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# Assessing the level of contamination of metals in surface soils at thermal power area: Evidence from developing country (India)

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ABSTRACT

The purpose of this study was to determine the concentrations and contamination level of heavy metals and metalloid (i.e., Zn, Fe, Cu, Mn, Pb and As) in sediment samples taken from a thermal power station's 5 km buffer area (Bandel thermal power station-BTPS) in West Bengal, India. The atomic absorption spectrophotometer (AAS) was used to determine the presence of heavy metals in soil samples. Heavy metal and metalloid concentrations such as Zn, Fe, Cu, Mn, Pb and As were studied using various contamination and pollution-related indexes such as geo-accumulation index, enrichment factor, contamination factor, contamination degree, modified degree of contamination index, and pollution load index, and spatial distribution was presented using interpolation technique. An ecological risk index for all metals and a forecasted ecological risk index are also used to investigate the impact of heavy metals on biological elements in the soil. ANOVA and the Kruskal-Wallis test were among the multivariate statistical procedures used. Hierarchical cluster analysis was used to estimate the spatial similarity of sample locations, and Pearson's correlation was used to determine the relationship between different metal concentrations and soil physico-chemical parameters. Almost all of the sample sites had soils of very good to medium quality, according to the study. All heavy metals at this research site, with the exception of arsenic and lead, behave as plant micronutrients. Furthermore, no heavy metal band, with the exception of As, had a consistent concentration. Almost all of the sampling locations had extremely low to very low levels of pollution.

## 1. Introduction

Coal-fired thermal power plants create electricity using fossil fuels, which have a high risk of damaging ecological factors such as soil. The soil quality around the thermal power station has been altered by the plume emission of particulate matter, SO2, NOX, and on the other hand, massive fly ash deposition on the land and deposition in the ash pond as wet ash has further altered the soil quality by releasing toxic elements [1]. As the amount of ash in the coal rise, the danger of toxicity augments [2–4]. Sub-bituminous coal comprised more than 30% to bituminous coal [5]. Fly ash, on the other hand, is carried across a vast area and deposited on the soil surface via atmospheric mobilization [6]. Fly ash affects the soil in two ways: positively and negatively. In consequence, industrial effluents generate a wide range of environmental issues, and health risks are getting increasingly complex and serious. The condition of metals in thermal power plant effluents is given special attention. It is important to remember that the tannery thermal power sector is a major polluter and donor of metals to the environment. Thermal power plants, which burn coal to generate electricity on a massive scale, are recognized as a major source of heavy metals in the environment and represent serious environmental hazards [3,5].

Toxic elements in fly ash, such as arsenic (As), cadmium (Cd), chromium (Cr), lead (Pb), nickel (Ni), mercury (Hg), iron (Fe), manganese (Mn), zinc (Zn), and many others, have been extracted and deposited on the soil, enriched toxic matters into the soil, and altered soil quality through atmospheric deposition, primarily affecting agricultural soil quality [7]. Previously, multiple studies from around the world proved that, for example, Lazar et al. [8] found high copper and zinc contamination at various distances around Romania's Gorj country, as well as a breach of Romanian legislation. Lu et al. [9] investigated the concentration of heavy metals and radio-nuclides near the Xi'an coal-fired thermal power station in China. According to the study, the contaminated soils had higher

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mean concentrations of Cu, Pb, Zn, Co, and Cr than the background soil, but lower mean concentrations of Mn, Ni, and V. The soil contamination was confirmed by the pollution load index. The impact of fly ash and bottom ash on soil deterioration in the Kolaghat thermal power station area was explored by Mandal and Sengupta [10]. The top soils closest to the ash pond have the highest concentration of hazardous components due to the influx of fly ash. Agrawal et al. [11] discovered increased mean Cadmium, Lead, Arsenic, and Nickel contamination along a 2–4 km radius of the predominant wind direction in the Singurali region of India. As a result, while most studies focused on the negative effects of fly ash deposition and ash ponds near thermal power plants, a few researchers also observed the positive effects of fly ash utilization, which reduced the negative environmental impact [12]. Higher concentrations of macro and micro nutrients in fly ash, such as potassium (K), sodium (Na), calcium (Ca), zinc (Zn), magnesium (Mg), and iron (Fe), may improve soil quality and agricultural production [12]. Fly ash, in particular, reduced bulk density, increased saturated hydraulic conductivity, and improved soil moisture retention capacity [13]. Aitken et al. [14] discovered a modest amount of nitrogen and a variable amount of phosphorus in Australian fly ash, which reduced salt levels to the equilibrium level through nutrition. Electrostatic precipitator exhibited a finer texture of ash with lower pH, and contained more nutrients than ash from a dumping site, yet both kinds of ash had a high saturation moisture percentage [15]. Fly ash also increased soil NPK and micronutrient levels while having no influence on pH, EC, or CEC (Cations Exchange Capacity) [16]. Fly ash altered the texture of topsoil by increasing the quantity of silt in the soil [13] and changing sandy and clayey textured soil into loamy soil [17,18].

Many researchers were drawn to explore eco-toxic elements, bioaccumulation, and non-degradation quality in both short and long-term storage in upper soil and aquatic habitats because of the existence of toxic components in soil [19]. Heavy metals may be disseminated with a variety of components on the top surface and throughout the river environment after being released [20]. In this circumstance, only few items permeate water columns, with the majority being collected in sediments and upper soil [21]. The creation of organic matter, surface absorption, and ion-exchange are the most common methods where dangerous compounds are mixed with sediments [21,22]. Metal buildup occurs in both natural and anthropogenic settings (for instance, precipitation, weathering, leaching, disintegration of parent materials for naturally and mining, industrial emission, sludge dumping, coal fired power station and waste water irrigation etc.). Heavy metal toxicity and suppleness in soil ecology are influenced by a variety of factors, including metal binding state, biochemical type, total accumulation, and metal physiognomies [23]. Heavy metal is divided into two categories: essential and non-essential. Non-essential metals are toxic even in small levels [24], whereas necessary metals are found in nature. Furthermore, heavy metal poisoning in soil can cause agricultural land degradation, eutrophication, and the assimilation of hazardous chemicals over time [24]. As a result of both natural and man-made causes, heavy metal levels have surged in recent years. As a result, in order to quantify heavy metal concentrations and comprehend soil quality, an examination is required. A scientific investigation into heavy metal exposure is urgently needed.

In recent years, research into the effects of fly ash on soil environment has grown more relevant. In the industrial sector, waste management is one of the most demanding and hard concerns. During the literature review, only a small amount of literature on the functioning and toxicity analysis of BTPS was discovered, which is critical because the buffer region of BTPS is densely packed with agricultural livelihoods and urban agglomeration. There is a dearth of analysis in buffer concentration difference between and within the buffers for contamination levels. It is critical to have a clear understanding of the pollution and contamination caused by environmental harmful chemicals. The stacks of Bandel Thermal Power Station are all equipped with Electrostatic Precipitators (ESP), although the efficacy of each of the five ESPs varies, resulting in variances in air composition and soil environment. The surrounding area of the thermal power station was given to locals by the BTPS administration for agricultural purposes, which included the use of fly ash. As a result, assessing the pollution situation within a 5 km radius of the Bandel thermal power station is an essential research topic (BTPS). However, the specific objectives of this study are to (i) assess the concentration of heavy metals and metalloid (i.e., Zn, Fe, Cu, Mn, Pb, and As) in soil samples collected from the BTPS 5 km buffer, (ii) determine the spatial distribution of heavy metals in the BTPS buffer area, (iii) determine the level of vulnerability for toxic metals using the soil quality index and pollution level index, and (iv) assess the potential ecological risk of heavy metals.

## 2. Methods and materials

### 2.1. Selection of study area

In 1965, the West Bengal Power Development Corporation limited commissioned the state's (West Bengal, India) first thermal power project at Bandel, with four units with a total installed capacity of 330 Megawatt (MW) but a generation capacity of 240 MW (having 60 MW for each unit). The fifth unit commissioned in 1983 with a capacity of 210 MW. As a result, the total installed capacity has increased to 450 MW. Units 2 and 3 have not been operational in recent years due to the presence of obsolete machinery. The total installed capacity is currently 330 MW. Two 60 MW units (units 1 and 2) and one 210 MW unit (unit 5) are operational. In addition, after the completion of a rehabilitation and modernization project of Unit-V, which overseen by the World Bank, 5 MW of installed capacity was added, bringing the total installed capacity to 335 MW. The Bandel Thermal Power Station is located in Bandel, near Tribeni, in the Hooghly district of West Bengal, about 50 km from Kolkata. It is located on the Gangetic plain of Bengal and in the seismic-III zone (Fig. 1). Kuntighat, on the Eastern Railway's Bandel-Katwa branch line, is the nearest railway station. The closest highway is Assam Road, which connects to NH-2 and is around 500 m away. The power station's urban and rural bodies are Triveni Tissue Township, BTPS Township, Bansberia Municipality, Chandrahati-I and II under Kuntighat, Benipur, Raghunathpur, Triveni, and Mogra Gram Panchayats (GPs). In general, coal-fired power facilities have required 3 to 4 acres of land per kilowatt-hours (KWh) of electricity generated which cause a vast area for both the installation of the power station and the disposal of the fly ash. Because this project now enclosed by various manufacturing businesses, brick kilns and urban areas, a 5 km radius (five 1 km consecutive buffers) around Bandel thermal power stations was chosen as the study area.

