

Exploring Soil Quality Variations across Upper, Middle, And Lower Ganga Regions: Leveraging GIS & Multivariate Statistical Methods to assess Organic Farming Viability

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Abstract

To assess the viability of organic farming by analyzing various characteristics, 26 soil samples were gathered from five states in three Indo-Gangetic regions for the current study. With a median pH of 6.7 and electrical conductivity ranging from 85.27 $\mu\text{s}/\text{cm}$ to 425.63 $\mu\text{s}/\text{cm}$, the sites from Upper Ganga Region (UGR) showed favorable soil conditions, leading to higher Soil Quality Index values (0.68 to 0.75; $p < 0.05$). On the other hand, the Lower Ganga Region (LGR) exhibited neutral to slightly alkaline pH of 7.7, greater EC levels (421.89 $\mu\text{s}/\text{cm}$ to 690.75 $\mu\text{s}/\text{cm}$), and lower SQI values (0.55 to 0.62; $p < 0.05$). The UGR had the highest nitrogen levels (153.87 kg/ha to 172.64 kg/ha; $p < 0.05$), while the Middle Ganga Region (MGR) had higher amounts of phosphorus (18.76 kg/ha to 24.59 kg/ha; $p < 0.05$) and potassium (204.15 kg/ha to 235.78 kg/ha). The amounts of each nutrient varied widely. The LGR exhibited higher levels of zinc (range: 48.26 mg/kg to 55.94 mg/kg) and lead (6.25 mg/kg to 8.31 mg/kg; $p < 0.05$) in comparison to the UGR and MGR, however the concentrations of heavy metals varied. In conclusion, organic farming is feasible along the Ganga basin region; however, because of its favorable soil conditions and higher SQI values, the UGR may be a better location for it, while the MGR & LGR might need more intensive soil management techniques to reduce the risk of contamination and promote sustainable organic farming practices.

Introduction

Traditionally known as the "breadbasket of India," the Gangetic basin region has enormous agricultural significance in South Asia (Bowden et al., 2023). However, it faces numerous challenges such as rapid urbanization, extensive use of chemical fertilizers and pesticides, and burgeoning population growth, all of which are compromising soil health and, thus, the overall ecosystem of the Gangetic basin as well as the river Ganges (Balkrishna et al., 2024; Bisht et al., 2020; Hoque et al., 2023; Khot et al., 2021; Maurya et al., 2019a; Shahane & Shivay, 2021; V. Srivastava et al., 2017). Mishra et al. used remote sensing and GIS techniques to investigate the impact of urbanization-induced land use changes on soil health in the Gangetic plains, revealing significant differences in soil properties in Uttarakhand, India (Mishra, 2022). Similarly, Matta et al. conducted a thorough investigation into chemical fertilizer and pesticide consumption patterns in the Ganges basin, highlighting their negative effects on soil quality (Matta et al., 2020). Furthermore, previous authors have also investigated the effects of chemical fertilizer application due to population growth on soil health in the Ganges River basin, emphasizing the critical need to address these issues (Amarasinghe, U. A; Muthuwatta, L; Smakhtin, V.; Surinaidu, L.; Rajmohan, N; Chinnasamy, 2016; Kumar Shukla et al., 2018; P. Srivastava et al., 2020).

Furthermore, the negative consequences of chemical or inorganic farming practices extend beyond soil quality to the water quality of the Ganga River. Runoff from agricultural lands laden with chemical fertilizers and pesticides contaminates the river, posing threats to both aquatic life and human health (Bagheri et al., 2023; Balkrishna et al., 2024). Excessive of chemical fertilizer application due to population growth on soil health in the Ganges River basin, depletion in the water, exacerbating ecological imbalances (DebRoy et al., 2012; Khot et al., 2021). Pesticide residues in water bodies accumulate over

time, posing long-term risks to biodiversity and human populations that rely on the river for drinking water and agricultural activities (Mukherjee et al., 2018; Khan et al., 2020). These findings back up the concerns about the negative effects of (PIB, 2022) population growth on soil health in the Ganges River Basin and the importance of implementing sustainable land management techniques (A. Kumar & Agrawal, 2020; Naveen et al., 2020). Thus, the Indian government's organic farming policy becomes increasingly important in mitigating the negative effects of these challenges on the soil health of the Ganges region. Organic farming provides a sustainable option for restoring soil health, preserving ecosystem integrity, and ensuring agricultural productivity in the Gangetic region. It would also contribute significantly to the Ganga River water quality (Bowden et al., 2023). Organic farming has the potential for sustainable agriculture, but its feasibility depends on the condition of the underlying soil quality (Gamage et al., 2023; Rigby & Cáceres, 2001; Shahane & Shivay, 2021; Soni et al., 2022). As a result, it is critical to understand the differences in soil health across the Ganga region. This study can be approached methodically by using multivariate statistical techniques and Geographic Information Systems (GIS), which are advanced geospatial and statistical methodologies (Babbar et al., 2022; de Andrade Barbosa et al., 2019). These methodologies allow for a comprehensive analysis of soil characteristics and their geographical distribution, laying the groundwork for informed agricultural management decision-making. As a result, the primary goal of this publication is to delve deeply into the complexities of soil quality disparities across the Upper, Middle, and Lower Ganga regions, and to investigate how these disparities affect the feasibility and success of organic farming efforts. Using modern geospatial and statistical methodologies, we hope to better understand the complex interactions between soil properties, land use patterns, and farming systems. This detailed research will provide critical insights into developing sustainable land management strategies tailored to the specific needs of each region.

Furthermore, it will provide insight into how to improve agricultural resilience, which is especially important given the changing environmental conditions. This research paper is closely related to the government's organic farming initiative because it addresses the importance of understanding and optimizing soil health to promote organic agriculture practices along the Ganga River belt.

Material & Methods

2.1. Selection of Sampling Sites

During the soil sampling site selection procedure, we employed a strategic approach with the goal of acquiring a thorough representation of soil properties over a considerable geographical span, spanning 2525 km from Gaumukh (Uttarakhand) to Ganga Sagar (West Bengal). As seen in Fig. 1, the selection criteria included locating 26 unique places spread throughout five Indian states. The selected sites were located no more than 100 km apart and no more than 10 km from either bank of the Ganga River to guarantee a varied and significant dataset. Further the sites are divided according to their altitudes which showcased that they are the part of Upper, Middle and Lower Ganga Regions. In the present study, the Upper Ganga region (UGR) begins in Gaumuk (S1), Uttarakhand and ends in Narora (S7), Uttar Pradesh. This plain is about 550 km long in the east-west direction and nearly 380 km wide in north-south

direction, covering an approximate area of 1.49 lakh sq km. Its elevation varies from 3714m to 179m above mean sea level. The Middle Ganga Region (MGR) runs from Buduan (S8), Uttar Pradesh, to Balia (S15), Uttar Pradesh. To the east of the Upper Ganga plain is Middle Ganga plain occupying eastern part of Uttar Pradesh that is Buduan () and Bihar. It measures about 600 km in the east-west and nearly 330 km in north-south direction accounting for a total area of about 1.44 lakh sq km. Its northern and southern boundaries are well defined by the Himalayan foothills and the Peninsular edge respectively. Lower Ganga Region (LGR) refers to the area between Revelgang (, Bihar, and Gangasagar (S26) in West Bengal. The following divisions help us comprehend the spatial variability of soil quality across the entire river Ganga basin.

2.2. Collection of soil samples

A randomised sampling technique was used in the georeferenced soil collection process, which was part of an experimental design with four replicates from either side of the Ganges. Twenty-five real soil samples made up each individual analytical soil sample, from which four duplicate samples were taken and well mixed before analysis. The maximum depth at which sampling was done was 5–8 cm below the soil's surface. To prevent contamination caused by humans, standard aseptic techniques were used for sampling soil. The details of the sampling sites along with the weather parameters during sampling have been registered in supplementary Table S1.

