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Spatial assessment of soil quality in an agriculturally intensive agro-industrial region of Baghpat District, Uttar Pradesh, India

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ABSTRACT

Soil quality is one of several critical components necessary for sustainable food production and long-term food security. This is especially true for areas undergoing rapid increases in agriculture and agro-industry. This paper assesses the soil quality of the Baghpat district of Uttar Pradesh, India, the district with the most dominant agriculture, and examines the spatial distribution of soil physicochemical properties, soil micronutrients, and soil quality changes. As varied land use affects soil quality, ten representative sampling sites were chosen from industrial, agricultural, and communal land use soil types. The present study sampled soils from the ten sites on a quarterly basis from October 2023 until September 2024, for a total of 40 samples. The following soil quality indicators: pH, moisture content, organic carbon, and nutrients (i.e. calcium, sulfur, manganese, iron, copper, zinc) were analyzed during the study. The data showed that soil characteristics studied heterogeneous patterns, with the soil characteristics varying as the impacts of land uses, agrochemicals, and localized industry and soil characteristics. Study sites had soil pH levels that varied from 6.56 to 7.14. This means that all the study sites had neutral to alkaline soil pH, the soil condition favors the presence and movement (availability and mobility) of essential macronutrients and micronutrients. The difference in the availability of the nutrients at the studied sites (where there is an industrial site) and the control site (where there is no industrial site) is from the influence of man-made activities (urban industrial) and industrial emissions, and also from the geogenic processes that control soil mineral content. This study also helps explain the interaction of natural soil formation processes and the impacts from man-made activities to end result of varying soil quality characteristics in cultivated and intensively utilized soil. This research will be valuable for those who require information for soil management, specifically soil conservation for even the future provision of nutrients for the soil for the long term positive aspect of the soil. This will assist decision and policy makers at all levels, environmental management, scientist in agriculture combining to allow the better land use, the better nutrient management, and the proper selection of improved cultivated plant varieties to soil conditions when all of the concerns are included in the integrative approach, the agricultural production will be increased and the preservation of the ecosystem will be improved.

Introduction

In the coming decades the world's population is projected to reach 9 billion, representing an unparalleled increase. This rapid growth causes extreme strain on the world's food supply systems. To satisfactorily respond to this demand great changes to the food supply systems must be made, including developing the systems to be more productive while simultaneously ensuring the systems rely on sustainable soil. Sustainable soil is the cornerstone of long term agricultural sustainability. Soil quality is the biological, chemical, and physical balance of the soil. Administrative units of the soil including the soil's nutrients and the biological reactions of decomposition and soil organism activity directly influence the productivity of the soil and the stability of the surrounding ecosystem. For the agricultural systems of the world to be sustainable, soil quality must be of paramount concern.

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Over the past several decades, the use of chemical fertilizers, pesticides, and other agrochemicals has been adopted. While these methods offer short-term gains, their long-term effects lead to soil degradation, imbalanced nutrient distribution, and decreased soil fertility. Extended agrochemical exposure leads to nutrient depletion and crop yield fatigue. Over time, soil productivity becomes compromised (Manna *et al*., 2005; Bünemann *et al*., 2018). Agrochemicals have compromised soil productivity. Alongside these practices, soil quality is also deteriorating due to the anthropogenic influence of industrial effluents, domestic wastewater discharge, and open dumping of solid waste. These practices contaminate soil, and negatively impact soil structure and nutrient dynamics (Singh *et al*., 2014). Soil degradation is an increasing threat to the environment and security of food (Lal, 2018).

Agriculture is a critical part of the economy in developing countries like India, where it accounts for around 16% of the Gross domestic product (GDP) and employs close to 45% of the workforce. Due to the significance of these socio-economic factors, the preservation of soil quality is vital in the context of agricultural productivity and the sustainability of livelihoods in rural areas (Bhardwaj *et al*., 2020; Ruhela *et al*., 2022). The urbanization and industrialization have accelerated solid and liquid waste production and improper disposal leads to waste flowing into soil. Such waste accumulation can damage soil and contaminate and reduce soil health (Bhutiani and Ahamad, 2018; Bougnom *et al*., 2020). Also, modern farming techniques (e.g. mono cropping and reduced crop rotation) cause serious imbalances and depletions of soil nutrients and threaten soil maintenance and sustainable fertility (Basak *et al*., 2021).

