Innovations

Assessment of Soil Suitability for Sugarcane Cultivation using GIS and Multivariate Analysis in Binauli Block, Western Uttar Pradesh, India

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Abstract: *This study assesses soil fertility in Binauli Block, Baghpat, India, using a nutrient index approach and GIS mapping. Soil samples from 54 sites were analysed for pH, organic carbon, electrical conductivity, macronutrients (nitrogen, phosphorus, potassium), and micronutrients (sulfur, zinc, boron, iron, copper, manganese). Soil samples were tested in the laboratory for various parameters. The obtained data was then analysed using SPSS and R software. The analysed values were interpolated using the Inverse Distance Weighting (IDW) method in Arc GIS. Results show low organic carbon (0.26), phosphorus (10.83), and electrical conductivity (0.75), while potassium (145.38) and nitrogen (149.01) are adequate. High pH (8.11) and optimal boron (0.94) and manganese (4.89) suggest fertility concerns impacting sugarcane productivity. Findings emphasize tailored fertilization to improve soil health and yields.*

Keywords: *Soil fertility, nutrient index, sugarcane productivity, macronutrients, micronutrients.*

1. Introduction

Balanced use of essential soil nutrients is a necessity for optimum growth of cultivated crop plants, and constitutes one of the important key inputs for achieving high productivity. This includes the availability or the application of high-analysis fertilizers (N, P, and K), as well as the availability of micronutrients. Although required in very small quantities, the latter has been found to play a critical role in crops' growth and production potential on a given soil (Shukla 2011). Nutrients such as "nitrogen, phosphorus, and potassium" are essential for plant nutrition and critical in promoting plant growth (Dong et al., 2017). Plants primarily absorb these nutrients from the soil. Optimal plant growth and crop yield are influenced not only by the total nutrient content in the soil at a given time but also by the availability of these nutrients. This availability is regulated by various physio-chemical properties, including "soil texture, organic carbon content, calcium carbonate levels, cation exchange capacity, pH, and electrical conductivity" (Bell and Dell, 2008). Although traditional methods for estimating soil nutrient levels are highly accurate, they are often labor-intensive and expensive, making them less practical for producing spatially detailed assessments across large study areas (Andrews and Carroll, 2001). In India, the nature and extent of macro- and micronutrient shortages in soils have been found to vary not only with the soil type, but also with the type of agricultural land use, crop genotype, agro-ecological situations and land management practices (Dhane 2011). Widespread soil nutrient deficiencies have also been observed in many Indian soils when put under intensive cultivation of crops using the Green Revolution concept, as this resulted in continuous removal of the soil nutrients without appreciable replenishment (Dwivedi 2017).In 2015, the Government of India (GOI) proposed the Soil Health Card (SHC) Scheme to encourage the balanced application of fertilizers. As part of the initiative, soil testing was conducted nationwide, and soil health cards were issued with crop-specific fertilizer recommendations to enhance productivity and reduce costs. Soil samples were analysed in laboratories nationwide, where experts assessed nutrient levels and suggested appropriate crops and fertilizer requirements for the SHCs. The scheme reached 120 million farmers, providing them with comprehensive information on the physical and chemical characteristics of their soil. Each SHC included details such as soil type, GPS location, irrigation source, farm size, and 12 chemical parameters: "soil pH, electrical conductivity (EC, indicating soil salinity), organic carbon (OC)", and available nutrients such as "nitrogen (N), phosphorus (P), potassium (K), sulfur (S), zinc (Zn), boron (B), iron (Fe), manganese (Mn), and copper (Cu)". Pilot studies of the SHC scheme yielded promising results (Chander et al., 2014; Fishman et al., 2016; Raju et al., 2015). Soil quality is closely connected to soil productivity, and a dependable evaluation needs precise and comprehensive quantification to ensure sustainable soil management (Lal et al., 2013). The Soil Quality Index (SQI) is defined as the soil's capacity within an ecosystem to provide plants with the necessary nutrients to sustain crop yield throughout various growth stages (Doran et al., 1994; Mukherjee et al., 2014). According to Karlen et al. (1997), soil quality is "the ability of a particular kind of soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or improve the quality of water and air, and support human health and habitation." As sugarcane is main crop of the farmers of Binauli, so 54soil samples from different sites of Binauli block have been collected and tested in laboratory.The results indicate that the status of organic carbon in the soil is very low in most of the parts of Binauli and the pH status is slightly alkaline in most of the places. This has to be taken into consideration and the soil has to be reclaimed. Regarding the nutrient status of the soil, the primary nutrients were found to low, with regards to the secondary and micronutrients, there was an imbalance which is highly influenced by the changes in pH.