2.2. Analytical Methods

The physical parameters that were analyzed for each of the soil samples included bulk density and soil moisture retention (measured in Pressure Plate Apparatus). The chemical parameters were pH, electrical conductivity (EC), available Nitrogen (N), available Phosphorus (P), available Potassium (K), cation exchange capacity (CEC), available sulfur (S), and the soil organic carbon fractions (very labile, labile, and less labile fractions distinguished based on the chemical oxidation method). Standard analytical protocols were used for estimating the soil quality parameters (Bhattacharyya et al., 2017a; Lenka et al., 2022).

The quantitative amount (mg/kg) of heavy metals like Chromium (Cr), Zinc (Zn), Arsenic (As), Cadmium (Cd), Mercury (Hg), Nickel (Ni), and Lead (Pb) were measured using ICP-MS. In summary, all samples were dried for 24 hours at 95°C. The samples of dry soil were blended for four minutes at 1000 rpm using a blender. Then, 1 g of the sample was extracted using an acid digestion system assisted by a microwave using a solution of 3 mL HCl and 9 mL HNO₃ (HiMedia, India). The digesting temperature of the microwave system reached 175°C in five minutes and stayed there for 15 minutes. Following the isothermal phase, the Teflon vessels were cooled, and the samples that were still within were moved to volumetric flasks that had been acid-cleaned and filtered through a Whatman No. 0.45 µm filter. Before analysis, the filtered digested solutions were diluted with 50 mL of deionized water. The metal contents

were ascertained using the utilization of an Inductively Coupled Plasma – Mass 188 Spectrometer (ICP-MS) (iCAP Qc, Thermo Fisher Scientific, Bremen, Germany).

Potential Ecological Risk Index

To determine the potential ecological danger of heavy metal deposition in soil, the ecological risk index (ER) was calculated. Soil heavy metal characteristics is used to determine the possible ecological harm of soil heavy metals. It can also consider the synergistic effects of multiple elements, the amount of pollution, and the environmental linkages with heavy metals. The integrated potential ecological risk index (RI) integrates each heavy metal's ER value. This method was retrieved from Zhao et al., (Zhao et al., 2022) with the following calculating formula.

$$R.I. = \sum (Tr \times C.F).$$

Where, C.F. represents Contamination Factor for individual metal & Tr represents Toxicological Response Factor for individual metal. The details calculation and background data of the heavy metals have been documented in Supplementary Table S2.

2.3. Soil Quality analysis & GIS mapping

The Simple Additive Soil Quality Index (SQI) method assesses soil health by combining multiple indicators into a single numerical value. Key principles include considering various aspects of soil quality, standardizing indicators to a common scale, assigning weights based on importance, assuming additivity of contributions, and facilitating interpretation. The procedure involves selecting relevant indicators, collecting soil samples, standardizing data, assigning weights, calculating the index, and interpreting results. Higher SQI values indicate better soil health, while lower values suggest degradation. Validation and refinement ensure accuracy and applicability. Overall, SQI offers a systematic approach to evaluate and monitor soil health, aiding sustainable land management decisions (Chaudhry et al., 2024). The SQI for each individual soil sample was calculated by summing the individual index values according to Eq. 1.

$$\sum SQI = \sum Individualsoilparameterindexvalues$$

1

To ensure comparability across the datasets, a scaled SQI (SQI) was computed using Eq. 2:

$$SQI = (\sum SQI - SQI_{Min}) / (SQI_{Max} - SQI_{Min}) \quad (2)$$

whereas SQI_{Min} = Minimum value of SQI, and SQI_{Max} = Maximum value of SQI from the total dataset.

Utilizing the 26 SQI values as input data, we further conducted an Inverse Distance Weighting (IDW) interpolation technique. IDW interpolation is a spatial analysis method commonly used in geostatistics and GIS (Geographic Information Systems) to predict values at unsampled locations based on nearby sampled points (Ouabo et al., 2020). The interpolation was performed systematically along the Ganga

region, covering the entire stretch from one endpoint to the other. This comprehensive approach allowed us to estimate the soil quality for the sections in between the sampled points. By doing so, we gained insights into the spatial variation and distribution of soil quality throughout the Ganga region, providing valuable information for land management, agricultural planning, and environmental conservation efforts.

Statistical Analysis

The descriptive statistics were utilized to elucidate the central tendency values of UGR, MGR, and LGR. The data was represented by Violin plot using Graph Pad Prizm (USA). The Shapiro-Wilk test was employed for normality testing. Hypothesis testing was conducted using the non-parametric Kruskal-Wallis H test followed by Dunn's post-hoc test with Bonferroni correction, with a significance level set at 5% in all cases (Ghosh et al., 2013). The relationships between soil quality parameters and their sources were clarified through correlation analysis. Individual heavy metal correlations were assessed using Pearson correlation, while multivariate analyses such as principal component analysis (PCA) and hierarchical cluster analysis were performed to speculatively identify pollution causes and agents (Balkrishna et al., 2024; Banerjee et al., 2021). Due to variations in data magnitudes, collected data for factor analysis were standardized as Z values to ensure uniformity. PCA was employed to ascertain the continuous presence of individual metals in sludge samples, with the highest contribution of each metal determined according to the method described by Banerjee et al. To validate the PCA results, Hierarchical Cluster Analysis (HCA) was also conducted (Banerjee et al., 2021).

Results and Discussion

3.1. Physicochemical properties

Understanding the physicochemical properties of soil is of paramount importance for effective agricultural management and environmental sustainability. In this study, we delve into key parameters including electrical conductivity (EC), pH levels, total moisture content (TMC), organic carbon (OC%), and bulk density across the Upper, Middle, and Lower Ganga regions BY violin plot (Fig. 2). Violin plots offer a concise yet powerful way to visualize data distributions, combining the simplicity of box plots with the richness of kernel density estimation. They display the probability density of the data at different values, showcasing central tendency, spread, and multimodal tendencies which facilitates comparisons between multiple groups in a straightforward manner.

Soil parameters such as electrical conductivity (EC) and pH are important in determining salinity, nutrient availability, and overall soil health. EC values vary significantly across the Upper, Middle, and Lower Ganga regions, ranging from 85.27 $\mu\text{s}/\text{cm}$ in the Upper Ganga Region (UGR), 425.63 $\mu\text{s}/\text{cm}$ in the Middle Ganga Region (MGR), and 352.87 $\mu\text{s}/\text{cm}$ in the Lower Ganga Region (LGR). Similarly, pH levels indicate soil acidity or alkalinity, with the UGR having a slightly acidic median pH of 6.7, the MGR varying in pH levels from 6.8 to 8, and the LGR remaining neutral to slightly alkaline at 7.7. These pH variations ($p < 0.05$) reflect diverse soil properties and regional influences, necessitating tailored agricultural practices

for optimal crop growth and environmental sustainability, findings supported by recent studies (Bagoria et al., 2020; Kim & Park, 2024) on pH & EC ranges in the Ganga River soil regions.