Numerous studies have documented the dynamics of soil quality across various agro-ecological zones of India. For example, Manna *et al*. (2005) studied the long-term effects of fertilizer use in the sub-humid and semi-arid zones and found different fertilizer management strategies resulted in different levels of varied SOC (Soil organic carbon) changes.

Masto *et al*. (2008) studied the effects of long-term soil management practices on soil quality in the semi-arid and tropical parts of India. Vasu *et al*. (2016) evaluated soil quality in the Deccan Plateau using the soil quality index (SQI), principal component analysis (PCA), and the expert opinion approach, and found SQI to be the most reliable method for assessing soil quality. In the same context, Rakshit *et al*. (2018) described the significance of soil quality and crop productivity parameters as organic carbon, electrical conductivity, microbial biomass, and microbial activity. Among the four zones of the Haridwar city (industrial, residential, forest, and agricultural), Bhardwaj *et al*. (2020) observed the impact of industrial activities on the physicochemical soil properties. Ruhela *et al*. (2022) conducted research on the soil quality of Karwi Town, Uttar Pradesh, and mentioned the soil conditions to be generally satisfactory.

The most recent work has focused on regional variations in soil quality in the Mainpuri district of Uttar Pradesh, which characterized soil as being neutral to mildly alkaline, containing relatively higher concentrations of nitrogen and phosphorus, and having lower concentrations of sulfur.

Despite these various contributions, very few studies have specifically focused on soil quality in the agriculturally dominant Baghpat district of Uttar Pradesh, especially in regions where agriculture and industry are growing simultaneously. In addition, the level of understanding among policymakers and local stakeholders regarding the systematic monitoring of soil quality has been inadequate. Thus, the purpose of this study is to provide an improved understanding of soil quality in the Baghpat district. The research analyzes some of the main physical and chemical parameters and micronutrients of soil and will attempt to determine the most relevant and feasible causes of soil deterioration in this critical food producing area. The findings of the study will hopefully provide a basis for the development of better practices in the area of soil management and for the development of policies to sustain agricultural productivity.

Materials and methods

Study area

The current study was carried out in the Baghpat district of Uttar Pradesh (UP), India. Uttar Pradesh is one of the most agriculturally productive states in the country. The western part of U.P. is particularly known for its fertile alluvial soil and for the cultivation of both cereals and cash crops. However, there is an increased agricultural intensification in this region. This includes increased application of agrochemicals, reduced fallow periods (between crops) that stop the natural rest of soil nutrients, and rapid expansion (of both small and large-scale) industries. This further increases soil contamination because of emissions and waste disposal. Therefore, the soil contamination in this region should be assessed in order to capture any existing and potential environmental and agricultural challenges.

Sample collection, preparation, and analysis

Soil sample collection consisted of ten locations, including agrarian, industrial, and communal zones of the Baghpat district (Table 1 and Figure 1). A site control located away from the agricultural and industrial influence zones of the district was also selected. A total of 40 soil samples were obtained each quarter from October 2023 - September 2024.

To avoid organic matter contamination from surface

Table 1: Selected study sites

Sampling site Code	Sampling Site Name	Co-ordinates
SSS 1 (Control site)	Near Baghpat Bus Stand	28.945451, 77.215679
SSS 2	Super Bharat Nursery	28.955378, 77.217477
SSS 3	Khandwari	28.969070, 77.226150
SSS 4	Sisana	28.962252, 77.21748
SSS 5	Baghu-N	28.978808, 77.213285
SSS 6	Baghu-S	28.976478, 77.212907
SSS 7	Niwara	28.982996, 77.208623
SSS 8	Palra	28.986274, 77.196295
SSS 9	Santoshpur	28.991833, 77.238449
SSS 10	Norozpur Goorjar	29.001630, 77.248834