2. Materials and Methods

2.1 Study Area

Binauli Block is situated in Baghpat District of Uttar Pradesh, with an average elevation of 233 meters. Its geographical boundaries are defined by the following coordinates: 29° 15' 00" N, 77° 17' 30" E, 29° 12' 00" N, 77° 31' 00" E, 29° 1' 30" N, 77° 27' 00" E, and 29° 1' 30" N, 77° 17' 30" E. It is situated approximately 27 km east of the district headquarters, Baghpat, and is bordered by several blocks: Baraut to the west, Pilana to the south, Rohta to the east, and Sarurpur Khurd to the east. Two rivers, the Krishna, and the Hindon, flow through the block, with the Hindon River creating a natural boundary between Binauli Block and Meerut District.The area undergoes harsh climate conditions, characterized by scorching summers and chilly winters. Binauli Block consists of 63 villages and is known as a premier agricultural zone. Of the population, 25,358 people are engaged in agricultural activities. A significant portion of the arable land supports double cropping. Irrigation is a crucial aspect of agriculture in the area, with a network of canals, wells, pump sets, and tube wells. Among these, tube wells serve as the primary source of irrigation, ensuring water supply (District Handbook Baghpat, 2011).

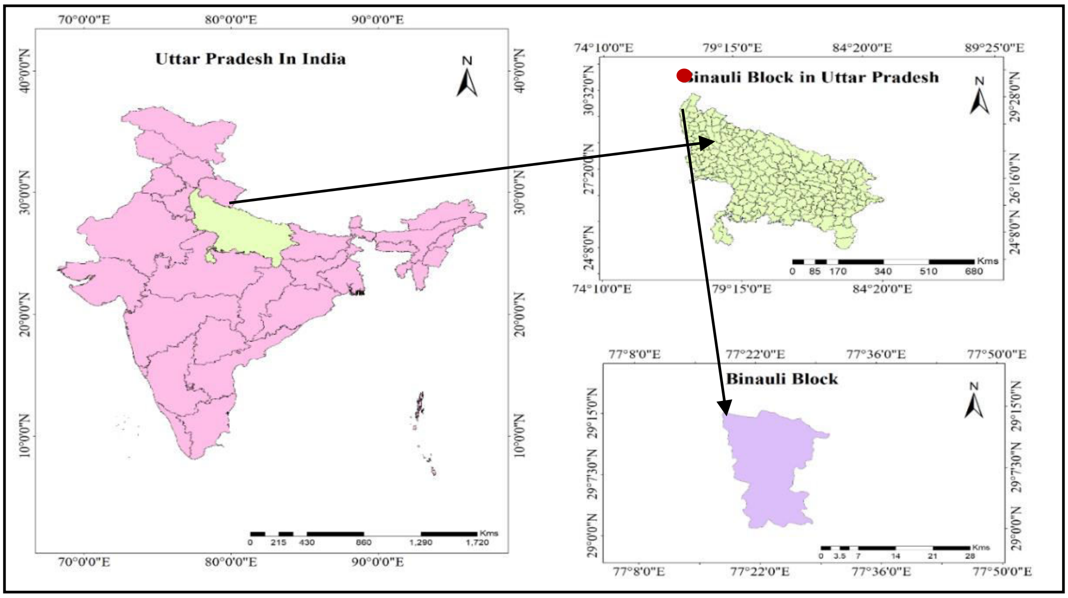


Fig.1"Study Area"

2.2 Soil Sampling:

Soil samples were collected from 54 sites in the study area using the coining and quartering method. This involved digging a V-shaped hole at each site and extracting a specific amount of soil. A total of 500 g of soil from each of the 54 sites and then tested in the laboratory. The samples in the laboratory were analysed for macro and micronutrients following standard procedures. The physicochemical properties measured included electrical conductivity (EC, dS/m), pH, organic carbon content (%), nitrogen, phosphorus, potassium, iron, manganese, zinc, and copper.

Soil Parameter	Testing Method
pH	Soil-water suspension using glass electrodes
Electrical Conductivity	Using Conductivity Bridge
Phosphorous	0.5M $NaHCO_3$
Potassium (K_2O)	Normal Ammonium Acetate Extraction
Organic Carbon	Walkley and Black Wet Digestion Method
Nitrogen	Alkaline Potassium Permanganate Method
Manganese	DTPA method through Atomic Absorption Spectrophotometer
Sulphur	0.15% $CaCl_2$ method
Zinc	DTPA method through Atomic Absorption Spectrophotometer
Iron	DTPA method through Atomic Absorption Spectrophotometer

Table 1: Soil Parameter Testing Method

2.3 Statistical Analysis and GIS Mapping and Interpolation

Descriptive statistics of the studied soil characteristics include the minimum, maximum, arithmetic mean, and standard deviation, which were computed using SPSS version 20. The Pearson correlation coefficient (r) was used to examine the linear relationships between the variables. R software 4.4.2 was used to conduct the principal component analysis (PCA). PCA was used to reduce the dataset into new variables, which are called principal components (PCs), as well as to avoid multicollinearity between the original variables. These PCs explain most of the variation present in the original variables. To map the distribution pattern of different soil nutrients, the data analyzed from sample sites were first fed into a geographic information system (GIS) as point-based and geo-referenced data through table management. The data were then processed through the inverse distance weighted (IDW) method and classified into homogenous groups of availability status of micronutrients as contours in vector maps, as per the classification.