Total moisture content (TMC) provides critical insights into the soil's ability to retain water, allowing for more effective irrigation system planning and drought mitigation methods. The observed decreasing trend in TMC from the Upper Ganga Region (UGR) to the Middle Ganga Region (MGR) and finally to the Lower Ganga Region (LGR) of 15.57%, 12.845%, and 9.73%, respectively, suggests a positive correlation (r^2 : 0.68) with altitude. This emphasizes how elevation gradients must be considered when managing soil, particularly in areas prone to water stress or irrigation difficulties, supported by studies published elsewhere (Ferreira, 2017; Kumawat et al., 2020). Furthermore, organic carbon content (in %) is an important indicator of soil fertility and carbon storage capacity, which is required for both climate mitigation and sustainable agriculture (Ogle & Paustian, 2005). The observed differences in organic carbon % across the Ganga regions, with the highest values in the UGR (0.69 %), MGR (0.4%), and LGR (0.48 %), indicate varying rates of decomposition ($p > 0.05$) and organic matter inputs driven by different environmental conditions. These observations are corroborated by a recent study conducted in Maharashtra, India, and Nepal (Hadole et al., 2019; Shapkota & Kafle, 2021).

Bulk density measurements also reveal the degree of soil compaction and structural stability, which influence key soil processes such as nutrient cycling, water infiltration, and root penetration. The bulk density readings range from 0.91 to 0.95 gm/ml, with no significant regional variations ($p > 0.05$); however, the continuous patterns indicate comparable levels of soil compaction across the Ganga regions. These findings reinforce the relationship between bulk density and soil organic carbon concentration, which was highlighted in the previous studies (Keller & Håkansson, 2010; Ruehlmann & Körschens, 2009), emphasizing the importance of targeted soil management interventions to reduce compaction risks and encourage sustainable land use practices, particularly in erosion and degradation-prone areas.

The observed values of key soil parameters, including electrical conductivity (EC), pH, total moisture content (TMC in %), organic carbon (OC in %), and bulk density, are critical indicators for determining the viability of organic farming practices (Bhattacharyya et al., 2017a) in the Ganga region. Comparing the data with the thresholds established by Bhattacharyya et al. (Bhattacharyya et al., 2017a), that suggest optimal ranges for organic farming in India, provides useful insights. To begin, the variability in EC levels across the Upper, Middle, and Lower Ganga regions is within the recommended range of 2–12 dS/m, indicating that the soil salinity conditions are suitable for organic crop cultivation. Second, pH levels in the studied regions range from 4.5 to 9, which correspond to the optimal pH values for organic farming (Aulakh et al., 2022; Bhattacharyya et al., 2017a; Haneklaus et al., 2005), ensuring appropriate soil acidity or alkalinity for nutrient availability and microbial activity. Furthermore, while the observed TMC values decrease with altitude, potentially affecting water retention capacities, they are still within acceptable limits for organic farming (Bhattacharyya et al., 2017a). While TMC values show a slight downward trend with altitude, a statistical test confirms that the differences between regions are statistically insignificant ($p > 0.05$), indicating that organic farming's water retention capacities remain acceptable. Furthermore,

variations in OC (%) values reflect differences in soil fertility, with values falling within the desirable range of 0–12 mg/kg, thereby supporting organic farming's sustainability objectives. Finally, despite minor variations, consistent bulk density values remain within the preferred range of 1–2 mg/m³, as evidenced by statistical analyses that show no significant differences ($p > 0.05$) across Ganga regions. Overall, the alignment of observed soil parameters with established thresholds highlights the favorable conditions (Aulakh et al., 2022; Bhattacharyya et al., 2017a; Haneklaus et al., 2005) for organic farming in the Ganga region, emphasizing its potential as a viable and sustainable agricultural practice in the area.

3.2. Nutrient availability

The inherent nutrient availability of soil like Nitrogen (N), Phosphorus (P), Potassium (K) and Sulphur (S) around the UGR, MGR and LGR has been showcased below (Fig. 3)

The concentrations of nitrogen (N) (kg/ha), phosphorus (P), and potassium (K) in the Ganga River vary significantly ($p < 0.05$) by region. The Upper Ganga region (UGR) has the highest nitrogen levels at 168.09, followed by the Lower Ganga region (LGR) at 152.62, and the Middle Ganga region (MGR) with the lowest nitrogen levels at 85.505. This pattern emphasizes the importance of nitrogen for plant growth, as well as the potential for super-eutrophic conditions caused by nitrogen loading in the river. Phosphorus concentrations vary by region, with the LGR having the highest levels (30.63), followed by the UGR (18.47) and the MGR (20.16). Potassium levels vary significantly ($p < 0.05$) across regions, with the LGR having the highest concentration (204.81), followed by the UGR (99.34) and the MGR (91.32). Sulfur concentrations follow a similar pattern, with the LGR having the highest concentration at 24.06, followed by the MGR at 19.825, and the UGR having the lowest concentration at 10.21. These nutrient concentration variations highlight the complex dynamics of nutrient distribution along the Ganga River, as well as the influence of environmental factors on nutrient levels, as demonstrated by soil health studies and the impact of saline-alkaline soils on nutrient content in the river. When the observed nutrient concentrations along the Ganga River are compared to the threshold values recommended for optimal agricultural productivity, they provide valuable information about the region's suitability for organic farming.

Nitrogen levels are highest in the Upper Ganga region (UGR) and lowest in the Middle Ganga region (MGR), falling within the threshold limit of 0-400 kg/hectare (Bhattacharya et al., 2017), indicating adequate nutrient availability for crop growth across the studied regions. Similarly, phosphorus concentrations, despite fluctuations, remain within the recommended threshold range of 0-500 kg/hectare, indicating adequate phosphorus levels for plant development. Potassium levels, while varying significantly across regions, fall within the threshold range of 0-400 kg/hectare (Aulakh et al., 2022; Bhattacharyya et al., 2017b; Haneklaus et al., 2005), indicating adequate potassium availability for crop nutrition.

Furthermore, Sulphur concentrations, while varying across regions, generally fall within the recommended threshold levels, bolstering the region's ability to sustain nutrient-rich soils suitable for organic farming practices. The observed nutrient concentrations, which are consistent with these threshold values,

highlight the Ganga region's suitability for implementing and sustaining organic farming practices, as well as its potential as an environmental and socially responsible agricultural production hub.

3.3. Heavy Metal Distribution

The data reveals substantial variations in soil concentrations of various parameters, including Zinc, Iron, Manganese, Copper, Chromium, Nickel, Arsenic, Cadmium, Mercury, and Lead, across the Ganga River basin (Fig. 4).

The concentrations of these metals differ significantly between the Upper Ganga region (UGR), the Middle Ganga region (MGR), and the Lower Ganga region (LGR). Zinc concentrations are highest in the LGR (52.48 mg/kg), followed by the UGR (47.05 mg/kg) and the MGR (46.36 mg/kg), indicating potential anthropogenic influences and raising concerns about environmental risks (Singh et al., 2017). Iron concentrations peak in the MGR (21,912.44 mg/kg), indicating favourable soil fertility conditions. Manganese concentrations vary inversely, with the MGR recording the lowest levels (329.95 mg/kg). The MGR has the highest copper concentrations (18.305 mg/kg), which could be attributed to human activity (Debasmita et al., 2022; M. Pandey et al., 2014). Chromium concentrations vary significantly across regions, with the MGR having the highest levels (22.145 mg/kg), indicating both natural and anthropogenic sources of contamination (Banerjee et al., 2021). Nickel concentrations vary similarly, with the UGR having the highest levels (20.3 mg/kg). The UGR has the highest arsenic levels (8.29 mg/kg), which are attributed to both natural and anthropogenic activities (Aguilar-Garrido et al., 2020). Cadmium concentrations (0.1 mg/kg) are consistent across all regions, posing environmental risks despite their low levels (Balkrishna et al., 2024; Tchounwou et al., 2012). Mercury concentrations are uniform, highlighting the need for monitoring and management (Sinha et al., 2007).