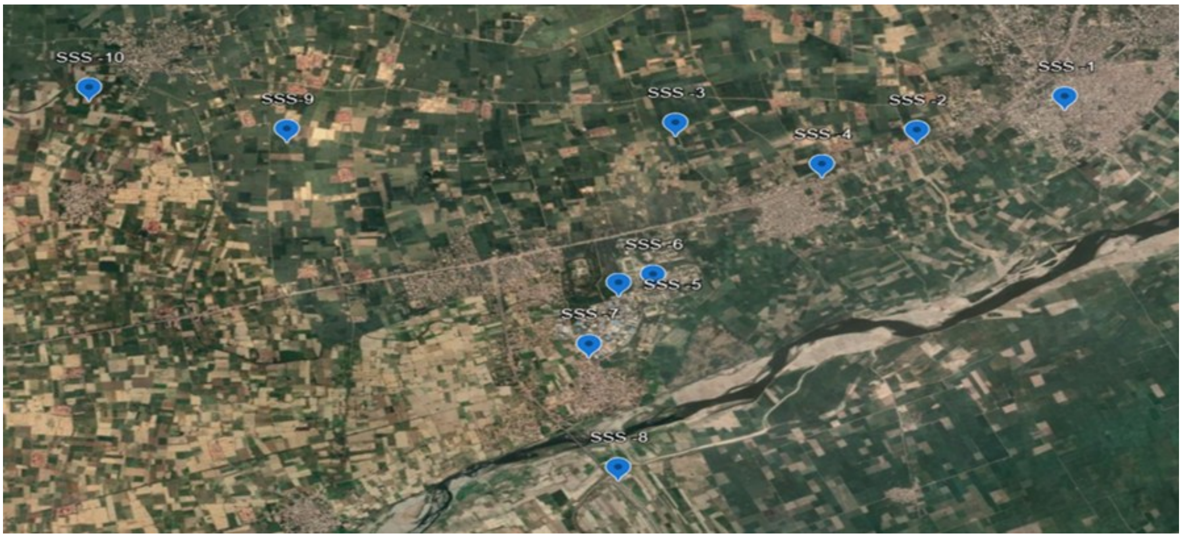

Figure 1: Google Earth map showing the selected sampling sites (for soil sampling)

litter, the layer was removed and the sampling site was dug 30 x 30 x 30 cm deep. Approx. 1 kg of soil was collected from each location. Clean tools were used, and the soil was stored in labeled zip bags. Each sample was given a unique ID. (SSS-1, SSS-2, SSS-3, etc.). The samples were transported to the laboratory for analysis.

Sampled soil materials were subjected to air drying, ambient drying, crushing, and hand sieving to remove larger particles and debris. The resulting finely crushed soil material was used for physical and chemical and micronutrient analyses. Very basic physical and chemical analyses including pH, moisture, organic carbon, calcium, sulphur, and manganese were carried out using the methods of Trivedi and Goel (1984) and Singh *et al*. (1999). Micronutrient analyses of soils for iron (Fe), copper (Cu), and zinc (Zn) were done using standard methods of APHA (2012) using Atomic Absorption Spectrophotometry (AAS).

Methodology for soil analysis and statistical procedure

Statistical analyses of the data were carried out using Microsoft Excel 2010 for descriptive and inferential statistics. Mean and standard deviation for the soil parameters were calculated in order to assess the variability and to determine the trends in soil quality in the study area.

Results and Discussion

Table 2 provides a summary of the descriptive statistics for the soil quality indicators, which include the mean, standard deviation, and the mean range for the soil quality parameters analyzed during the course of the study. The results reveal a great deal of variability, which indicates variability of land use, agricultural systems, and the human impact of the study area.

Soil pH

Soil pH is one of the key parameters in the evaluation of soil quality. The soil pH regulates the nutrient availability, microbial activity, and the solubility of macro and micro nutrients, which influences the crop nutrients and crop productivity (Masto *et al*., 2008a; Zhang *et al*., 2019; Geng *et al*., 2021; Barrow and Hartemink, 2023).

Table 2: Physicochemical and heavy metal concentrations in the soil samples of the selected sites of the study area (n=8)

