sample (ppm), while B denotes its corresponding background concentration (ppm). A constant factor of 1.5 is incorporated to account for possible variations in background values arising from lithogenic effects. The calculated Igeo values are classified into seven categories: Class 0 (Igeo ≤ 0), indicating practically unpolluted conditions; Class 1 (0 < Igeo ≤ 1), unpolluted to moderately polluted; Class 2 (1 < Igeo ≤ 2), moderately polluted; Class 3 (2 < Igeo ≤ 3), moderately to heavily polluted; Class 4 (3 < Igeo ≤ 4), heavily polluted; Class 5 (4 < Igeo ≤ 5), heavily to extremely polluted; and Class 6 (Igeo > 5), representing extremely polluted conditions.

The application of geochemical indices such as contamination factor, pollution load index, and geo-accumulation index has been widely adopted in recent studies to assess the degree of soil contamination and associated environmental risks (Tume *et al.*, 2026). These indices provide a quantitative framework for evaluating pollution intensity and guiding land-use planning and management decisions.

Evaluation of Human Health Risk

Soil is an essential component of the ecosystem. Human health is considerably affected by the soil either it can be positive or negative, direct or indirect. Over exposure of soil elements to the human are capable of malevolent hazards. Health risk assessment predicts the health effects resulting from exposure to the elements. Heavy exposure to metals even can lead to cancer (Bray *et al.,* 2013). Estimating daily consumption, non-carcinogenic hazard indices, and lifetime carcinogenic hazards for adults and children are all part of evaluating the possible health effects of soil-borne elements. Inhalation, ingestion, and skin absorption are the three main exposure modes (Dick, 2014). Children and Infants are more likely to be affected by bioaccumulation of elements. In the present study, risk assessment is done by the standard set of the United States Environmental Protection Agency (USEPA, 2011). The study evaluated three possible pathways through which soil can enter the human body: (i) ingestion through the mouth, (ii) inhalation via the nose and mouth, and (iii) dermal contact. According to the 2011 USEPA guidelines, the average daily doses (ADDs) of toxic elements for each exposure route can be estimated.

$$ADD_{ing} = [(C_s \times IngR \times EF \times ED) / (BW \times AT)] \times 10^{-6}$$

$$ADD_{inh} = (C_s \times InhR \times EF \times ED) / (PEF \times BW \times AT)$$

$$ADD_{dermal} = [(C_s \times SA \times AF \times ABF \times EF \times ED) / (BW \times AT)] \times 10^{-6}$$

In this study, the concentration of Cs, representing the levels of toxic elements was examined in all soil samples collected from the basin. Additionally, the values of various exposure-related parameters such as IngR (ingestion rate), EF (exposure frequency), ED (exposure duration), BW (body weight), AT (average time), InhR (inhalation rate), PEF (particulate emission factor), SA (skin surface area exposed), AF (skin adherence factor), and ABF (dermal absorption factor) were compiled. Amongst the elements that we are studying, only chromium and nickel are carcinogenic, rest (vanadium, copper, zinc, manganese, aluminium, iron and barium) all are non- carcinogenic.

Hazard Quotient (HQ) and Hazard Index (HI)

The Hazard Quotient Index (HQ_i) represents the ratio of the Average Daily Dose (ADD) of each element to its respective Reference Dose (RfD) for a given exposure pathway. It can be calculated by assessing the degree of exposure to a material with a reference value for toxicity. It a unitless number typically used to calculate the potential non-carcinogenic risk. Thus, we are using this for studying non-carcinogenic elements (vanadium, copper, zinc, manganese, aluminium, iron and barium). The HQ is calculated for each element for different routes (ingestion, inhalation and dermal).

Hazard index (HI) is the sum of all hazard quotients by the individual elements. It is calculated by:

$$HI = \Sigma HQ = HQ_{ing} + HQ_{inh} + HQ_{derm}$$

If HI is less than 1, then no significant health risk and the exposure is safe. If HI is greater than 1, then a significant health risk exists. A measure called the total hazard index (THI) can be calculated by summing the hazard indices (HIs) of each elements. This approach is described and has been previously discussed by Chen *et al.* (2024) and the United States Environmental Protection Agency (US EPA, 2011). According to Usero *et al.* (1996), non-carcinogenic risks are considered significant only when HI or THI values surpass 1; results below this limit suggest the absence of adverse health impacts.