The MGR has the highest lead concentrations (7.895 mg/kg), indicating potential contamination from industrial and mining activities, necessitating vigilant environmental management efforts (Singh et al., 2017). These findings highlight the complex dynamics of metal contamination in the Ganga River basin, emphasising the need for comprehensive pollution control measures and environmental conservation efforts to protect ecosystem health and human well-being. According to the current study findings, the feasibility of organic farming in the Ganga River basin is influenced by varying concentrations of essential micronutrients such as zinc, copper, iron, and manganese. While zinc concentrations are typically within the organic farming threshold range (0-1.5 mg/kg), the presence of heavy metals such as arsenic (As), mercury (Hg), lead (Pb), and chromium (Cr) at elevated levels presents significant challenges. Arsenic, for example, exceeds permissible limits for organic farming, with the highest concentrations recorded in the Upper Ganga region (UGR). Similarly, mercury concentrations, while consistent across regions, may endanger soil health and crop quality due to its toxicity and bioaccumulation properties (Balkrishna et al., 2024; Maurya et al., 2019a). Lead concentrations in the Middle Ganga region (MGR) exceed safe levels for organic farming, potentially compromising soil fertility and ecosystem integrity. Chromium (Cr) concentrations, which are particularly high in the Lower Ganga region (LGR), raise further concerns about soil contamination and agricultural sustainability. Heavy metals higher than its threshold level, might pose severe threat to the effectiveness of organic farming,

manifesting through detrimental impacts on soil health, contamination of organic produce, and substantial challenges for farmers (Gamage et al., 2023; Rigby & Cáceres, 2001). These metals could disrupt soil properties, diminishing fertility and microbial activity critical for plant growth, while their accumulation in crops jeopardizes organic certification and consumer health (Gamage et al., 2023). Addressing heavy metal contamination is imperative to sustain the integrity and viability of organic agriculture, necessitating urgent action and collaborative strategies to mitigate these detrimental effects.

3.3.1. Potential Ecological Risk Index

The examination of the prospective potential ecological risk index (RI) of heavy metals based on their order reveals important perspectives on the relative danger provided by different metals (Kowalska et al., 2018; V. Kumar et al., 2019). The investigation into potential risk index (RI) values of heavy metals in soil samples from various regions along the Ganga River reveals significant variations in contamination levels. The Upper Ganga Region (UGR) has an average RI of 306.04, indicating moderate risk ($150 \leq \text{RI} < 300$) (Kowalska et al., 2018; Zhao et al., 2022). Individual RI values across UGR range between 278.33 and 325.13, indicating a consistent but moderate level of heavy metal contamination. Similarly, the Middle Ganga Region (MGR) has an average RI of approximately 331.09, indicating moderate risk (Kowalska et al., 2018), with individual values ranging from 289.48 to 418.01. The Lower Ganga Region (LGR) has a significantly higher average RI of 389.19, placing it in the considerable risk category ($300 \leq \text{RI} < 600$) (Kowalska et al., 2018; V. Kumar et al., 2019). Individual RI values in LGR range from 292.20 to 802.36, indicating a wider range and greater variability in contamination levels than UGR and MGR. Further the results display a significant difference in RI values between UGR, MGR, and LGR ($p < 0.001$) at 95% confidence interval. According to Dunn's test, the mean RI values of UGR and MGR are not significantly different ($p > 0.05$), implying that the two regions have similar levels of contamination. However, UGR and MGR have significantly lower RI values than LGR ($p < 0.001$), indicating a higher risk of heavy metal contamination in the Lower Ganga region. The findings support previous research highlighting the impact of anthropogenic activities and municipal or industrial effluent discharge on heavy metal pollution along the Ganga River basin (Bai et al., 2022; V. Kumar et al., 2019; Kumari et al., 2023; Maurya et al., 2019b; J. Pandey & Singh, 2017; M. Pandey et al., 2014).

3.4. Overall pollution source analysis

The correlation analysis of heavy metals and associated physicochemical parameters is pivotal in deciphering potential sources of pollution and understanding their interrelationships within the studied soil samples. Correlation coefficients serve as a measure to assess the similarity or dissimilarity between different parameters. In this context, high correlation coefficients imply potential similarities in pollution sources, while low or negative correlations suggest disparate origins. The findings of the correlation analysis highlight a diverse range of relationships among the eight heavy metals and various physicochemical parameters (Fig. 5A). Notably, specific heavy metal pairs exhibited notably high correlation coefficients, such as Pb and Cu, Zn and S, Zn and Pb, as well as Cu and P, all surpassing the 0.70 threshold ($r > 0.70, p < 0.05$). These robust correlations strongly indicate a common source of pollution for S, Pb, Cu, and Zn heavy metals within the studied soil samples. This insight is invaluable as

it suggests a potential linkage in the origins or pathways of these pollutants, aiding in targeted identification and remediation strategies for mitigating their impact. Conversely, certain physicochemical parameters displayed moderate correlations with specific heavy metals. For instance, Cr exhibited a moderate correlation with N and Fe ($r = 0.5-0.6$, $p < 0.05$), while electrical conductivity (EC) demonstrated a similar level of correlation with metals like Pb, Cu, and S ($r = 0.5$, $p < 0.5$).

Additionally, factor analysis was performed to understand the inner relations of the variables in the soil samples at various sites. To obtain a uniform magnitude of the observed data, the Z values of the data were taken into consideration. The sufficient sampling in the study is indicated by the KMO test value of 0.83 ($p < 0.05$). Varimax Rotation was used to increase the factor coefficients' sum of variance, which better explained the potential pollution sources. A total of 85.74% of the variability in the data could be explained by the six primary components, which satisfy the minimum variance criteria of PCA. The components have been chosen whose Eigen values are greater than 1. The loading of each variable with the components has been documented in Table 4. In the Principal Component Analysis (PCA) conducted on the soil dataset, seven principal components (PCs) were extracted, each shedding light on different aspects of soil quality and environmental factors. PC-1, explaining 17.381% of the variance, suggests contamination primarily by heavy metals like Arsenic (As), Manganese (Mn), and Iron (Fe), potentially originating from industrial or anthropogenic sources. PC-2, explaining 14.214% of the variance, indicates a different contamination source, possibly from Lead (Pb) and Sulfur (S), highlighting the importance of monitoring pollution from industrial activities. PC-3, explaining 12.707% of the variance, reflects soil fertility and nutrient availability, with high loadings of Nickel (Ni) and Zinc (Zn), emphasizing their role in agricultural productivity. PC-4, explaining 12.013% of the variance, reveals a contrasting pattern, indicating pollution alongside agricultural practices, as shown by Cadmium (Cd) and Nitrogen (N) loadings. PC-5, explaining 11.935% of the variance, suggests contamination by toxic elements, particularly Mercury (Hg), requiring attention due to its toxicity. PC-6, explaining 10.194% of the variance, emphasizes the importance of soil structure and organic matter, as indicated by Bulk Density (BD) and Organic Carbon (OC) loadings. PC-7, explaining 7.471% of the variance, underscores the influence of moisture content on soil properties, with high loadings of Total Moisture Content (TMC). These insights, derived from the PCA results, provide valuable information for understanding soil quality, contamination sources, and guiding efforts toward sustainable soil management and environmental protection. (Fig. 5B). Integrating the results of correlation and factor analysis yields a comprehensive understanding of soil pollution sources and their interrelationships. The strong correlations between certain heavy metals indicate common sources or environmental processes governing their presence in soil. This is supported by factor analysis, which identifies specific components that explain the variance in the dataset. For example, the first principal component in the factor analysis, which contains high levels of Pb, Cu, TS, OC, Zn, and Cd, corresponds to the correlated heavy metal pairs identified in the correlation analysis, implying a possible common source for these pollutants.