Site/ Parameter	pH	Moisture (%)	Organic Carbon (%)	Calcium (mg/Kg)	Sulphur (mg/Kg)	Manganese (mg/Kg)	Iron (mg/Kg)	Copper (mg/Kg)	Zinc (mg/Kg)
SSS 1	6.99 ±0.09 *(6.92-7.12)	1.57±0.05 *(1.51-1.63)	0.54±0.05 *(0.49-0.59)	24496.37±12.55 *(24478.17-24506.97)	32.24±2.64 *(28.99-35.43)	291.83±4.46 *(285.19-294.83)	18038.37±26.20 *(18008.56-18072.34)	18.20±0.69 *(17.23-18.78)	41.44±0.75 *(40.76-42.49)
SSS 2	6.89±0.07 *(6.82-6.98)	3.37±0.18 *(3.12-3.56)	5.04±0.21 *(4.89-5.34)	14956.12±55.03 *(14874.59-14989.36)	36.47±0.55 *(35.67-36.89)	282.82±1.71 *(280.78-284.67)	13950.26±54.51 *(13869.56-13989.56)	16.29±0.59 *(15.76-16.99)	57.46±1.68 *(55.17-59.08)
SSS 3	6.91±0.09 *(6.83-7.03)	0.77±0.21 *(0.65-1.08)	1.46±0.29 *(1.27-1.89)	28596.64±94.75 *(28457.45-28669.57)	34.55±0.43 *(33.99-34.98)	245.84±2.85 *(242.16-249.12)	13468.82±6.83 *(13464.24-13478.87)	13.17±0.71 *(12.14-13.67)	33.95±1.20 *(32.96-35.67)
SSS 4	6.87±0.02 *(6.84-6.89)	12.96±0.25 *(12.76-13.32)	0.74±0.07 *(0.63-0.78)	12279.75±77.29 *(12208.19-12367.45)	33.06±1.01 *(31.66-33.89)	308.45±6.90 *(298.19-313.05)	10028.48±100.89 *(9897.56-10123.79)	15.57±0.19 *(15.34-15.78)	47.44±1.12 *(45.77-48.17)
SSS 5	6.94±0.04 *(6.91-6.99)	4.73±0.12 *(4.62-4.89)	2.37±0.17 *(2.14-2.54)	25540.33±9.27 *(25531.52-25551.79)	29.86±0.75 *(28.76-30.39)	226.72±2.69 *(223.19-229.64)	13849.72±52.11 *(13789.12-13894.96)	17.28±0.25 *(17.09-17.62)	80.22±2.76 *(76.09-81.76)
SSS 6	6.69±0.09 *(6.56-6.75)	4.39±0.18 *(4.12-4.52)	2.75±0.08 *(2.63-2.79)	23426.92±19.90 *(23398.56-23445.12)	28.22±0.80 *(27.59-29.31)	227.52±1.76 *(225.89-229.89)	14322.48±10.53 *(14309.12-14334.65)	17.15±0.49 *(16.78-17.86)	77.73±0.76 *(77.02-78.43)
SSS 7	6.92±0.06 *(6.84-6.99)	1.75±0.12 *(1.59-1.89)	1.68±0.05 *(1.61-1.73)	7954.52±53.94 *(7874.34-7986.41)	37.18±1.32 *(35.31-38.38)	366.49±3.45 *(361.45-369.24)	20017.79±27.52 *(19989.56-20054.78)	18.26±0.49 *(17.59-18.76)	56.01±2.51 *(54.62-59.76)
SSS 8	6.89±0.13 *(6.79-7.08)	1.04±0.09 *(0.92-1.12)	2.52±0.20 *(2.32-2.78)	15023.39±32.64 *(14989.78-15067.89)	29.92±0.79 *(28.93-30.72)	535.23±1.82 *(532.59-536.64)	23672.65±18.78 *(23565.29-23689.34)	26.79±0.84 *(25.67-27.71)	69.62±1.10 *(68.32-70.78)
SSS 9	7.07±0.05 *(7.02-7.14)	1.50±0.08 *(1.42-1.58)	1.86±0.14 *(1.72-2.04)	11266.80±58.40 *(11214.42-11345.09)	32.08±1.00 *(31.23-33.52)	454.51±1.88 *(451.87-456.34)	22362.49±33.54 *(22341.23-22412.56)	26.25±0.60 *(25.42-26.78)	69.19±1.53 *(67.06-70.67)
SSS 10	6.92±0.02 *(6.89-6.93)	3.27±0.25 *(2.98-3.56)	0.93±0.03 *(0.89-0.96)	21355.69±9.31 *(21345.67-21368.19)	33.74±2.47 *(32.12-37.41)	378.18±3.74 *(372.73-381.13)	21097.49±8.13 *(21085.75-21103.41)	24.78±0.46 *(24.12-25.12)	60.17±1.64 *(58.23-62.23)

***Range**

The imbalances and physiological stress of the soil can be caused by the deviation from the optimum pH (Msimbira and Smith, 2020). Present study showed soil pH in all sampling sites (6.56 and 7.14), which is neutral and is therefore a good indicator of possible land productivity. Mean soil pH of the sites was close to the neutral soil pH of 7.0, which is an indicator of the balanced soil chemical.

Minor differences were noted against the control site (6.99 ± 0.09), suggesting localized impacts from anthropogenic activities. Variations might be caused by arbitrary application of fertilizers and agrochemicals, and the dumping of domestic and industrial waste, which, as illustrated by Lestari *et al*. (2024), can progressively change the chemical composition of the soil. With the large-scale farming activities in the region, it is reasonable to assume that the cycle of growing crops and the inputs used during this phase are the primary factors driving soil pH changes (Uwiragiye *et al*., 2023).