Carcinogenic Risk Assessment

The cancer risk (CR_i) is determined by multiplying the Average Daily Dose (ADD) of the carcinogenic element by its respective slope factor (SF). Similar to the Total Hazard Index (THI), the Total Carcinogenic Risk Index (TCRI) is obtained by summing the individual cancer risks (CR) of all elements.

$$CR = \Sigma CR_i = \Sigma ADD_i \times SF_i$$

$$TCRI = \Sigma CR$$

If the values of CR or TCRI is greater than 1×10^{-4}, the risk for cancer is high whereas if the values are between 1×10^{-6} and 1×10^{-4} then it is at tolerable risk (Fryer *et al.*, 2006).

Results and Discussion

Elemental Concentration in Soils of Tamiraparani River Basin

The descriptive statistics of 8 metallic elements (ppm) in soils of the Tamiraparani River Basin compared with local background values (Krishnakumar *et al.*, 2023) is shown in Table 1.

The enrichment of Cu, V, and Ni above local background levels in soils of the study area reflects a combination of lithogenic control and anthropogenic inputs. Elevated Cu is likely influenced by agricultural practices, including the use of Cu-based fungicides, fertilizers, and organic amendments. In contrast, the high concentrations of V and Ni, particularly in selected samples, indicate a strong geogenic origin, associated with the weathering of mafic to ultramafic parent rocks and their affinity with Fe–Mn oxides. The spatial distribution of these elements suggests that V and Ni are predominantly controlled by parent material, whereas Cu shows mixed geogenic and agricultural influence.

Assessment of Elemental Contamination

The assessment of Contamination Factor (CF) and Geoaccumulation Index (Igeo) indicates variable contamination levels among the studied elements, depicted in Table 2. Igeo values are used for assessing soil quality where they are not compared to other indices due to the nature of calculation involved, use of log function and a background multiplication of 1.5. It consists of seven classes. The mean of contamination factor of elements were in the

Table 1: Descriptive Statistics of Concentration of metal elements (ppm) in soils of Tamiraparani River Basin

Soil Sample	Metal							
	V	Cr	Ni	Cu	Zn	Rb	Sr	Ba
Local Background Value	170.28	171.86	55.43	37.14	75.14	114.14	201.85	954
Min	111	58	15	35	81	24	28	265
Max	560	189	156	182	476	503	281	655
Mean	192.64	113.77	73.21	97.85	139.69	126.10	102.31	509.24
SD	76.04	32.32	32.89	35.29	67.05	94.19	63.57	96.28

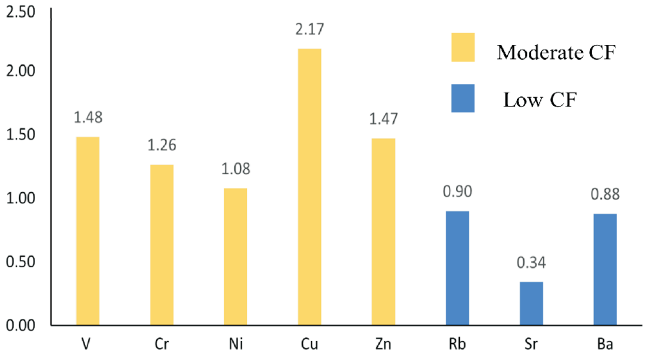

Fig. 2. Contamination factors of metal elements in soils of Tamiraparani River Basin

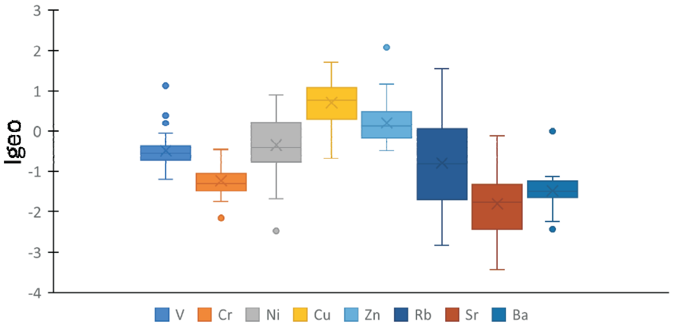

Fig. 3. Box and whisker plot showing variation of Igeo values of metal elements in soils of Tamiraparani River Basin

order [Cu(2.17)>V(1.48)>Zn(1.47)>Cr(1.26)>Ni(1.08)> Rb(0.90)>Ba(0.88)>Sr(0.34)] (Fig. 2).