### 2.2. Collection of samples

During November–December 2020, 51 soil samples were collected from agricultural and non-agricultural fields at various locations within each buffer distance from 0 to 15 cm depth of soil profile after removing the initial layer of surface soil 2 cm within a 225 $cm^2$ area per sample (Fig. 1). The soil samples were carefully transferred to clean and dry self-sealing polyethylene bags for transport to the laboratory for further investigation shortly after they were collected. All samples were sieved through a 2 mm sieve after being air-dried in paper lined propylene trays at room temperature and disaggregated with a wooden roller. Fully mix and normalized the soil samples has been stored in tightly sealed polyethylene bags until further examination. Finally, at SGS Pvt. Ltd. in Joka, West Bengal, India, the solution was used for elemental analysis using atomic absorption spectrometry. On an agricultural field 20 km away from BTPS, a background soil sample was also taken. According to Bhuiyan et al. (2010) [25], a sample of unaffected soil with alluvium as parent material (beyond 20 km from BTPS) was taken to evaluate the regional background value of metal content in the soil. The details of the background soil sample has been summarized properly for further analysis (see Supplementary Sheet-Appendix Table 1) . Numerous studies have accepted soil quality standards (SQGs) for toxicological assessment of sediment-related metals, supporting the inspection of ecological environmental policies and guidelines [26]. To evaluate the likely biotic influence of metal(*oid*)s estimated in the sediment

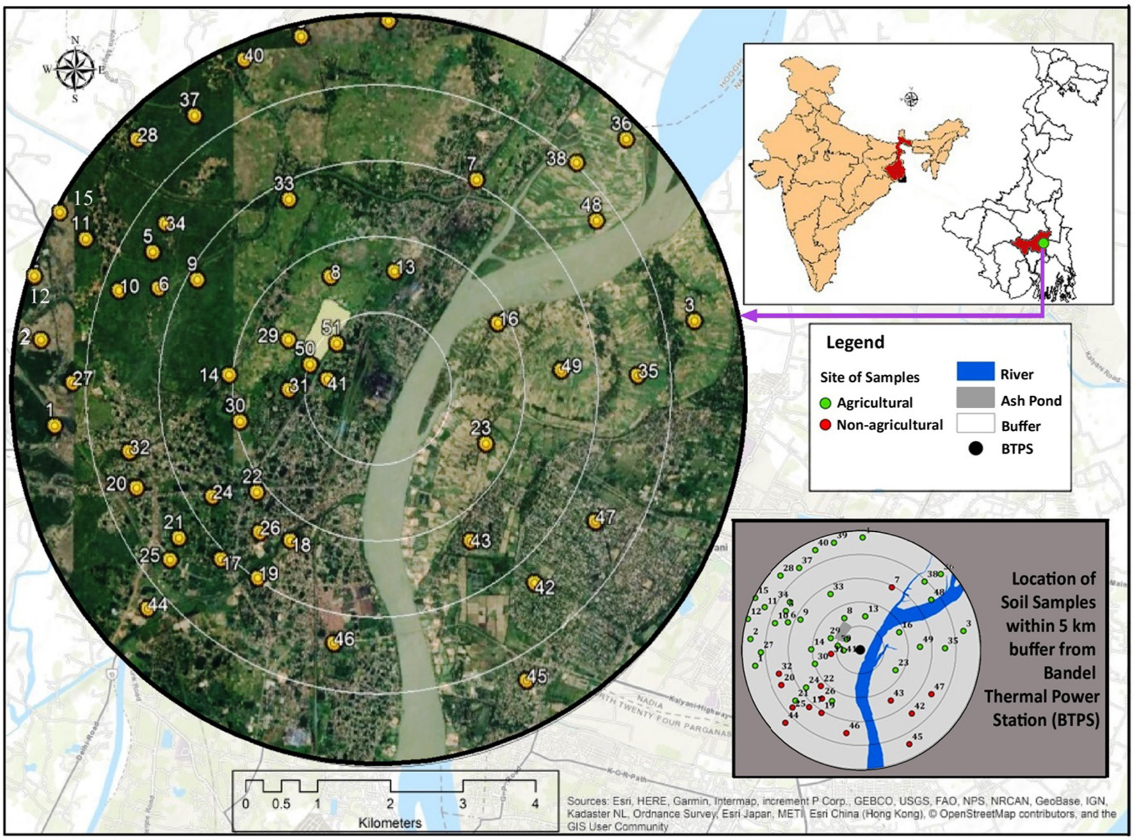


**Fig. 1.** Location of Bandel Thermal Power Station (BTPS) in study area and its surroundings (within 5 km buffer marked in Google Image).

samples, SQGs such as threshold effect level of the distant village was taken into consideration.

### 2.3. Soil quality index (SQI)

The optimal availability of macronutrients and desirable physical qualities for plant growth or crop production are determined by soil quality. Plant development is mostly influenced by NPK, pH, and electrical conductivity or salinity. First and foremost, the actual values of the above-mentioned characteristics are scaled according to the importance of availability in soil for optimal fertile soils. The pH measurements were scaled from 0 to 1 and the other parameters were assigned a value between 4 and 1. The optimal concentrations of the above-mentioned components, as well as their corresponding scales, are listed in *Appendix* (see Supplementary Sheet-Appendix Table 2). Finally soil quality index calculated by sum of all corresponding scale values (21).

$$SQI_t = \sum_{i=1}^{n=6} S_i \quad (1)$$

Where, $SQI_t$ is the total score of soil quality index, n indicates number of parameters and $S_i$ indicates scale value of individual parameters. The final index value lies between 17 and 5. Further calculated values converted between 0 and 1 and assessed the soil quality (SQI) by the following equation:

$$SQI = \frac{(Actual-5)}{(17-5)} \quad (2)$$

The final index values further classified into five classes like very low quality (SQI < 0.2), low quality (0.2–0.4), medium quality (0.4–0.6), high quality (0.6–0.8) and very high quality (>0.8).

### 2.4. Quantify soil contamination through indices

#### 2.4.1. Geo-accumulation index ($I_{geo}$)

Muller [27] proposed the Geo-accumulation index ($I_{geo}$) to quantify and define metal pollution in sediments by comparing present concentrations to preindustrial levels. The Geo-accumulation index showing the degree of contamination is estimated using the following formula:

$$I_{geo} = \log_2\left[\frac{C_{metal\ of\ sample}}{1.5 \times C_{metal\ of\ background}}\right] \quad (3)$$

where, $C_{metal\ of\ sample}$ is the observed value of individual metal and $C_{metal\ of\ background}$ is the background value. In contamination-related analysis, background values are crucial [28]. Because the area and its surrounding area are largely agriculturally dominated, and there is a dense urban population jammed here, shale values have been adopted as background values [27,29]. The correction factor for minimizing variability owing to lithological variation is 1.5 [31]. For the preparation of geo-accumulation index seven categories [31] have been developed and these are (i) practically uncontaminated = ≤0, (ii) uncontaminated to moderately contaminated = 0–1, (iii) moderately contaminated = 1–2, (iv) moderately to heavily contaminated = 2–3, (v) heavily contaminated = 3–4, (vi) heavily to extremely contaminated = 4–5, (vii) extremely contaminate ≥5.

#### 2.4.2. Enrichment factor (EF)

The enrichment factor (EF) is a convenient tool for shaping the amount of contaminants in soils. To compute how much metal is resulting from anthropogenic activities in soil, the EF for each metal must be calculated. EF is mostly used to distinguish between natural and anthropogenic metal sources. Iron (Fe), a reference element best symbolized by Loska [32], was used to measure anthropogenic metal enrichment. The following equation is used to calculate the EF:

$$EF = \frac{\left(C_{metal}/C_{Fe}\right)_{sample}}{\left(C_{metal}/C_{Fe}\right)_{background}} \quad (4)$$

where, $C_{metal}$ is the concentration of individual metal of samples and background. $C_{Fe}$ is the concentration of iron (reference metal) of samples and background. Fe is more feasible for calculating EF, iron has more similar geochemical nature to many metals in oxic or anoxic environment [33]. Few researcher classified as a source appropriation, EF < 2 values indicate to crustal origin, EF > 2 indicate likely to be anthropogenic origin and greater than 10 indicates purely anthropogenic origin [34,35]. Several authors [36,37] classified EF into five classes on nature of enrichment of heavy metals which are as follows: (i) deficiencies to minimal ≤2, (ii) moderate = 2–5, (iii) significant = 5–20, (iv) high to very high = 20–40 and (v) strongly very high ≥40.