Furthermore, the moderate correlations observed between certain physicochemical parameters and heavy metals shed light on the environmental factors that influence metal concentrations in the soil. For

example, the moderate correlation between Cr and N or Fe suggests that nutrient availability may interact with metal uptake by plants or microorganisms.

Table 3
Component loadings in Principal Component Space

Factors	Principle Components (PC)						
	PC-1	PC-2	PC-3	PC-4	PC-5	PC-6	PC-7
Loading values							
As	.904						
Mn	.887		.261				
Zn	.806			.525			
Cd	.696			.559	.326		
Fe		.871	.261				
BD		-.805			-.324		
N		.706	-.360			.458	
pH		-.633	.449		.412		.208
Ni			.916				
Cr			.800	.311			
Pb				.960			
Cu	.334		.528	.726			
S					.922		
EC	.463				.853		
P						.913	
K	.306		.299			.756	
OC		.419			.422	.462	.201
Hg							-.870
TMC		.350		.279		-.246	.709
Variance explained (%)	17.381	14.214	12.707	12.013	11.935	10.194	7.471
Total variance (%)	85.914						

Extraction Method: Principal Component Analysis. Rotation Method: Varimax with Kaiser Normalization. Rotation converged in 10 iterations.

Cluster analysis (CA) validates the results obtained from correlation values and PCA (Fig. 5C). Site-specific clustering is classified into three broad groups. Samples collected in Uttarakhand (S2, S3, S4) are grouped together from UGR due to similar pollution levels, whereas sample S1 forms a separate cluster. This clustering suggests a distinct pattern of pollution distribution within the UGR region, which may be influenced by local sources or environmental factors specific to that area. In contrast, samples collected from MGR (S6-S16) show a more diverse classification. This indicates that pollution levels vary across sampling sites in Uttar Pradesh. Factors such as industrial activities, agricultural practices, and urbanization may all contribute to the diverse distribution of pollutants. Overall, cluster analysis supports the findings of correlation analysis and PCA, providing new information about the spatial distribution of soil pollution. These clusters can help to guide targeted remediation efforts and policy interventions tailored to specific regions or sites, effectively addressing soil pollution and its associated environmental and health risks. case.

Comparing the findings of the pollution source analysis with existing literature reveals alignment with established patterns and provides further validation. For instance, heavy metal contamination corroborates studies linking industrial activities and anthropogenic sources to elevated levels of Arsenic, Manganese, and Iron in soils of specially in the state of Uttar Pradesh in MGR region (Goyal et al., 2022; Singh & Singh, 2018; Tyagi et al., 2022). Similarly, Lead and Sulfur contamination resonates with research highlighting industrial emissions and atmospheric deposition as significant contributors to soil pollution in both MGR and LGR (Banerjee et al., 2023; Mandal et al., 2021; Pal et al., 2023; Singh & Singh, 2018). Additionally, association with soil fertility and nutrient availability, particularly with Nickel and Zinc, aligns with studies emphasizing the importance of these elements in enhancing agricultural productivity and plant growth (Ahmed et al., 2024; Bici et al., 2023). These parallels with existing literature not only support the validity of the obtained results but also underscore the relevance of the identified factors in shaping soil quality and environmental dynamics.

3.4. Soil Quality analysis.

The Soil Quality Index (SQI) has emerged as a critical tool for assessing soil health and fertility. SQI provides useful information about soil condition and productivity potential by combining various soil parameters into a single numerical value.

The datasets present a detailed profile of soil parameters across a spectrum of sampling sites (S1 to S26) and IDW technique has been used to interpolate the soil quality by predicting model (Fig. 6). The Electrical Conductivity (EC) values, reflecting soil salinity, range widely, from relatively low levels in sites of UGR such as S3, S4, and S5 to remarkably high values in LGR sites like S25 and S26. Total Moisture Content (TMC) varies across sites, with S18 site in MGR displaying the lowest %age and others like S3 in UGR and S23 in LGR showing relatively higher values. Organic Carbon (OC) %ages vary modestly among the sites, with discernible differences seen in S1, S2, in UGR and S9 in MGR.

Additionally, the dataset includes information on essential nutrients such as Nitrogen (N), Phosphorus (P), and Heavy Metal concentrations like Mercury (Hg). These data points collectively contribute to a

comprehensive understanding of the soil characteristics at each sampling site, offering valuable insights for agricultural and environmental assessments. The visual representation of parameter spatial distribution serves as a clear indicator, allowing the differentiation between high and low values for each parameter, where the dominance of the red color emphasizes elevated parameter values. After this visualization, the Soil Quality Index (SQI) was computed using the additive method, and the results were spatially interpolated across the four states to capture the substantial variability. The site codes, spanning from S1 to S26, uniquely label individual sampling locations, constituting a pivotal element in the comprehensive assessment of soil quality along the Ganga River.

The values of the Soil Quality Index (SQI) collected from the sampling sites in the UGR, MGR, and LGR sections of the Ganga River offer important information about the different levels of soil fertility and health in the states of West Bengal, Uttarakhand, Uttar Pradesh, Bihar, and Jharkhand. The region of Gaumukh in UGR has the best soil quality, with a SQI of 16.33%, suggesting strong soil conditions there. This result is consistent with the commentary's focus on the value of healthy soils for organic farming methods because Gaumukh's high SQI indicates favourable circumstances for long-term agricultural development. Conversely, Varanasi in MGR has a lower SQI of 10.33%, suggesting possible soil issues that would imperil attempts to practice organic farming in this region.

This discrepancy highlights how crucial soil quality evaluations are for informing focused soil management plans that deal with particular problems related to soil health. For instance, treatments like soil amendment with organic matter and microbial inoculants may be required in areas with lower SQI values, like Varanasi, to improve soil fertility and resilience. With a SQI of 14%, Prayagraj in MGR also stands out from Varanasi and suggests healthier soil conditions. This variation within the same area emphasizes how crucial site-specific methods are for managing the soil in organic farming systems. Organic farmers can enhance soil health by using practices that sustain and enhance soil quality over time, by finding regions with higher SQI values, like Prayagraj. Moving on to the LGR, locations with SQI scores between 13% and 15.67%, such as those close to Revelganj and Patna, show moderate to high soil quality. This result is in line with the commentary's analysis of the relationship between agricultural productivity and soil quality because more resilient and productive organic farming systems are likely to be found in areas with higher SQI values. Significant variations in soil quality are observed in West Bengal in the LGR, with Hooghly displaying the highest SQI of 16.67%. This variation draws attention to the intricate interactions between a variety of variables, including soil management techniques, land use practices, and climate. In addition to providing a starting point for conversations regarding regional differences in soil health, the SQI assessment can be used to build focused interventions to address particular soil issues and advance sustainable land use practices along the Ganga River.

The Soil Quality Index (SQI) is an important tool for assessing the viability of organic farming, especially in India (Bhattacharyya et al., 2017a). This index provides valuable insights into soil health and fertility, as well as essential guidance for implementing organic farming practices (Bhattacharyya et al., 2017b; Haneklaus et al., 2005; Lal & Stewart, 1995). Drawing on previous scientific literature, we can explain how the SQI promotes organic farming in India. To begin, the SQI is a comprehensive indicator of soil health

that considers a variety of physical, chemical, and biological parameters (Brown & Jacobsen, 2003; Marinari et al., 2006). The present study would highlight the importance of soil quality assessment in organic farming systems, emphasizing the need to maintain soil fertility and structure for long-term agricultural production (Rani et al., 2023; Tahat et al., 2020), allowing farmers to make informed decisions about organic farming practices. By identifying areas with higher SQI values, such as Gaumukh in the Upper Ganga region, organic farmers can capitalize on existing soil health strengths and implement practices tailored to local soil conditions. Moreover, the SQI assessment helps to develop sustainable land use practices by identifying soil health disparities and potential challenges. In support of the above statement previous studies could showcased that monitoring soil quality is critical for mitigating soil degradation and promoting agroecosystem resilience (Davis et al., 2023; Lal, 2012, 2015; Tahat et al., 2020). In India, where land degradation is a major concern (Mythili & Goedecke, 2015), the present study could act as a useful literature for assessing the viability of organic farming and developing long-term strategies to increase soil fertility and productivity.