Vanadium, Nickel, Copper, and Rubidium exhibit CF values ranging from low to considerable contamination, with geoaccumulation index (I_{geo}) values suggesting conditions from practically unpolluted to moderately polluted. Chromium, Strontium, and Barium generally fall within low contamination categories and remain practically unpolluted based on I_{geo}. In contrast, Zinc shows the highest degree of contamination, with CF values reaching moderate to high levels and Igeo values extending up to heavily polluted, marking it as the most critical element of concern. Overall, the findings suggest that while most elements are within safe to moderate contamination levels, Both copper and zinc stand out as the potential elements posing ecological risk in the study area. Similar patterns of elemental enrichment and spatial variability have been reported in recent studies, where both natural geological processes and anthropogenic activities were identified as key controlling factors (Khundrakpam *et al.,* 2026). Such findings support the interpretation that soil geochemistry is strongly influenced by land-use changes and environmental conditions.

The degree of contamination (Cd) across the soil samples varied between 6.47 and 14.54, corresponding predominantly to the moderate contamination class, with only three samples (1, 16, and 18) falling into the low contamination category. In terms of Pollution Load Index (PLI), values ranged from 0.73 to 1.26. The majority of samples exhibited PLI values below 1.0, reflecting a baseline level of pollution. However, several sites (notably samples 4, 8, 9, 17, 19, 20, 22, 23, 27-29, 31, 33, 35–37) recorded PLI values greater than 1.0, signifying a state of progressive deterioration. Overall, while most soils indicate only baseline pollution levels, the presence of multiple sites with progressive deterioration highlights localized hotspots of ecological stress, warranting closer monitoring and management. The box and whisker plot evaluating geo-accumulation index for metal elements is depicted in Fig. 3.

Multivariate Statistical Analysis (PCA)

Principal Component Analysis (PCA) is a commonly employed multivariate statistical method used to evaluate relationships among variables by simplifying complex datasets through dimensionality reduction. In this study, PCA was applied to the geochemical dataset of 39 soil samples collected from the Tamiraparani River Basin. A total of six principal components with eigenvalues greater than 1 were identified, together accounting for a substantial proportion of the overall variance. The rotated component matrix, derived using Varimax rotation with Kaiser normalization (Table 3), illustrates the distribution and associations of trace elements among the extracted components.

The first principal component (PC1) is dominated by strong positive loadings of Sr (0.606), Zn (0.537), with a strong negative loading of Ba (-0.775). This component represents lithogenic control, primarily associated with carbonate and silicate mineral weathering. The second principal component (PC2) shows very high loadings of V (0.967), along with Zr (0.885). This component reflects mafic mineral influence and heavy mineral fraction, indicating the contribution of resistant minerals such as ilmenite, rutile, and zircon. The third principal component (PC3) is characterized by high positive loadings of La (0.751), Ga (0.735), and Ni (0.681), along with moderate contributions from Ba (0.477). This component represents clay mineral association and aluminosilicate fraction, indicating intense weathering and secondary mineral formation. The fourth principal component (PC4) is dominated by strong loadings of Rb (0.891), Y (0.845) with moderate contribution from Sr (0.472). This component is indicative of feldspar weathering and felsic source contribution, where Rb and K are typically associated with K-feldspar and mica minerals. The presence of Y further suggests association with accessory minerals and geogenic inputs.

The fifth principal component (PC5) shows strong loadings

Table 2: Contamination Factor and Geo-accumulation index in soils of Tamiraparani River Basin

Metals	Contamination Factor Range	Mean CF	Category of Contamination Factor	Igeo Range	Mean Igeo	Category of Geoaccumulation Index
V	0.65 - 3.29	1.48	Low to considerable	-1.20 - 1.13	-2.33	Practically unpolluted to moderately polluted
Cr	0.34 - 1.10	1.26	Low to moderate	-2.15 - -0.45	-1.7	Practically unpolluted
Ni	0.27 - 2.81	1.02	Low to moderate	-2.47 - 0.91	-3.38	Practically unpolluted to moderately polluted
Cu	0.94 - 4.90	2.17	Low to considerable	-0.67 - 1.71	-2.38	Practically unpolluted to moderately polluted
Zn	1.08 - 6.33	1.47	Moderate to high	-0.48 - 2.08	-2.56	Practically unpolluted to heavily polluted
Rb	0.21 - 4.41	0.90	Low to considerable	-2.83 - 1.55	-4.38	Practically unpolluted to moderately polluted
Sr	0.14 - 1.39	0.34	Low to moderate	-3.43 - -0.11	-3.32	Practically unpolluted
Ba	0.28 - 0.69	0.38	Low	-2.43 - -1.13	-1.3	Practically unpolluted