### 2.4.3. Contamination factor (CF)

Contamination factor (CF) is supposed to be an effective method for monitoring sediment pollution over time. It is the ratio of each metal in the current sample to the same metal's background values.

$$CF_i = \left(\frac{C_{metal\ of\ sample}}{C_{metal\ of\ background}}\right) \quad (5)$$

where, $C_{metal\ of\ sample}$ is the observed value of individual metal and $C_{metal\ of\ background}$ is the background value. This single pollution index indicates the contamination nature of individual metal. $CF_i$ is the contamination factor of individual metal. Sadhu et al. [36] and Likuku et al. [38] further classified as level of contamination into four classes as follows: (i) low ≤1, (ii) moderate = 1 ≤ CF <3, (iii) considerable = 3 ≤ CF <6 and (iv) very high ≥6.

### 2.4.4. Degree of contamination (CD)

Hakanson [39] provided a method for determining the degree of contamination based on the contamination factor of all metals in a sample which is known as degree of contamination (CD). This index depicts the current state of heavy metal contamination in general. The CD's purpose is to provide a measure of overall contamination in surface layers at a given sampling site.

$$CD = \sum_{i=1}^{n=6} CF_i \quad (6)$$

The researcher in this study modified the factor used by Krzysztof et al. [40], which used a 20-km distance based soil sample (from an agricultural area) as a reference value, comparable to the other variables and further [35] divided the CD into four categories which are as follows: (i) low ≤n, (ii) moderate = n ≤ CD < 2n, (iii) considerable = 2n ≤ CD <4n and (iv) very high ≥4n.

### 2.4.5. Modified degree of contamination (MCD)

Abrahim and Parker [39] define a modified degree of contamination index based on Hakanson [39] for a comprehensive assessment of contamination degree by heavy metal. The modified formula is generalized by defining MCD as the sum of all contamination factors for a particular set of pollutants divided by the total number of pollutants evaluated. This index must be estimated using at least three samples. Where 'n' indicates numbers of pollutants or heavy metals.

$$MCD = \frac{CD}{n} \quad (7)$$

Abrahim and Parker [41] divided modified degree of contamination (MCD) into seven categories as follows: (i) nil to very low ≤1.5, (ii) low = 1.5 ≤ mcd < 2, (iii) moderate = 2 ≤ mcd <4, (iv) high = 4 ≤ mcd <8, (v) very high = 8 ≤ mcd <16, (vi) extremely high = 16 ≤ mcd <32 and (vii) ultra high ≥32.

### 2.4.6. Pollution load index (PLI)

The pollution load index (PLI) measures the quantity of harmful heavy metals in the area. Tomlinson et al. [42] were the first to use this pollution index to measure the concentration of various heavy metals in an estuary. The PLI was calculated as a ratio of each heavy metal's concentration to the soil's background value. The index value PLI ≤ 1 shows that background levels of pollution are present, whereas PLI > 1 indicates a significant pollution load, in which the soil has degraded due to metal concentrations, and prompt intervention is required to reduce pollution.

$$PLI = \left(CF_1 \times CF_2 \times \ldots\ldots \times CF_n\right)^{1/n} \quad (8)$$

The study considered the contamination factors of six heavy metals.

### 2.4.7. Ecological risk factor (ERF) and potential ecological risk index (PERI)

Hakanson [39] first proposed a way to measure various levels of ecological risk in sediments. To analyze potential risks and levels of metal pollution index, this method evaluates different degrees of pollution in sediment while combining environmental and ecological concerns with toxicological.

$$ER_i = T_r \times CF_i \quad (9)$$

Where, $ER_i$ indicates the ecological risk of individual metal, $T_r$ is the toxic response factor of heavy metal. Here, four heavy metals (Pb, As, Cu and Zn) considered for assessment of ecological risk factor due to the availability of toxic factors; the toxic factors of such metals are 5, 10, 5 and 1 respectively. $CF_i$ is the contamination factor of individual metal. Potential Ecological Risk Index (PERI) assessed the level of environmental sensitivity due to the concentration of toxic heavy metals in soil [43].

$$PERI = \sum_{i=1}^{n=4} ER_i \quad (10)$$

Here, four heavy metals are used for assessing the potential risk of these heavy metals in soil environment and classified into five grades: (i) slight <40, (ii) medium = 40–80, (iii) strong = 80–160, (iv) very strong = 160–320 and (v) extremely strong ≥ 320.

### 2.5. Statistical analysis

The clustering of geographic similarities was determined using a variety of multivariate statistical methods based on Hierarchical Cluster analysis (HCA). To uncover more discriminating parameters across the space, discriminant analysis (DA) with buffers and clusters is also utilized. ANOVA and the Kruskal-Wallis test were used to estimate the mean concentration difference of metals in various buffers. The association between metal concentration and nature of soil quality was investigated using Karl Pearson's correlation coefficient analysis and partial correlation, and linear regression analysis was utilized to examine the influence of various metal concentration indices on nature of soil quality.

## 3. Results and discussion

### 3.1. Spatial concentration of nutrient and its characteristics

The effluents from thermal power station make a direct impact on the surrounding soils which are basically used for agricultural activity. pH values range between 4.4 and 7.32 (Fig. 2a). The acquired soil samples in this study area range from strongly acidic to moderately alkaline. At Ganegar (S-40), the pH was 7.32, while at Taragun (S-27), it was 4.40. Moreover, more acidic soil was discovered far away from BTPS, although

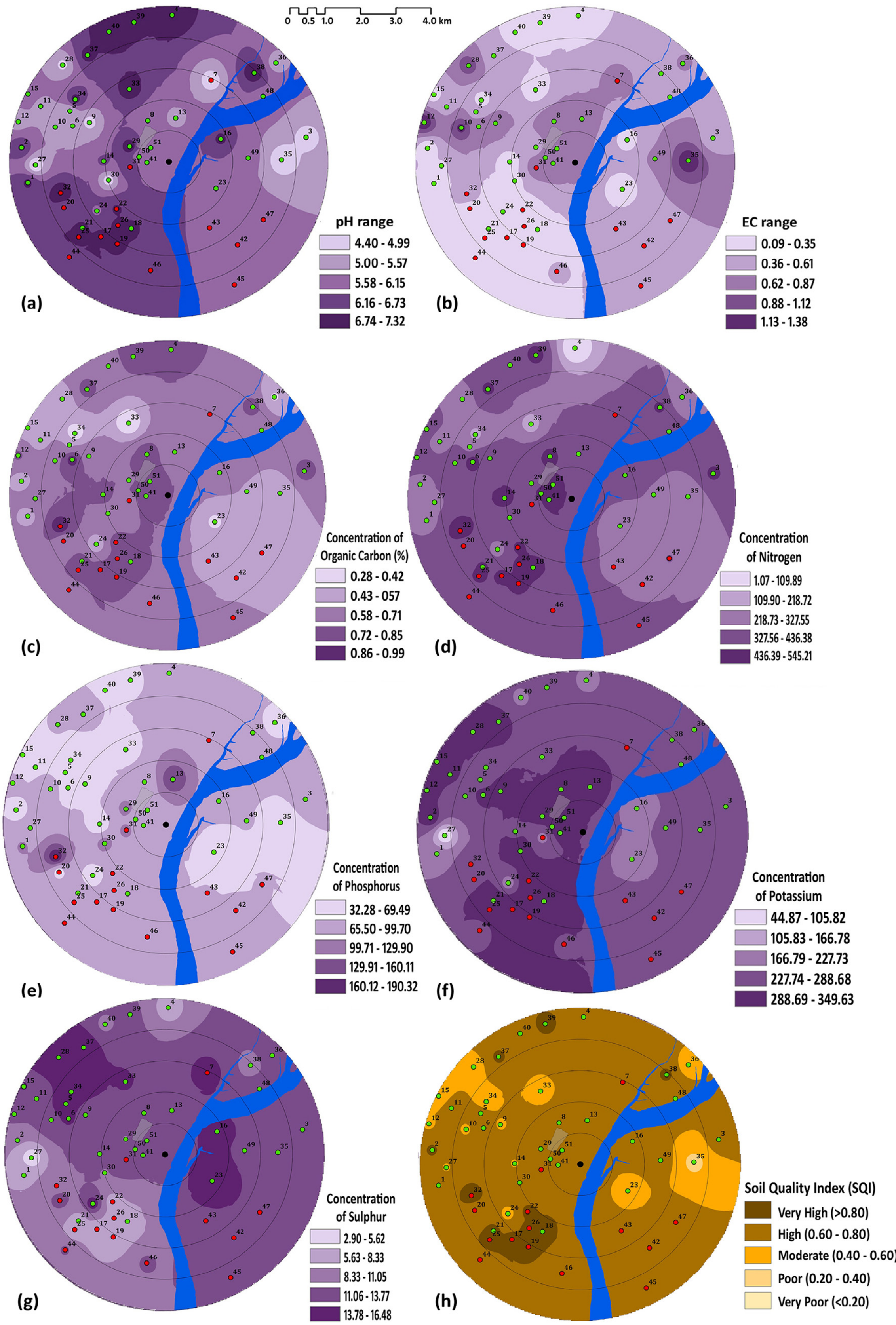


**Fig. 2.** Spatial concentration of (a) soil pH (b) electrical conductivity (EC), (c) organic carbon (OC), (d) nitrogen (N), (e) Phosphorus (P), (f) Potassium (K), (g) Sulphur (S) and (h) soil quality index (SQI) in spatial dimension in and around BTPS.