Soil moisture content

Soil moisture is critical for soil-atmosphere energy exchanges, nutrient transport, and physiological activities of plants, thus it is one of the most important factors that determines the productivity of a given land (Wenwu *et al*., 2018; Wang *et al*., 2023). There are varied factors that affect soil moisture such as, climate, soil texture, structural and vegetation cover, topography and even human activities such as irrigations and land management (Suo *et al*., 2018; Zhang *et al*., 2024).

In this study, soil moisture content was found to have a significant degree of variability at the sampling locations, ranging from 0.65% to 13.32%. The lowest mean value was found at SSS3 (0.77 ± 0.21%) while the highest value was found at SSS4 (12.96 ± 0.25%). These values remain significantly below the moisture range of 10-20% which is optimal for crop growth (Lovino *et al*., 2024) and to far below the average field capacity of soils (approximately 20-30%). Leaving soils at such low moisture level's can be a result of limited water retention, which can be indicative of low organic matter content and or soil structure issues. The soil moisture deficiency can limit the water uptake of the plants and can also necessitate further irrigation which could be an indirect factor for soil salinization over time.

Soil organic carbon (SOC)

Soil organic carbon is one of the key elements for soil fertility and the functioning of the ecosystem. As per Omnec (2025) it plays a vital role in soil structure, nutrient cycling, water retention, and also microbial activity. In the present study, SOC values ranged from 0.49% to 5.34%. The mean values have an even broader range from 0.54 to 5.04% at the sampling sites.

The control site (SSS1) with a mean value of (0.54 ± 0.05%) SOC is attributed to poor vegetation cover and a low supply of organic matter. On the other hand, the higher SOC values at agricultural field and vegetation cover margins are indicative of the positive contribution of the field residues and vegetation covers to the soil carbon sink. These are also the opposite of those at the industrial and bare land margins (i.e. SSS10, SSS4, and SSS7) which recorded SOC values due to poor soil biological activity and low organic matter supply.

These results are similar to other studies noting the influence of land use, vegetation cover, and management on the SOC (Sharma *et al*., 2014; Nazir *et al*., 2024; Skalsky *et al*., 2024). Skalsky *et al*. (2024) who, in agricultural lands of Slovakia, recorded SOC concentration of 2.13%, which depended on latitude, land cover, soil type and texture.

Calcium

Calcium is a crucial macronutrient that contributes to soil stability, pH and cation exchange, and therefore, the availability of nutrients in the soil (Luo *et al*., 2023; Jing *et al*., 2024). In this study, the measured calcium ranged between 7874.34 and 28669.57 mg/kg. The lowest mean value of calcium concentration was observed in SSS7, (7954.52 ± 53.94 mg/kg), while the highest mean concentration was at SSS3 (28596.64 ± 94.75 mg/kg).

Compared to some studies across the globe, these values are considerably higher. For example, a mean calcium concentration of 13,000 mg/kg in the soil of Southwest China was reported by Luo *et al*. (2023). The difference in concentration of calcium may result from the difference in parent material of the soil, the agricultural amendments, and the irrigation. Sufficient calcium levels are a prerequisite to the normal physiological processes of plants such as cell wall construction and transport of nutrients.

Sulfur

Sulfur, being the fourth most essential macronutrient after nitrogen, phosphorus, and potassium, is of immense importance in the synthesis of proteins and acts as a catalyst in many enzymatic activities (McLaughlin *et al*., 2015; Chaudhary *et al*., 2023). The top layers of soil are rich in organic sulfur.

Analyses of sulfur from the current research revealed concentrations between 28.76 to 38.38 mg/kg, while the means also varied by site. The minimum mean was from site SSS6 with 28.22 ± 0.80 mg/kg, while site SSS7 had the maximum mean with 37.18 ± 1.32 mg/kg. Soil sulfur concentrations can be impacted by land-use, soil depth, pH, and fertilizer application (Padhan *et al*., 2023). Zhao *et al*. (2024) describe soil sulfur concentrations of 1-5 g/kg in resilient soil of China while Khandare *et al*. (2024) reported an average of 37.13 mg/kg of organic soil sulfur, which fall in line with the values of the current study. Very little research has been done with sulfur in Indian agrarian soils, so this study becomes more significant.

Manganese

Manganese is considered a vital micro-nutrient, where it is needed for photosynthesis, activation of enzymes, and metabolism of plants (Montgomery *et al*. 2023). Availability of manganese can be influenced by soil pH, and content of organic matter and redox (Khoshru *et al*., 2023; Paulus and Vitousek, 2024).