Conclusion & Recommendation

According to our research, organic farming is possible throughout the Ganga region, though to differing degrees in the Upper, Middle, and Lower regions. According to our data, organic farming is more viable in areas with acceptable physicochemical characteristics, nutrient availability within ideal limits, and lower levels of heavy metal contamination. With its more balanced soil qualities and reduced amounts of heavy metals, the Upper Ganga region stands out among them as being especially suitable for organic agriculture. On the other hand, the Lower Ganga region has higher levels of heavy metal contamination, which makes the implementation of organic farming challenging. Thus, while organic farming is feasible throughout the Ganga region, heavy metal contamination, nutrient levels, and soil quality must all be carefully considered.

Targeted soil management treatments are advised, particularly in regions with greater contamination levels like the Lower Ganga region, to improve soil health and support sustainable organic agricultural methods. These interventions include organic matter replenishment and pollution control techniques. In addition, to reduce environmental risks and guarantee the long-term viability of organic agricultural operations in the Ganga basin, routine monitoring and adaptive management techniques are essential.

Declarations

Conflicts of Interest

The authors declare that there are no conflicts of interest.

CRedit authorship contribution statement

Sourav Ghosh: Writing – review & editing, Writing – original draft, Supervision, Project administration, Conceptualization. Acharya Balkrishna, Vedpriya Arya: Resources, Conceptualization. Srimoyee Banerjee,

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Supplementary Tables

Supplementary Tables S1 and S2 are not available with this version.