pH values ranging from 5.58 to 6.73 were discovered near BTPS, indicating that the soil was moderate to slightly acidic (see Appendix Table 3). Sample sites in the study region, which are extremely close to the BTPS, have a pH of around 5, which could be attributable to the acid neutralizing action of fly ash, and these sites are also prone to water logging and fugitive dust [4,44,45]. The spatial distribution of EC at different buffer distances is shown in Fig. 2b which varied 0.62 to 0.87. The EC ranged from 1.38 dS $m^{-1}$ at Rajarambati (S-12) to 0.09 dS $m^{-1}$ at Demra (S-14) in the study region (see Appendix Table 3). Organic matter has the greatest impact on soil fertility and regulates the soil's physical and chemical qualities. Deposition of fly ash, significantly greater EC in soil was detected near BTPS and also in the direction of downstream wind [46]. Increased NPK concentrations in agricultural fields due to overuse of chemical fertilizers surpass the ideal NPK ratio in soils and market demand for Boro paddy, potato, and oil seeds drove agricultural diversification and increased fertilizer use in the Hooghly district [47–49]. Soil fertility improves when organic carbon concentrations are higher. At S-32 and S-33, the OC concentration ranged from 0.99% to 0.28% (Fig. 2c) and 0.64% is the average concentration which is at par with the background soil. Results show that the concentration of N range from 546 kg $ha^{-1}$ in Asfal (S-32) to 1.09 kg $ha^{-1}$ at Bagri (S-4), with an average of 363 kg $ha^{-1}$. Near the BTPS and surrounding the ash pond, the nitrogen concentration was determined to be between 436.39 and 545.21 kg $ha^{-1}$, and the same concentration of N was found near the BTPS and around the ash pond (Fig. 2d). At Asfal (S-32), Phosphorus concentration was 191 kg $ha^{-1}$, while at Demra it was 39.10 kg $ha^{-1}$ (S-14). 76.90 kg $ha^{-1}$ was the average concentration (see Appendix Table 3) and near the BTPS a greater concentration of P (99.71–129.90 kg $ha^{-1}$) indicates that the soil has a sufficient amount of fertility. At Demra (S-13), the concentration of K range from 350 kg $ha^{-1}$ to 44.50 kg $ha^{-1}$. At Taragun (S-27) the average concentration found 274 kg $ha^{-1}$ (see Appendix Table 3) when near the BTPS and surrounding the ash pond concentration has found between 288.69 and 349.63 kg $ha^{-1}$ (Fig. 2f). At Digsui (S-28), the concentration of S was 16.50 mg $kg^{-1}$, while at Taragun, it was 2.89 mg $kg^{-1}$ (S-27). 11.58 mg $kg^{-1}$ was the average concentration of S (see Appendix Table 3). The largest S concentration was discovered near the BTPS and ash pond (Fig. 2g). BTPS administration provided local farmers with ash-mixed fertile soils for farming. Weathered fly ash boosted the amount of potassium and phosphorus in the soil, as well as improving other physico-chemical features, improving soil quality even further [12,18,50]. As a result, a substantial amount of phosphorous concentration was discovered in the fly ash application field, as well as the downstream wind direction. Phosphorus concentration in soil is abundant across the research area, owing to the use of phosphate fertilizers [47]. Raja et al. [4] also found increased nitrogen and organic carbon concentrations near NALCO in Odisha, as well as higher phosphorous content near NTPC. Verma et al. [51] also found increased levels of organic carbon in the vicinity of thermal power facilities, possibly due to coal dust deposition. Due to the existence of mainly fertile soils [52] and excessive application of chemical fertilizers for high yields, maximum area covered by high soil quality for optimum availability of macronutrients (pH and EC) and physical features [47]. As a result, there was no discernible median difference in soil quality along the buffer distance, which was found primarily in agricultural fields. Notably, the administration of fly ash improved the soil's physico-chemical characteristics, hence improving soil quality [53] in a fly ash-applying agricultural field. Furthermore, a healthy soil has a high concentration of diverse macronutrients as well as strong physical features. Nearly all samples in this study location had a significant concentration, which improved soil quality.

Furthermore, ANOVA was used to test the significance of mean differences in different buffer areas for pH, N, K, OC and S (all of which have a near-normal to normal distribution), while Kruskal-Wallis was used for Electrical Conductivity and Phosphorous (which have a non-normal distribution). Table 1 shows the results of the Shapiro-Wilk normality test. Table 1 shows the significance of the mean difference in nitrogen and organic matter concentrations, as determined by the Welch's test. Games-Howell According to the Post-Hoc test for uneven variance (Table 2), there is a significant difference in nitrogen content at 2, 4, and 5 km buffer distances compared to 1 km buffer distance. However, the Kruskal-Wallis test insignificantly measures the mean difference of EC and P in the case of organic carbon detected at 3 and 5 km in comparison to 1 km.

**Table 1**
Normality test (Shapiro-Wilk).

| Element | W | p | Element | W | p |
|---|---|---|---|---|---|
| pH | 0.936 | 0.009 | Nitrogen (Kg/ha) | 0.954 | 0.044 |
| Sulphur (mg $kg^{-1}$) | 0.956 | 0.056 | Organic Carbon (%) | 0.987 | 0.859 |
| Phosphorous (Kg/ha) | 0.816 | <0.001 | Electrical Conductivity (dS/m) | 0.879 | <0.001 |
| Potassium (Kg/ha) | 0.927 | 0.004 | | | |

Note: *p* value less than 0.001 indicates non-normality.

The spatial distribution of soil quality has a great regularity, as seen in Fig. 2h. In general, the higher the soil quality, the closer the study area is to the BTPS. The distribution of soil with a moderate to low grade is dispersed. Overall, the soil quality in the BTPS environs is low in the western and eastern parts, with the finest soil quality in the southern half. The proportion of very high to poor soil quality in the study region was 4.59%, 83.71%, 11.39% and 0.31%, according to statistical analysis. S- 32, which is located in the southwest within a 3–4 km buffer distance, has the best soil quality, whereas S-35, which is located in the east within the same buffer distance, has the least. Findings show that 12 sample locations have very high-quality soils, while 26, 12, and 1 have high-to-low-quality soils (see Appendix Table 4). This study location does not have very poor soil quality. As a result, the majority of understudies discovered high-quality soils, particularly near BTPS and around the ash pond. Within a 2–4 km buffer space, high-quality soils were discovered in the SSW direction. Furthermore, medium-quality soils were found scattered around the region. The biggest variance was discovered at 4 km buffer distance (0.584) and the highest median quality was found at 1, and 2 km buffer distance (0.750). The co-efficient of variation shows that sample locations within 0–1 km had higher consistency than those within a 2–3 km buffer region, where there was more unpredictability (Table 3). The assessed SQI values were correlated with recorded yield of rice. To assess the relationship of SQI with crop yield, $R^2 > 0.65$ ($n = 27$) has been clear as significant. In SQI method, additive index in different buffer had good correlation with yield of rice except with the scenario in the eastern part of the study area and however the SQI values clearly showing the positive relation of crop yield with very high to poor section of the surveyed soil samples. However, in SQI by additive and weighted index had higher $R^2$ values indicating their better relationship with crop yield.

### 3.2. Soil contamination through metal elements

Zn regulates chlorophyll formation, which aids in normal photosynthesis, and carbohydrate content has decreased due to zinc insufficiency. At Kabirhati (S-6) the concentration of Zn was 2.25 mg $kg^{-1}$, while at Bharatpur it was 0.48 mg $kg^{-1}$ (S-3). The average concentration was 1.06 mg $kg^{-1}$, which was higher than the region's background norm. Zn concentrations were observed to be higher near BTPS and around the ash pond (Fig. 3a). The maximum mean zinc content was recorded at a distance of 1 km (1.81 mg $kg^{-1}$) (see Appendix Table 5). The majority of the research area's soil has 6.96–8.98 mg $kg^{-1}$ Fe. Fe concentrations of 11.02–13.04 mg $kg^{-1}$have been discovered near the BTPS (Fig. 3b). The concentration ranged from 15.11 mg $kg^{-1}$ at Asfal (S-32) to 4.91 mg $kg^{-1}$ at Amodghata (S-16) in the research region. The average concentration was 8.97 mg $kg^{-1}$, which is significantly higher than the background norm. Cu concentrations range from 0.56–0.72 mg $kg^{-1}$ in the study region, with 0.73–0.89 mg $kg^{-1}$ copper concentrations reported near the ash pond (Fig. 3c). The concentrations varied from 1.24 mg $kg^{-1}$ (S-32) to 0.38 mg $kg^{-1}$ (S-33). The average concentration was 0.69 mg $kg^{-1}$, which is higher than the background concentration. The biggest variation was found at a distance of 4 km (1.24–0.388 mg $kg^{-1}$), whereas the highest mean concentration was recorded at a distance of

**Table 2**
Mean difference of characteristics in different buffer.

| Characteristics of elements | Games-Howell Post-Hoc Test | | | | | | | One-Way ANOVA (Welch's) | |
|---|---|---|---|---|---|---|---|---|---|
| | Buffer | | 1 | 2 | 3 | 4 | 5 | F | p |
| Nitrogen | 1 | Mean difference | – | 97.60* | 102.24 | 80.30* | 136.70** | 12.92 | 0.001 |
| | | *p*-value | – | 0.037 | 0.057 | 0.038 | 0.004 | | |
| Organic Carbon | 1 | Mean difference | – | 0.150 | 0.178* | 0.118 | 0.159 | 10.83 | 0.001 |
| | | p-value | – | 0.077 | 0.041 | 0.115 | 0.004 | | |

* $p < .05$.
** $p < .01$.