Table 3: Rotated Component Matrix and Variance Contribution of Heavy Metals in Soils

Metals	Components					
	1	2	3	4	5	6
V	-0.092	0.967	0.139	-0.063	-0.021	-0.079
Cr	-0.03	-0.054	0.035	-0.148	0.875	0.155
Ni	-0.339	-0.042	0.681	-0.123	0.231	-0.135
Cu	0.243	-0.243	-0.021	-0.114	0.17	0.852
Zn	0.537	-0.227	-0.024	0.152	-0.011	0.29
Rb	0.149	0.031	-0.294	0.891	-0.091	-0.075
Sr	0.606	-0.041	-0.229	0.472	-0.249	0.195
Ba	-0.775	0.122	0.477	0.157	-0.134	0.165
Eigen Value	5.04	2.67	2.34	1.78	1.91	1.22
Variance	28.00%	14.83%	13.00%	9.89%	10.61%	6.78%
Cumulative	28.00%	42.83%	55.83%	65.72%	76.33%	83.11%

of Cr (0.875). This component reflects Fe–Mn oxide phase and redox-controlled processes, which play a crucial role in the adsorption and mobility of heavy metals. The presence of Cr indicates possible contributions from ultramafic rocks as well as potential anthropogenic inputs. The sixth principal component (PC6) is dominated by a very strong loading of Cu (0.852), suggesting a distinct anthropogenic influence, likely linked to agricultural activities, industrial inputs, or localized contamination sources. The relatively isolated loading pattern of Cu indicates its independent behaviour compared to other metals.

Overall, the PCA results suggest that the geochemistry of soils in the Tamiraparani River Basin is primarily controlled by natural geological processes, including weathering of silicate and mafic rocks, along with secondary contributions from anthropogenic activities such as agriculture and localized contamination. The separation of elements into distinct components highlights the combined influence of lithogenic, pedogenic, and anthropogenic factors governing soil chemistry in the study area.

Human Health Assessment

Soil plays an important role in maintaining human health. More than 78% of calories consumed are obtained from the soil. Through crop absorption, potentially harmful compounds in the soil, such as heavy metals, can be transferred to humans. The person who works directly with the soil like farmers, miners, and construction workers are prone to face health issues related to direct soil contact. Some dust from the soil can travel thousands of miles and have an impact on humans far from their source of origin. Soil can be enriched with the elements either naturally or through anthropogenic activities. If the elemental concentration falls from the optimal range, it will result in deficiency while if it goes above the optimal range it will result in toxicity. Therefore, depending on the concentration of elements and level of exposure humans can be potentially hazardous, adequate, or deficient (Steffan *et al.,* 2018).

To assess the health risk of metal in TRB soil, the average daily dose is intimated for three exposure pathways such as ADD_{ing}, $ADD_{inh,}$ and ADD_{dem}. For adults and children, calculation is done separately, as the rate of effects due to exposure is different. The hazard quotient of elements such as V, Cu, Zn, Mn, Al, Fe, and Ba are presented in a series of values, indicating varying levels of HI in children and adults as represented in Table 4. HI value of Al in children is higher than 1, which has significant health risk indicating it may result in non-carcinogenic effects while other values are under permissible levels only. For adults HI values are under the permissible level. HI value in children shows a trend of Al >V> Fe >Ba>Mn >Cu >Zn and for adults Al >Fe> V>Ba>Mn >Cu >Zn. The THI values is greater than 1 in children and less than 1 in adults. This means that children are more prone to be affected in their health due to non-carcinogenic impact.