Figures

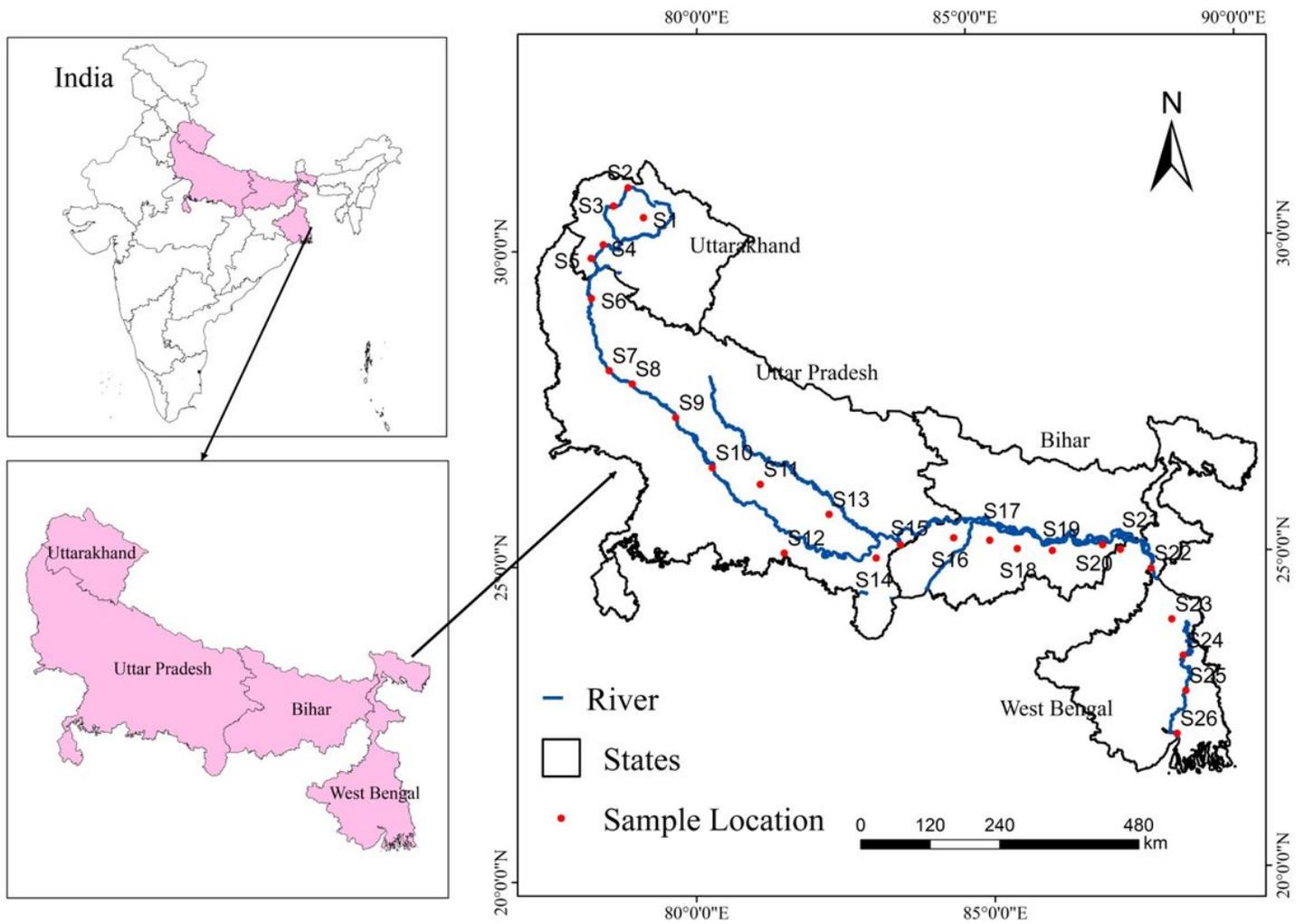


Figure 1

Soil sampling Sites

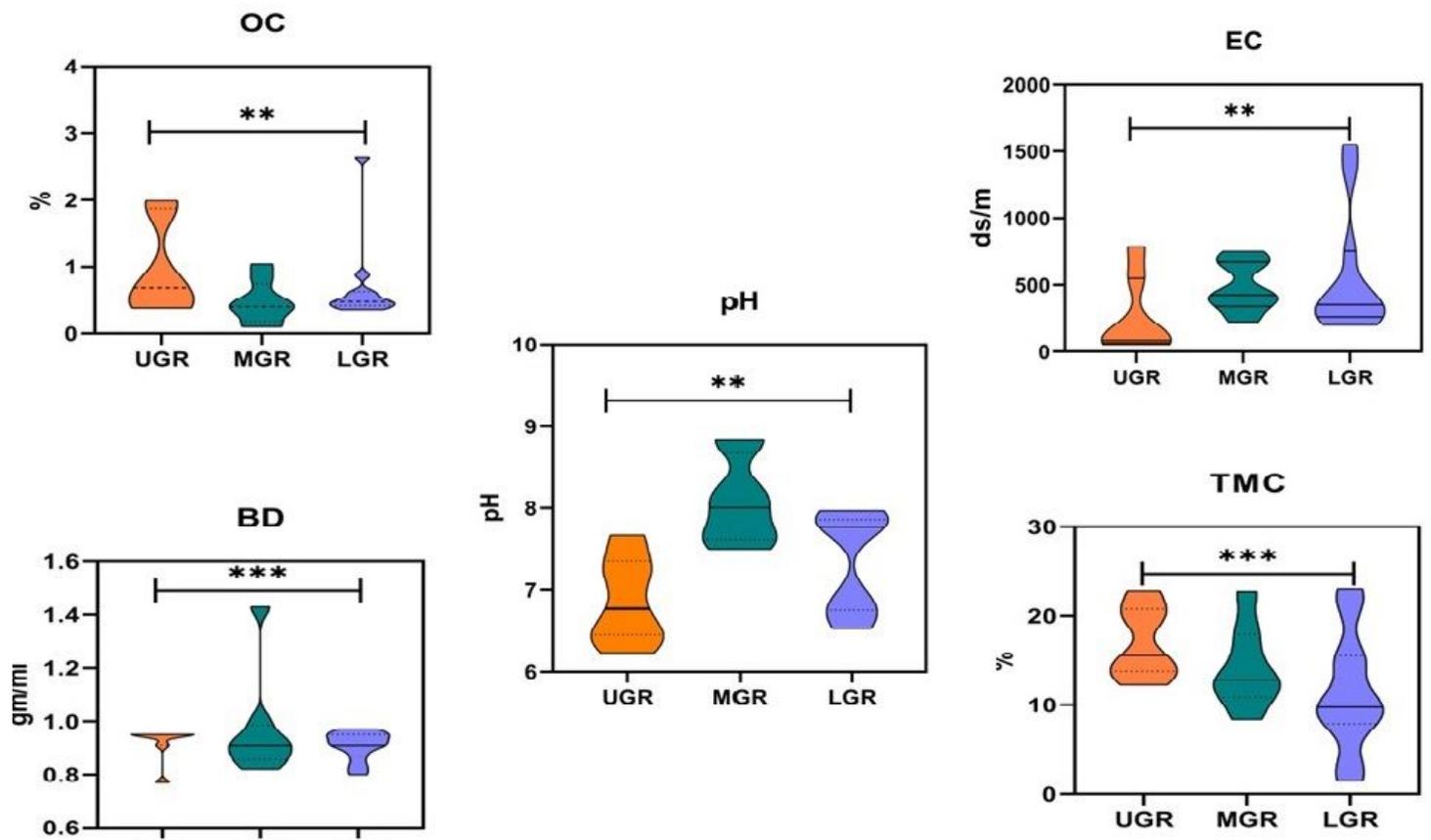


Figure 2

Comparison of different physicochemical attributes among regions of river Ganga; Comparison of N, P, K, S among regions of Indo-Gangetic region. **signifies the $p < 0.05$ at 95% confidence interval whereas ***signifies $p < 0.01$ at 99% confidence interval

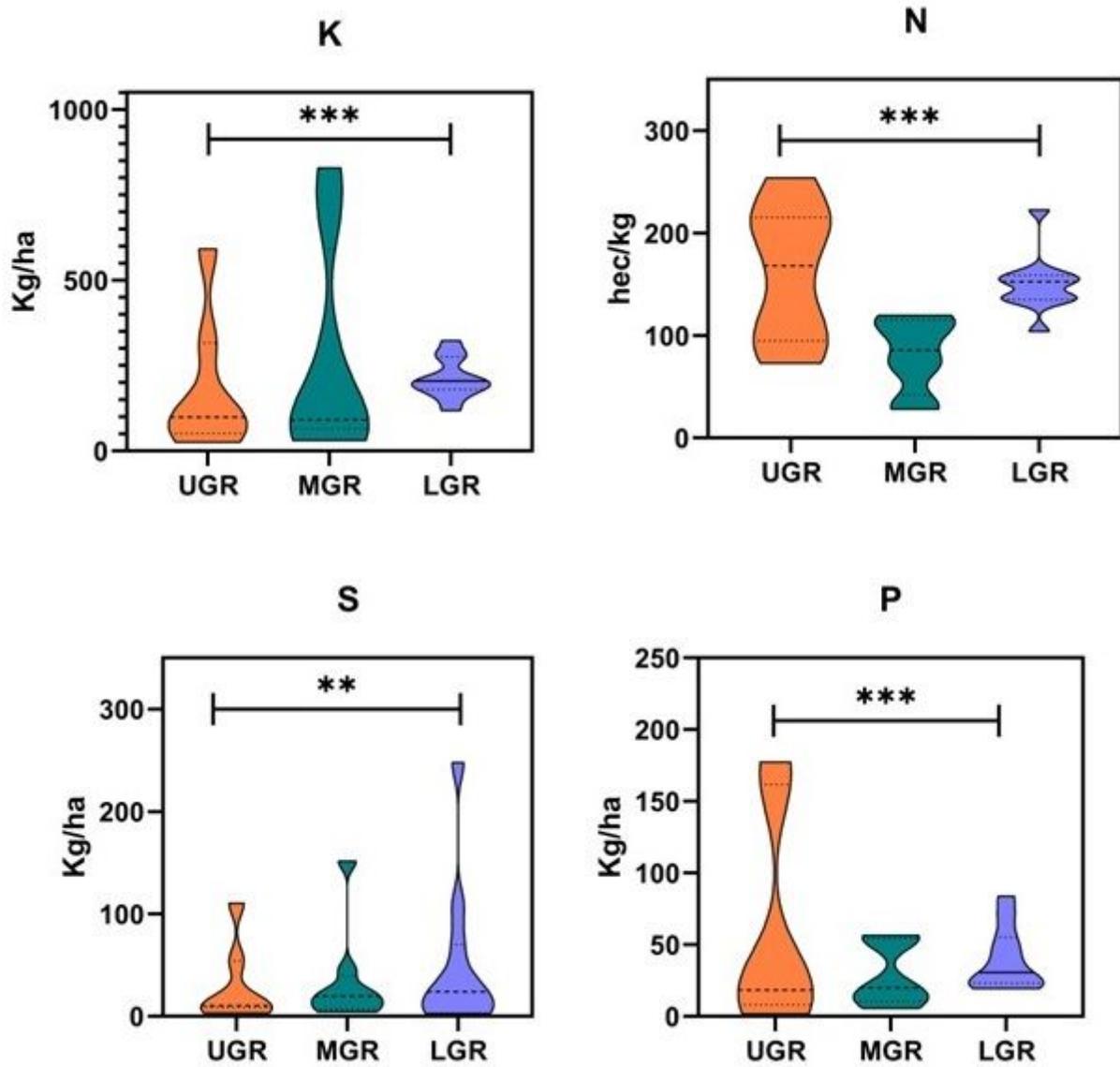


Figure 3

Comparison of N, P, K, S among regions of Indo-Gangetic region. **signifies the $p < 0.05$ at 95% confidence interval whereas ***signifies $p < 0.01$ at 99% confidence interval