1 km (0.720 mg kg$^{-1}$). Mn levels in the soil range from 2.18 to 3.21 mg kg$^{-1}$ in the majority of the research region, as well as near BTPS (Fig. 3d). The concentrations varied from 6.35 mg kg$^{-1}$ (S-32) to 1.13 mg kg$^{-1}$ (S-7). The average concentration was 2.7 mg kg$^{-1}$, which was quite close to the background soil sample levels. The majority of the research area has Pb content of 12.18–13.33 mg kg$^{-1}$, however less (11.00–12.17 mg kg$^{-1}$) was observed near BTPS and surrounding the ash pond (Fig. 3e). The concentrations ranged from 16.83 mg kg$^{-1}$ (S-43) to 11 mg kg$^{-1}$ in total (S-8). The mean concentration was 12.61 mg kg$^{-1}$, which was higher than the background level. The major fluctuation was found at a distance of 3 km, and the highest mean concentration was recorded at a distance of 5 km. As because As is a metalloid, its mobility increases as the pH rises, and arsenic compounds strongly adsorb in soil, quicker movement in groundwater and surface water from the source is seen. The average concentration of As in this study area is 1.77 mg kg$^{-1}$, which is higher than the background sample but lower than the global average value. Sample sites 8 and 15 had concentrations ranging from 2.25 mg kg$^{-1}$ to 0.53 mg kg$^{-1}$. From north to south, the maximum concentration (15.67–16.83 mg kg$^{-1}$) was reported in the central region of the research area (Fig. 3f). The Games-Howell Post-Hoc Test and Dwass-Steel-Critchlow-Flinger Pairwise Comparison revealed a significant difference in mean iron, zinc, and arsenic concentrations (Table 4) in the study area.

Several heavy metals were found in the topsoil and affected the soil quality due to the coal composition, burning process, and amount of unburned coal from thermal power stations in the form of fly ash. According to previous study, thermal power stations are the primary source of heavy metals in soil around the world [53–56]. Such a tendency can also be found in India [10,11]. However, such a common occurrence was not discovered correctly. Surface soil arsenic contaminations were from 2.25–0.53 mg kg$^{-1}$, well below the Dutch ecologist's maximum permitted limit of 4.5 mg kg$^{-1}$. Higher concentrations were detected along the river's flow, which was also related to the presence of arsenic in the sediments. The sediments of the Hooghly River's meandering river channels, in particular, are rich in arsenic and iron, and were deposited (early-mid Pleistocene and Holocene deposition) on both bank and paleo-channel [57]. Furthermore, the maximum concentration of fly ash deposition in this study area was reported near BTPS, with a significant difference between the 1 and 3 km buffer. Arsenopyrite mineral may be present in coal [58] as well as in fly ash [59]. It's possible that the lower lead content around BTPS and higher at a distance (non-agricultural location) is due to downstream fly ash deposition (both April and November) [60,61]. However, the region is also near a brick kiln complex, and other heavy industries are present in this study, which may have increased the lead concentration. Although lead is not a necessary element for soil fertility and crop development, a concentration of more than 55 mg kg$^{-1}$ has been found to harm plants, according to a Dutch ecologist [62]. Because of the presences in fly ash, the concentration near BTPS and ash applied soils clearly demonstrated the impact of fly ash [12]. The considerable median changes between 5 and 1 indicate the consequences of both fly ash deposition and traffic contamination. Near a road and in a densely inhabited neighbourhood, the whole non-agricultural sample site was collected. Other heavy metals, such as Fe, Mn, Cu, and Zn, are used as micronutrients to boost soil fertility below dangerous levels. According to the Indian standard [63] as well as the Dutch Ecologist, the concentration of these heavy metals was below the acceptable range [62]. The presence of greater to moderate concentrations near the BTPS and in ash-applied soils corroborated the beneficial effects of fly ash as a soil enhancing agent [12]. Adriano [53] described the role of fly ash as a soil fertility enhancer through improving soil physicochemical parameters.

**Table 3**
Descriptive statistics.

| Buffer (in km) | Mean | Median | SD | Range | CV |
|---|---|---|---|---|---|
| 1 | 0.750 | 0.750 | 0.001 | 0.001 | 0.067 |
| 2 | 0.714 | 0.750 | 0.095 | 0.250 | 13.235 |
| 3 | 0.667 | 0.667 | 0.130 | 0.333 | 19.490 |
| 4 | 0.703 | 0.667 | 0.149 | 0.584 | 21.195 |
| 5 | 0.678 | 0.667 | 0.121 | 0.333 | 17.847 |

Source: Computed by Authors.

### 3.3. Accumulation and enrichment of metals

Mn (0.704 to −1.78) has the highest range of $I_{geo}$ values among all the metals, followed by Zn (1.14 to −1.08), As (0.905 to −1.18), Cu (0.781 to −0.918), Fe (0.873 to −0.748), and Pb (0.873 to −0.748). (0.138 to −0.476). As (0.650) had the highest mean accumulation, followed by Fe (0.030), Zn (−0.120), Cu (−0.080), Pb (−0.290), and Mn (−0.650) indicated practically uncontaminated situation ($I_{geo} \leq 0$) in nature, except for As and Fe, which were moderately contaminated ($I_{geo}$ 0–1). Furthermore, in the case of Pb, all samples were found to be practically uncontaminated, with the exception of S-23 and S-43, which were determined to be uncontaminated to moderately contaminate. A total of 31 sample sites resulted zero value, indicating virtually uncontaminated, while 19 have uncontaminated to moderately contaminated soil, and one sample site (S-6) has moderately contaminated soil for Zn (Fig. 4a-f). The contamination factor (CF) was used to examine the levels of contamination of individual heavy metals. Zn range from 3.31 to 0.708, with As (2.810–0.663), Mn (2.440–0.435), Fe (2.750–0.893), and Pb (1.65–1.07) grouped in descending order. As (2.36) had the highest median contamination, followed by Fe (1.53), Cu (1.42), Zn (1.38), Pb (1.23), and Mn (0.960), indicating that only Mn has low contamination and the rest heavy metals have intermediate contamination levels across the research area. The consistent distribution of moderate lead contamination has been discovered throughout the research region, although others do not. In the case of arsenic, S-15 and S-11 were found to have almost uniform mild contamination with low contamination, despite being far from the BTPS and ash pond. In addition, moderate contamination was found around the ash pond and the adjoining BTPS.

All metal enrichment factors have been determined using the Fe as a normalize unit. As > Cu > Zn > Mn > Pb > As > Cu > Zn > Mn > Pb (1.41) has the highest median content, followed by Zn (0.904), Cu (0.878), lead (0.857), and Mn (0.597), indicating minor enrichment in soil due to crustal origin (EF > 2). Due to crustal origin, all of the sample sites had low enrichment of Pb, Cu, Zn, and Mn in soil over the research area. However, sample sites 16, 3, 17, 18, 19, 21, 22, 25, 26, 14, 7 have high anthropogenic arsenic enrichment in soil (EF > 2), while the