The carcinogenic risk (CR) for Cr and Ni was determined. Children have higher CR_{ing}, CR_{inh}, and CR_{derm} values for Cr and Ni than adults. Nickel poses a higher total cancer risk than chromium in both adults as well as in children. In the present study, the TCRI for children was calculated as 2.00×10^{-4}, which exceeds the threshold of 1×10^{-4}, signifying a high cancer risk. Among the analyzed elements, Nickel (Ni) contributed more significantly (1.37×10^{-4}) to the total risk than Chromium (Cr) (6.31×10^{-5}), indicating that Ni exposure poses a greater carcinogenic concern for children. For adults, the TCRI was found to be 1.08×10^{-4}, which lies slightly above the acceptable limit, also reflecting a borderline high-risk level. Similar to children, Ni exhibited a higher contribution (7.38×10^{-5}) than Cr (3.40×10^{-5}) in adults. Overall, the findings reveal that both children and adults are exposed to potential carcinogenic risks exceeding the tolerable threshold, with Nickel being the dominant contributor.

Conclusions

A comprehensive geochemical assessment of soils from the Tamiraparani River Basin indicates that the soils vary from acidic to basic in nature. When compared to the local background values, trace metals (V, Cr, Ni, Cu, Zn, Rb, Sr, Ba) in the study area generally exhibit lower concentrations, suggesting minimal anthropogenic enrichment. However, certain samples show localized enrichment of specific elements such as Fe, Mn, Cu, Zn, and V, indicating possible natural geochemical variability or minor

Table 4: Non-Carcinogenic Risk Assessment (Hazard Quotient and Hazard Index) of Trace Metals for Children and Adults

Category Pathways		V	Cu	Zn	Mn	Al	Fe	Ba
Children	HQ ing	3.52×10^{-1}	3.13×10^{-2}	5.95×10^{-3}	5.99×10^{-2}	1.16×10**?**	1.14×10^{-1}	9.06×10^{-2}
	HQ inh	1.29×10^{-5}	1.15×10^{-7}	2.19×10^{-7}	2.20×10^{-6}	8.56×10^{-3}	1.60×10^{-1}	1.63×10^{-3}
	HQ derm	9.85×10^{-2}	2.92×10^{-4}	8.33×10^{-5}	1.28×10^{-2}	1.63×10^{-2}	3.82×10^{-2}	3.63×10^{-3}
Hazard Index		4.50×10^{-1}	3.16×10^{-2}	6.04×10^{-3}	7.26×10^{-2}	1.19×10**?**	3.12×10^{-1}	9.59×10^{-2}
Total Hazard Index					2.16			
Adult	HQ ing	3.77×10^{-2}	3.35×10^{-3}	6.38×10^{-4}	6.42×10^{-3}	1.25×10^{-1}	1.22×10^{-2}	9.71×10^{-3}
	HQ inh	5.54×10^{-5}	4.93×10^{-7}	9.38×10^{-8}	9.43×10^{-7}	3.67×10^{-3}	6.85×10^{-2}	6.99×10^{-4}
	HQ derm	1.50×10^{-2}	4.46×10^{-5}	1.27×10^{-5}	1.95×10^{-3}	2.49×10^{-3}	5.84×10^{-3}	5.53×10^{-4}
Hazard Index		5.27×10^{-2}	3.40×10^{-3}	6.51×10^{-4}	8.36×10^{-3}	1.31×10^{-1}	8.65×10^{-2}	1.10×10^{-2}
Total Hazard Index					0.29			

anthropogenic influence in those areas. Although most elements are below local background levels, contamination indices (CF and PLI) indicate localized enrichment (particularly for Zn and Cu) suggesting moderate to considerable site-specific contamination. Overall, the study confirms that the TRB soil poses a significant health hazard, particularly to children, who exhibit higher vulnerability across all exposure pathways. The dominance of Nickel and Aluminum in exceeding safety thresholds indicates that anthropogenic or natural soil enrichment in this area has reached levels that require systemic intervention to mitigate long-term health consequences. The present study highlights localized enrichment of elements such as Zn and Cu, indicating that certain agricultural zones may be at risk of gradual soil quality deterioration. These findings underscore the need for site-specific interventions, including regulated fertilizer and agrochemical use, periodic soil quality monitoring, and promotion of sustainable agricultural practices. Strengthening policy implementation, enhancing farmer awareness, and encouraging stakeholder participation are essential to translate scientific insights into effective soil management strategies in the basin. Such targeted measures will support long-term soil health, agricultural productivity, and environmental sustainability in the TRB.

Authors' Contributions

UBV: Writing Original Draft, Software, Editing. **AA:** Laboratory Analysis, Data Compilation. **TMVM:** Field Work, Software. **KAK:** Investigation, Methodology, Formal Analysis. **AK:** Project Administration, Conceptualisation, Reviewing and Editing

Conflict of Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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