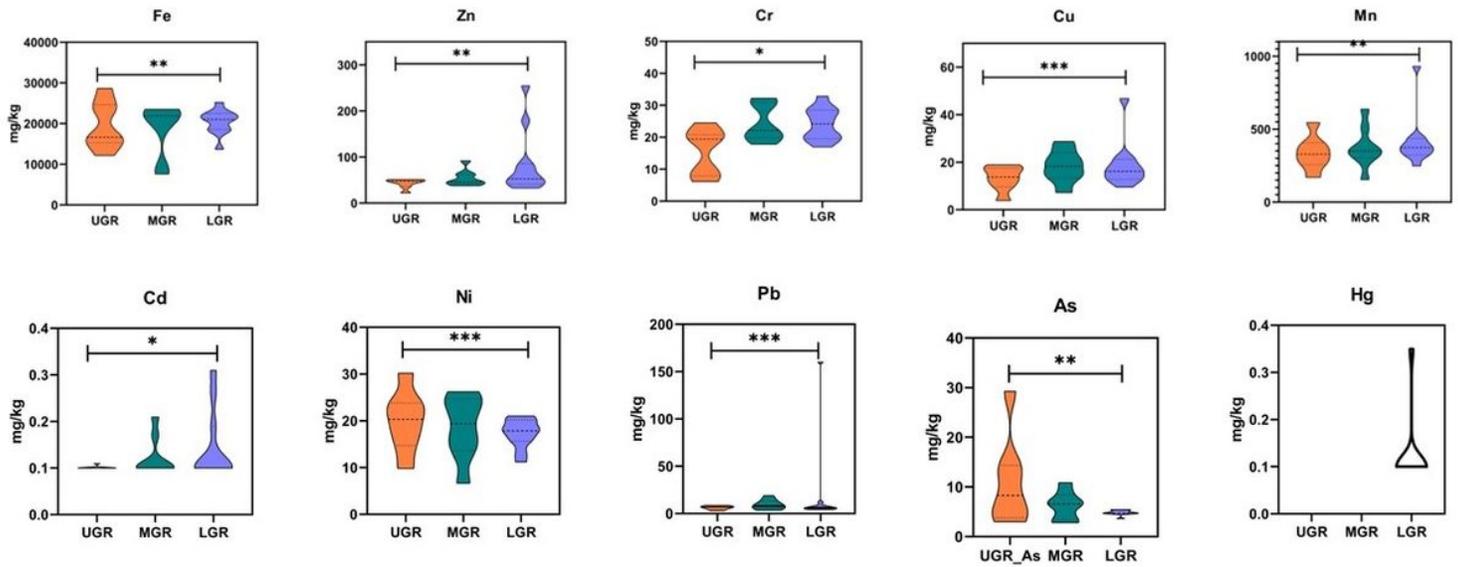
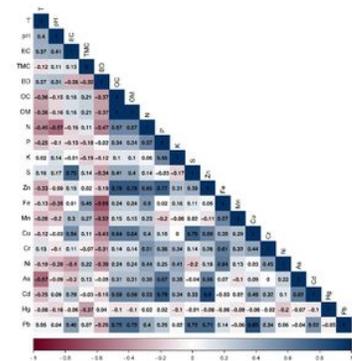
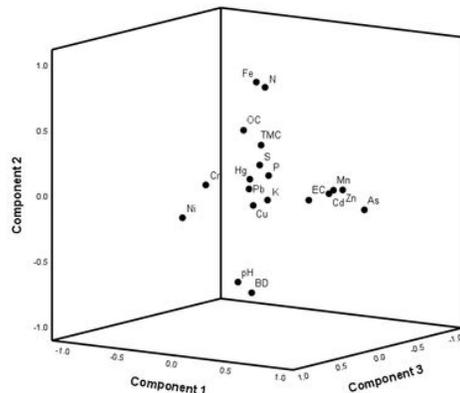


Figure 4

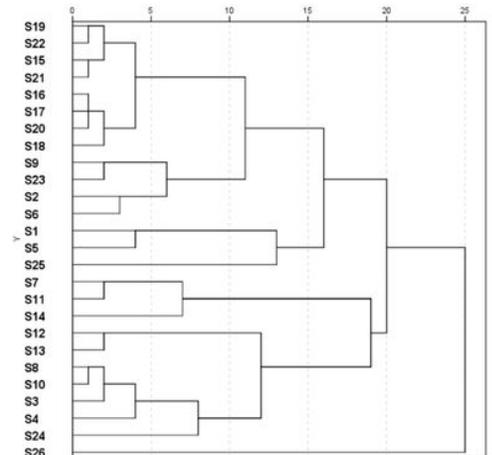
Comparison of Heavy metals in different regions of river Ganga; Comparison of N, P, K, S among regions of Indo-Gangetic region. **signifies the $p < 0.05$ at 95% confidence interval whereas ***signifies $p < 0.01$ at 95% confidence interval



5A



5B



5C

Figure 5

Pollution source analysis: (A) Correlation matrix of the computed variables. (B) Principal components analysis of the variables. (C) Cluster Analysis of study site

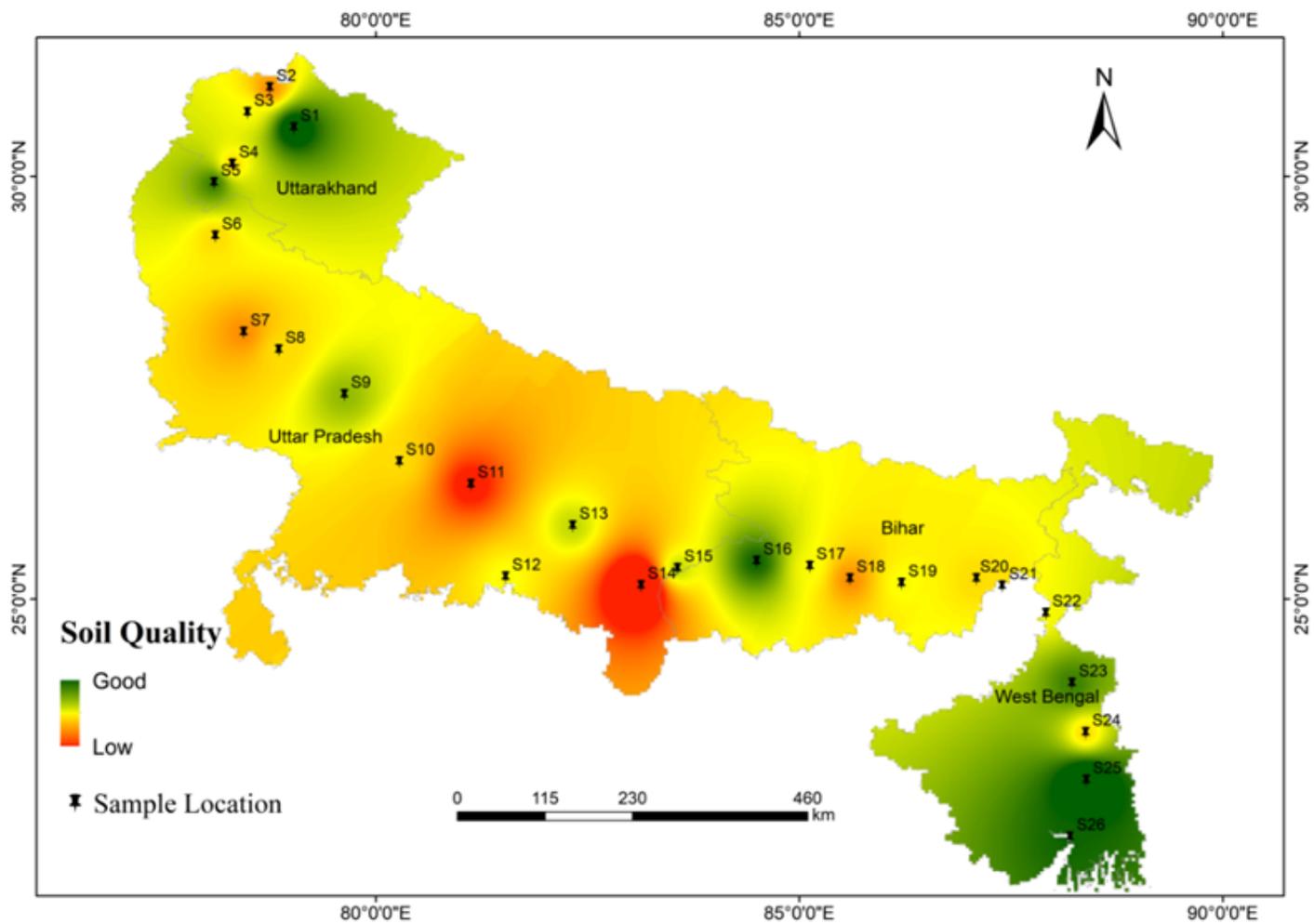


Figure 6

IDW interpolation of Soil quality index in Upper, Middle and Lower Ganga Regions