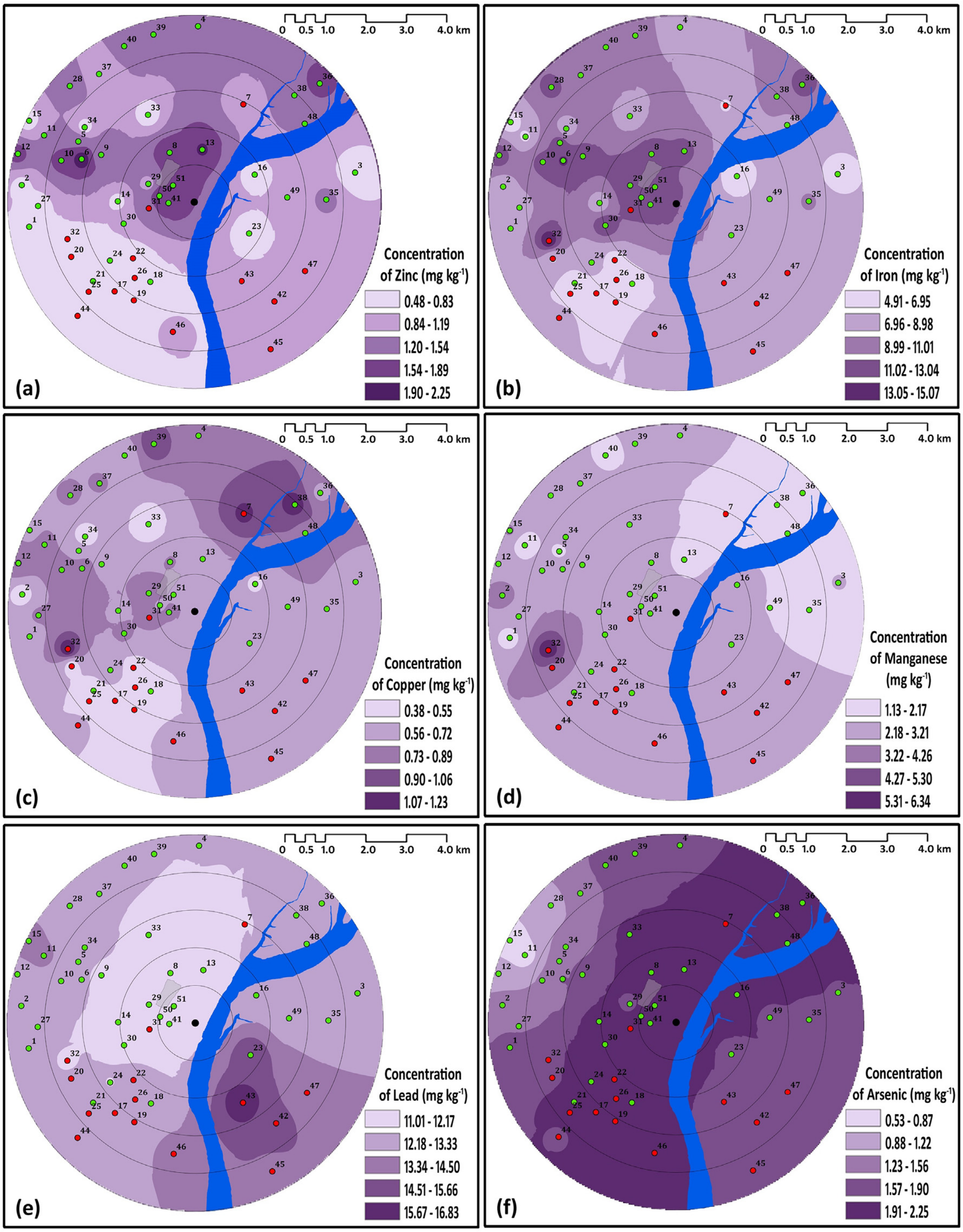


**Fig. 3.** Spatial distribution of soil contamination in and around BTPS (within 5 km buffer) through metals (a) Zinc, (b) Iron, (c) Copper, (d) Manganese, (e) Lead and (f) Arsenic.

remaining sample sites have little anthropogenic arsenic enrichment in soil (EF > 2). Moderate enrichment was discovered distant from the BTPS and ash pond, near the adjacent road and in the urban area, as well as in the downstream of Hooghly River. As a result, there was insufficient data to support the enrichment of metals from a nearby ash pond. The maximum variance of Pb and AS EF was reported at a 2 km buffer distance, followed by Mn at 4 km, copper at 3 km, and Zn at 5 km. Furthermore, the largest median EF of Pb, As, and Mn was found at a distance of 3 km, when Cu at at 5 km and Zn at a distance of 1 km.

The accumulation index demonstrated uncontaminated to severely contaminated arsenic and iron concentrations when compared to the background soil (25). As a result, the soils have significant amounts of arsenic and iron contamination. The accumulation index values are not uniform throughout the buffer zone, with the exception of As. The highest median concentration of heavy metals, with the exception of Mn, was found in the 0–1 km buffer region, i.e. near BTPS, indicating a contaminated scenario in compared to normal soil conditions (55,57). Furthermore, due to higher concentrations than normal soil concentrations, the above-

**Table 4**
Mean/Median concentration difference of heavy metals.

| Heavy metals | | Games-Howell Post-Hoc Test | | | | | | One-Way ANOVA (Welch's) | |
|---|---|---|---|---|---|---|---|---|---|
| | | Buffer | 1 | 2 | 3 | 4 | 5 | F | p |
| Iron | 1 | Mean difference | – | 1.24 | 4.24 | 2.8 | 3.1 | 23.737 | <0.001 |
| | | p-value | – | 0.816 | <0.001 | 0.01 | <0.001 | | |
| Zinc | 1 | Mean difference | – | 0.63 | 1.03 | 0.764 | 0.743 | 52.589 | <0.001 |
| | | p-value | – | 0.136 | <0.001 | <0.001 | <0.001 | | |

| Heavy metals | | Dwass-Steel-Critchlow-Flinger Pairwise Comparison | | | | | | Kruskal-Wallis | |
|---|---|---|---|---|---|---|---|---|---|
| | Buffer | | 1 | 2 | 3 | 4 | 5 | Chi square | p |
| As | 1 | W | – | −1.45 | −3.61 | −3.81 | −3.77 | 25.27 | <0.001 |
| | | p-value | – | 0.844 | 0.08 | 0.055 | 0.059 | | |
| | 2 | W | – | | −1.66 | −3.03 | −4.24 | | |
| | | p-value | – | | 0.767 | 0.202 | 0.023 | | |
| | 3 | W | – | | | −3.24 | −5.02 | | |
| | | p-value | – | | | 0.149 | 0.004 | | |
| | | W | | | | | −3.47 | | |
| | 4 | p-value | | | | | 0.102 | | |

Source: Computed by Authors.

mentioned areas are mostly uncontaminated to moderately contaminate by As, Fe, Zn, Cu which could be attributed to the accumulation nature and presences of trace elements in fly ash. The large median difference between the closest buffer and the others was also confirmed (56). Whatever the background situation for the presence of arsenoferrous materials in the delta plan, the concentration of arsenic and iron in the meander belts is explained in various ways, such as geomorphological impacts [58]. Overall, the median enrichment factor for all heavy metals indicates crustal origin, with the exception of arsenic enrichment in distinct sample sites far from the BTPS, where values more than 2 indicate anthropogenic origins. It could be due to fly ash deposition or other anthropogenic factors, although the ash-applied soils showed very minor heavy metal enrichment. The synergetic effects of fly ash deposition and other anthropogenic activities resulted in a significant change in median concentration.

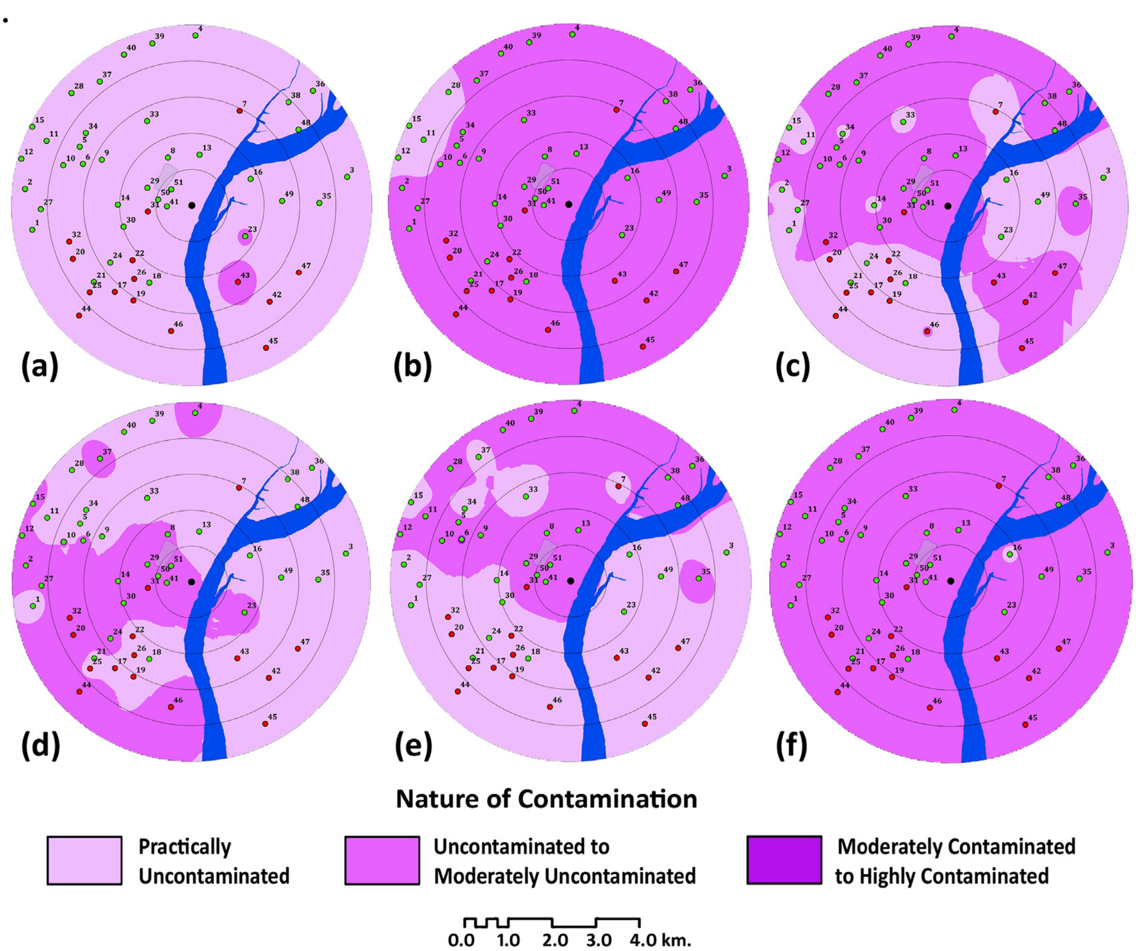


**Fig. 4.** Nature of contamination in and around BTPS (within 5 km buffer) by (a) Lead (Pb), (b) Arsenic (As), (c) Iron (Fe), (d) Manganese (Mn), (e) Zinc (Zn) and (f) Copper (Cu).