In the current research, manganese concentrations were observed between 223.19 and 536.64 mg/kg. The lowest mean concentration (SSS5) is 226.72 ± 2.69 mg/kg, while SSS8 has the highest concentration, recorded at 535.23 ± 1.82 mg/kg. Due to the conditions in the study area, it's possible to find lower availability of manganese in more neutral or slightly alkaline soils, due to the lower solubility. In a few localized spaces, the higher concentrations may be explained by the soil parent material or by human impact.

Fully developed green tissue in plants require iron as it is critical for the formation of chlorophyll, respiration, and other enzymatic processes. In the soil, iron is found in both forms; the ferrous (Fe^{2+}) form, which is more readily available to plants and is more soluble, and the ferric (Fe^{3+}) form.

Iron concentrations in the study area ranged between 9897.56 and 23689.34 mg/kg. The minimum mean value (SSS4) is recorded as 10028.48 ± 100.89 mg/kg and the maximum mean value (SSS8) is 23672.65 ± 18.78 mg/kg. Previous studies report that approximately 7 mg/kg of available iron is sufficient for the growth of crops and that a deficiency of iron may lead to a considerable decline in the yields of the crops (Porkodi *et al*. 2023). In the current research, iron was found at high concentrations, which confirm that it is readily available for agricultural purposes.

Copper

Copper is a critical micronutrient fundamental to photosynthesis, enzyme function, and structural support of plants (Maurya *et al*., 2020). Inadequate or excessive copper is detrimental to plant health. For the present study, copper concentration was 12.14 to 27.70 mg/kg. The lowest concentration was at SSS3 (13.17 ± 0.71 mg/kg) and the highest was at SSS8 (26.79 ± 0.84 mg/kg).

The neutral soil pH throughout the study site may promote the liberation and plant assimilation of copper. The copper concentrations found in this study is in contrast to those reported by Ruhela *et al*. (2022) for the soils of Karwi Town, Uttar Pradesh, which speaks to the regional variability of soil micronutrient composition.

Zinc

Zinc is vital for the metabolic activity of plants and the stimulation of enzymes, hormones, and chlorophyll (Noulas *et al*., 2018). Its availability is dictated by soil pH, quantity of organic matter, temperature, and the level of phosphorus.

In the study area, the concentrations of zinc varied from 32.96 to 81.76 mg/kg. The lowest mean value (33.95 ± 1.20 mg/kg) was found at SSS3, while the highest figure (80.22 ± 2.76 mg/kg) was found at SSS5. Other studies have documented the average soil zinc concentration of 64 mg/kg (Noulas *et al*., 2018). In the current study, approximately 40% of the sampling sites have zinc concentrations above the global average, representing a sufficient concentration of zinc for plant growth. Also, a neutral soil pH enhances the mobility of zinc and its uptake by the plants.

Conclusion

The current study assesses the soil quality of Baghpat district in Uttar Pradesh, a region with agricultural activities where intensive farming practices and industrial activities have been growing. They indicate that the study area soils are mostly neutral in pH. This neutral pH increases the availability and mobility of several nutrients such as sulfur, manganese, zinc, and organic carbon. The primary macro and micronutrients are in sufficient to adequate concentrations in all of the studies conducted in the different regions of Uttar Pradesh.

Based on low levels of moisture retention, there is a clear need for improved retention strategies within the soil, particularly through the management of organic soil matter/compost, to improve moisture retention within the soil structure itself. Processing soil to a structure that allows moisture retention may reduce the need to irrigate the area, which could lead to problems such as soil salinity and nutrient imbalances.

The lack of any clear trends or patterns regarding methodology, techniques, and soil types present within a certain area create an absence of soil homogenization. This is attributed to parent material, management soil practices, and the presence of cosmic dust soil and soil management strategies, as well as the presence of human activity. This created a determined need for an organized, periodic check of the soil within the region.

The results of the study created the foundational framework for soil nutrient management, anticipating retention, and creating a plan for the region for agricultural work. groundwater, and the region for soil ecology. The study of the structure of soil should be directed toward measurement and theories of the soil quality framework, management, and the study of the area to gain control of the variability of a region meaning about the quality soil and the soil of the area in control of a region of the soil quality. This policy should be directed toward establishing the area of soil management and establishing the region within the area.

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Conflict of interest

The authors declare that they have no conflicts of interest.

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