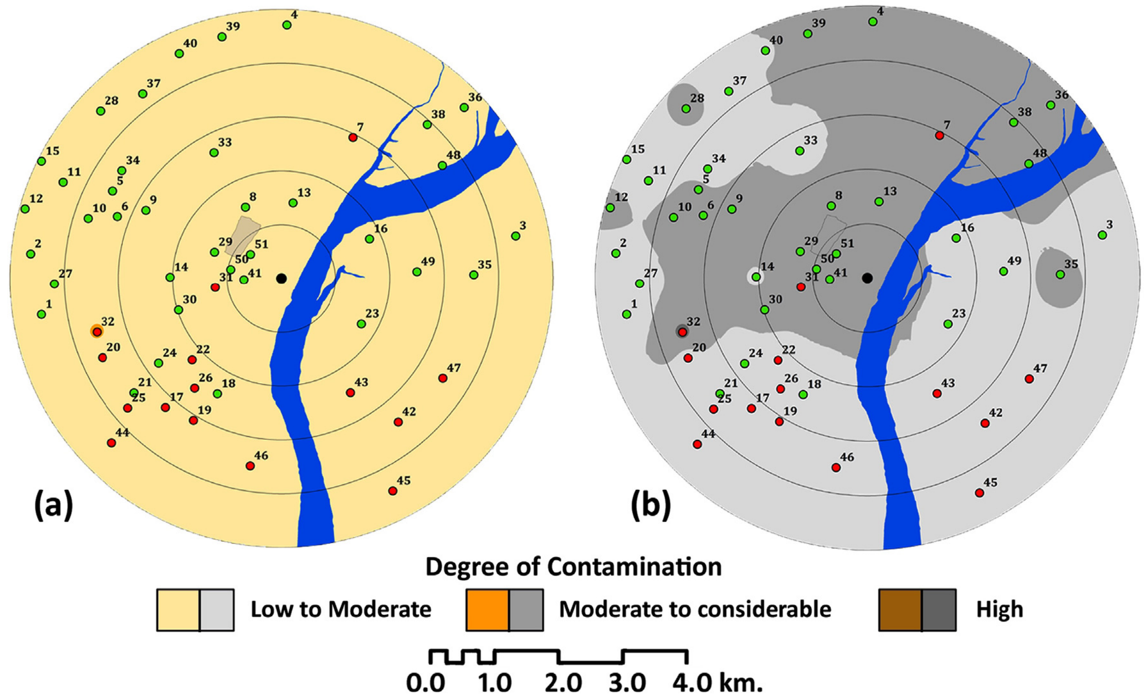


**Fig. 5.** Degree of contamination in and around BTPS (within 5 km buffer) by (a) Contamination degree index (CD) and (b) Modified degree of contamination (MCD).

### *3.4. Level of overall pollution in soil*

The Contamination degree index (CD), Modified Contamination degree index (MCD), and Pollution load index (PLI) were used to assess overall pollution caused by heavy metals in the research area. The overall index value reflects the contaminant nature of all heavy metals. The degree of contamination, according to the CD values, ranged from 12.58 at sample site 32 to 6.34 at sample site 15 (see Appendix Table 6). Furthermore, a high level of contamination was discovered at site (32) in the WWS direction within a 3–4 km buffer distance and throughout the research area, with a moderate level of contamination (Fig. 5a). The research area's median degree of contamination was 9.06, which indicates a moderate level of pollution. The greatest variation was discovered at a distance of 4 km. 1 (11.1) km had the greatest median concentration, followed by 2 (10.2), 4 (8.93), 5 (8.60), and 3 (8.58) km, suggesting moderate contamination.

The modified degree of contamination (MCD) index is more accurate than the degree of contamination index at distinguishing contamination levels. MCD ranged from 2.10 (moderate) to 1.06 (low to very low) for study sites 32 and 15. As a consequence, two contamination degree indices identified the identical sample sites with different amounts of contamination (in case of sample site 15). The median score (1.51) indicates that heavy metal pollution is low across the whole study area. Fig. 5b demonstrates that the ash pond and the BTPS have moderate contamination, whereas the rest of the region has nil to very low contamination, with a small patch of intermediate pollution. The greatest deviation was found at 4 km, while the median was found at 1 km. The median degree of pollution is almost the same beyond 2 km, and it is the second highest at 2 km. By computing geometric tendency, the PLI index effectively shows the pollution load on a sample location. The range of values was from 1.99 to 1.04. The greatest and minimum concentrations were discovered in the same two locations that were previously identified by two indices. In this study location, the median pollution load in soil was 1.44, indicating degraded soil. The regional pattern of soil deterioration near Bandel Thermal Power Station is depicted in Fig. 6a. The majority of the land is polluted to a moderate degree. Because of plume deposition as well as ash mixed soil, sample sites near the ash pond and near BTPS (8, 29, 31, 41, 50, and 51) exhibit greater pollutant loads. Meanwhile, pollution levels are very low to low in the southern and eastern directions. Fig. 6a also shows that the biggest variation is observed at 4 km, with the median at 1 km, followed by 2, 4, 5, and 3 km.

All heavy metals were moderately contaminated by the synergetic impact of anthropogenic activities and fly ash on soils, with the exception of manganese, which confirmed the median values of CF. Mn has an unfavorable relationship with Fe, since Mn levels rise as Fe fall [64]. In comparison to the background soil scenario, there was moderate contamination for all metals identified extremely close to the ash pond due to fly ash. The contamination of soil by fly ash was confirmed, although concentrations below the highest allowed limit for plant growth had no effect on plant growth. As a result, the low level of contamination observed near BTPS and along the downstream path. The PLI results indicate damaged soils in comparison to background soils throughout the research area, with the worst deterioration reported near BTPS and ash applied soils just for the presence of trace elements in fly ash. Other circumstances could be the result of anthropogenic activity, crustal origin, or geomorphological traits. The ecological risk factors, or toxic response of individual heavy metals, were below 30, indicating a minor impact on the environment, and the overall risk index, which is a potential ecological risk index for all sample sites, indicated a minor to moderate risk in terms of environmental sensitivity due to toxic heavy metal concentrations. In the downstream of BTPS and the other two heavy sectors, there is mostly a medium risk zone. Aside from that, there is a little risk. It could be due to the reduced impact of fly ash, which was monitored by the installation and maintenance of an efficient Electrostatic Precipitator, as well as the collection of dry fly ash and storage in the ash silo, as well as careful transportation of fly ash, and the planting of tolerance sapling around the power station and ash pond site. Sushil and Batra [65] revealed that dry ash collected and carried carefully, as well as deposited site covered by vegetation, had lower concentrations of heavy metals and pollution or degree of contamination than wet disposal sites.

### *3.5. Ecological risk of the heavy metals*

The study area's ecological risk (ER) has been assessed using four heavy metals (As, Pb, Zn, and Cu) to determine the availability of toxicity factors. Cu concentrations ranged from 12.9% at sample site 32 to 3.97% at sample

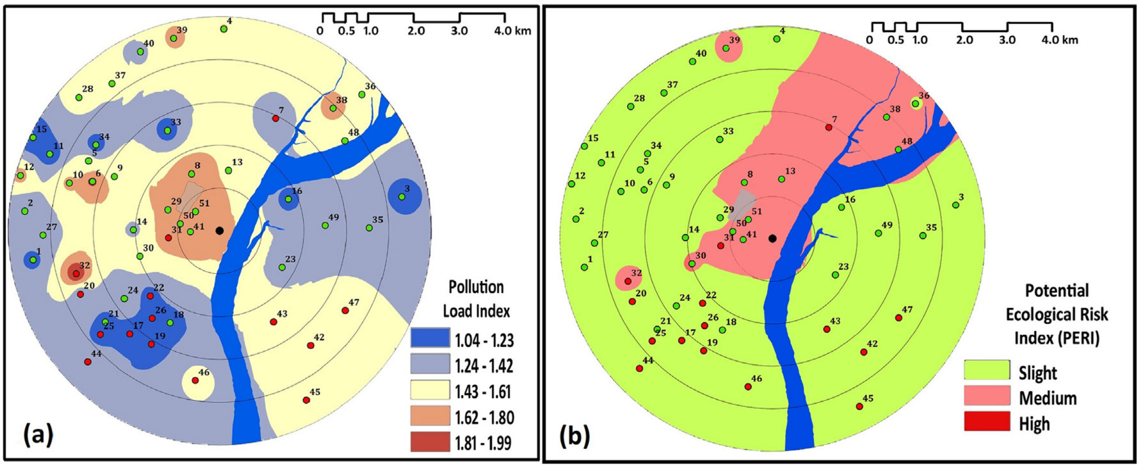


**Fig. 6.** (a) Spatial distribution of Pollution Load Index (PLI) in spatial dimension and (b) Spatial distribution of Potential Ecological Risk Index (PERI) in and around BTPS (within 5 km buffer).

site 33. Cu had a median ecological risk of 7.10. ER values of Pb varied from 8.25 to 5.39 at sites 43 and 51, respectively. 6.14 was the median value. Arsenic levels varied widely, ranging from 28.1 at sample site 8 (very close to an ash pond) to 6.63 at sample 15. The ER value has been found 23.6 on average. The highest ER of Zn (3.31) been found measured at sample site 6, while the lowest (0.71) been found reported at sample site 3.15. The median value has been found as 6.0. As a result, there is a substantial risk of arsenic contamination near the ash pond. Furthermore, all metals' average risk levels have a low ecological risk (ER 30). The biggest variation in ecological risk was reported at 3 km for lead, 5 km for arsenic, and 4 km for copper and zinc. Moreover, the maximum median ER for lead was discovered at 4 km, for zinc and arsenic at 1 km, and for copper at a buffer distance of 0–2 km. Potential Ecological Risk Index (PERI) has examined the sensitivity of biological environs. According to the conventional classification, all of the sample locations have a low to moderate level of ecological risk. The spatial distribution of potential ecological risk in relation to the research area is depicted in Fig. 6b. The majority of the research area was classified as low risk, with medium risk occurring near the BTPS and ash pond, as well as on the northern side.

pH has a substantial positive relationship with Mn, but a negative relationship with Fe, Zn, Cu, and EC (see Appendix Table 7). This suggests that alkaline soil contains more manganese, whereas acidic soil contains more iron, copper, and zinc. Meanwhile, different ion and cation concentrations have a moderate correlation under the same acidic state, as seen by the positive association with iron, copper, and zinc. As a result, acidic soils had higher ion and cation concentrations, while alkaline soils had higher manganese concentrations. The positive connection of manganese with iron and organic carbon, on the other hand, implies that higher levels of organic matter concentrated higher levels of manganese and iron, limiting their mobilization in soil solution. All metals, save Pb, have a positive connection with organic carbon, indicating that metals are immobilized in larger levels of organic matter. In an ironized soil environment, a positive relationship between iron and zinc also suggests a higher concentration of heavy metals. The negative relationship between lead and arsenic shows a lower concentration of one heavy metal in a bigger proportion in soil solution over time. According to the previous discussion, organic matter binned the metals more in this region, limiting their mobilization in the soil solution. Furthermore, in an acidic environment, higher levels of iron, copper, and zinc, as well as manganese, are concentrated, whereas in an alkaline environment, manganese is concentrated. Metals that have a strong association demonstrate that they come from the same formation and travel together. The positive correlation between pH and manganese indicates that alkaline soils contain manganese.

According to Hodges [64], pH is the most critical factor affecting Mn availability in soils. Maximum availability was obtained below pH 5.5, while significant availability was observed at pH 6.5. Strong alkaline soils, on the other hand, have the lowest concentration. Because the pH in this study area ranged from 4.4 to 7.32, a poor positive relationship was discovered in this situation. Furthermore, there was a substantial negative relationship between pH and iron, copper, and zinc, showing the creation of free iron and zinc at low pH. Low pH, according to Hoyt et al. [65] and Rengel [66], is advantageous for the generation of free metallic cations and anions. The Indo-Gangetic plain [59] revealed similar results. In the region of Serbia's major coal-fired thermal power stations, Ćujić et al. [67] found a substantial positive association between pH and Cu and Zn. Other research, on the other hand, found no link [1,34,68,69]. Cu, Fe, and Zn exhibit a positive significant connection with EC, indicating that these concentrations cause soil salinization. Shukla et al. [61] found a similar correlation in the soils of the Indo-Gangetic plain (IGP), with the research region being a section of the IGP. All of the metals had a positive and substantial relationship with organic carbon, implying that organic matter bound the metals and limited their mobility [70] Similar associations have been reported in this area by Shukla et al. [61]. Several researchers [70–72] found a strong link between metals and OC. The fact that the metals have a strong association suggests that they formed from the same source. As a combined element, Fe, Zn, and Cu in soil have a positive relationship and travel together. Because of its unfavorable connection with organic matter, lead is a free metallic element in soil solution.

**Table 5**
Mean concentration of parameters in different clusters.

| Cluster | pH | Mn (mg kg$^{-1}$) | Cu (mg kg$^{-1}$) | Fe (mg kg$^{-1}$) | Zn (mg kg$^{-1}$) | Pb (mg kg$^{-1}$) | As (mg kg$^{-1}$) | S (mg kg$^{-1}$) | K (Kg ha$^{-1}$) | P (Kg ha$^{-1}$) | N (Kg ha$^{-1}$) | OC (%) | EC (dS m$^{-1}$) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 6.25 | 2.22 | 0.580 | 8.80 | 1.13 | 12.20 | 1.80 | 11.90 | 266 | 59.30 | 161 | 0.448 | 0.490 |
| 2 | 5.96 | 2.46 | 0.679 | 8.34 | 0.945 | 13.20 | 1.71 | 12.60 | 236 | 72.10 | 318 | 0.561 | 0.421 |
| 3 | 6.15 | 2.73 | 0.712 | 9.53 | 1.15 | 12.20 | 1.82 | 10.60 | 308 | 84.40 | 442 | 0.746 | 0.512 |

Source: Computed by Authors.
Note: unit of the parameters given in parenthesis.

The HCA sorted the sample sites into three distinct groups. Cluster-I has five sample sites, Cluster-II has twenty-one sample sites, and Cluster-III has twenty-five sample sites. Table 5 displays the mean concentrations of nutrients and heavy metals. Cluster II has a more acidic soil than the other two clusters. This cluster also has the highest mean lead and sulphur concentrations. Cluster-III has the highest levels of manganese, copper, iron, zinc, arsenic, potassium, phosphorous, nitrogen, organic carbon, and EC (Table 5). In terms of soil fertility, cluster-III is highly fertile, cluster-II is moderately fertile, and cluster-I is low fertile. Cluster-III has a greater metal concentration, cluster-I have a moderate quantity, and cluster-II has a low degree of heavy metal contamination. The mean EC values of three clusters ably support this assertion. In November, Cluster-III was centered near BTPS and the ash pond, as well as the downstream wind path and adjacent roadways. The macronutrients and metal (micronutrients) concentrations are higher in the macronutrients and metal (micronutrients) cluster than in the other two clusters, according to HCA analysis. The concentration of metals, on the other hand, never exceeds the dangerous limit, indicating that fly ash acts as a supplement, improving soil physic-chemical properties and soil quality [12,53].

## 4. Conclusions

Soil samples with 5 km buffer of BTPS (51 samples from villages located in the buffer) were analyzed to determine the concentration of heavy metal (oid). The mean pH and potassium concentrations were lower than the background value, despite the fact that mean EC, organic carbon, and sulphur concentrations were almost identical, and nitrogen and phosphorous concentrations were higher. All nutrients were found to be at higher amounts near BTPS. Soils of extremely good to medium quality were found at nearly every sampling site. The average soil quality rating within 0–2 km indicates acceptable soil quality, while medium quality soils appear to be for ash deposition and other anthropogenic activities. Few sampling sites have higher heavy metal contents than background soils, indicating that fly ash has an impact on soil quality, yet none have ever exceeded toxicity standards. All heavy metals in this research location, with the exception of arsenic and lead, behave as plant micronutrients. Furthermore, all heavy metals, with the exception of As, did not follow a steady pattern in terms of concentration.

All the heavy metals, with the exception of Mn, were found to have a moderate level of pollution in soils. Almost all of the sample sites had extremely low to low pollution levels, indicating that the soil had moderate level of degradation. In addition, there was a moderate quantity of hazard in the research area's northern direction. Medium risk was observed around the BTPS and the ash pond's surroundings. The positive association of heavy metals in soil solution with organic carbon (organic matter) verified their immobilisation; however, Pb was free in soil solution, as seen by its negative interaction with soil organic content. Cu, Fe, and Zn concentrations are primarily enhanced in acidic soil, while Mn concentration is primarily enriched in alkaline soil. Cluster study of improved nutrient soil sample sites, especially in the vicinity of BTPS and ash mixed soils, as well as the ash pond. In practically all study sites, low to moderately contaminated soils around BTPS, on the other hand, never crossed the dangerous level when compared to background soil. To limit wind spread, the BTPS authority is increasingly leaning toward dry fly ash collection and careful transport with covered bunker type vehicles, as well as sapling planting around the ash pond and BTPS. Soil pollution has arisen in the research region as a result of the synergetic impact of BTPS with other industries and urban output. In addition, the study showed that ash application has good impacts in the agricultural sector. According to local farmers, crops in certain fields grew faster.

## Credit author statement

Somnath Mandal (Author 1): Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Supervision, Validation, Visualization, Writing Original Draft, Subhasis Bhattacharya (Author 2): Writing Review, EditingSuman Paul (Author 3): Writing Original Draft, Writing Review, Editing.

## Declaration 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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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enceco.2021.11.003.

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