3. Results and Discussion:

Total 54 samples were collected from the study area to analysed soil nutrients.

3.1. Soil nutrients:

3.1.1. Macronutrients

Soil macronutrients are vital elements that plants require in large quantities for healthy growth and development. These essential nutrients include nitrogen (N), phosphorus (P), potassium (K), and sulfur (S). Each of these macronutrients serves a specific function in promoting plant health.

A). Nitrogen: Nitrogen is essential for plants, forming amino acids, proteins, and enzymes. Deficiency causes light green leaves, with lower leaves yellowing and drying out. Soil nitrogen levels in the study area range from 84 to 285.55 kg/ha, averaging 149.0 kg/ha, indicating low nitrogen status. Villages like Tera, Titrauda, and Fazalpur show signs of deficiency, emphasizing the need for better nitrogen management**.**

B). Phosphorous: Phosphorus is vital for legume growth, aiding nodular bacteria in nitrogen fixation. Deficiency causes stunted growth and smaller leaves. Soil phosphorus levels in the study area range from 4.5 to 26.9 kg/ha, averaging 10.83 kg/ha, indicating low availability. Villages like Mawi Kalan, Binauli, and Galheta have even lower phosphorus levels.

C).Potassium: Potassium is crucial for amino acid and protein synthesis, aiding ammonium ion utilization. Deficiency causes browning leaf margins and slender stems. Soil potassium levels range from 102 to 300.7 kg/ha, averaging 145.38 kg/ha, indicating medium availability. While most areas have adequate potassium, Hazarabad and Ranchar show higher levels. Excessive KCl use may increase soil salinity and nutrient imbalances.

D). Sulphur: Sulfur is essential for plants, aiding in the production of amino acids, proteins, and oils, as well as being essential for chlorophyll production. In the study area, sulphur levels in the soil vary from 6.5 to 10.4 mg/kg, with an average concentration of 8.60 mg/kg.

3.1.2 Soil organic carbon, pH and EC Soil

A). Organic carbon: Soil organic matter, resulting from plant remains, serves as a nutrient reservoir. Humus preserves nutrients for plant use. In this Block, organic carbon levels range from 0.1% to 0.5%, indicating low content.

B). Soil pH: The optimum pH range for sugarcane growth in soil is typically between 6.0 and 7.5. Soils within this range are generally conducive to nutrient availability and overall plant health. However, sugarcane can tolerate a wider pH range, from about 5.5 to 8.0, although extreme conditions may affect growth and yield. But at some regions(Dhanaura, Gaindabara, Bopura, Tabelagarhi) this pH is higher than 8.

C). Soil EC: Soil electrical conductivity (EC) measures the salt content in the soil and serves as a crucial measure of soil vitality. It influences crop productivity, soil suitability, and nutrient accessibility to plants, and microbial action. Excessive salt levels can hinder plants growth by disturbing the balance between soil and water. Soils with excessive salts are commonly found in arid and semiarid regions. In the study area, the EC values vary from 0.2 - 0.9 dS/m, with a mean value of 0.75 dS/m.

3.1.3 Micronutrients

A). Iron: Iron is essential for oxidation in leaf cells, and its deficiency causes chlorosis, leaf whitening, and stunted growth. In Binauli, iron levels range from 2.1 to 5.7 mg/kg, averaging 3.51 mg/kg, which is insufficient for healthy plant growth.

B). Manganese: Manganese is a vital element for chlorophyll synthesis. Its deficiency disrupts carbohydrate production, leading to stunted growth. In the study area, manganese levels in the analysed samples extended from 2.29 to 6.67 mg/kg, with an average content of 4.89 mg/kg.

C). Zinc: Zinc plays a significantpart in chlorophyll development in leaves, with higher zinc levels linked to greater chlorophyll content. Severe zinc deficiency leads to chlorosis and darkened leaf veins. In the study area, zinc concentrations in the soil samples extended from 0.14 to 2.08 mg/kg, with an average content of 0.68 mg/kg.

D). Copper: Copper is crucial for the enzyme in leaf chloroplasts that facilitates oxidation-reduction processes, playing a significant role in photosynthesis. In cases of severe copper deficiency, excessive leaf drop can occur. In the study area, copper levels in the analysed samples extended from 0.1 to 1.2 mg/kg, with an average of 0.35 mg/kg, it is regarded as extremely low.

E). Boron: Boron is avital nutrient for the proper growth, development, yield, and quality of crops. It plays a vitalpart in various plant functions, mainly in cell wall synthesis and structural integration. In the study area, boron levels in the analysed samples ranged from 0.32 to 1.56 mg/kg, with an average of 0.94 mg/kg, which is adequate for plant growth.

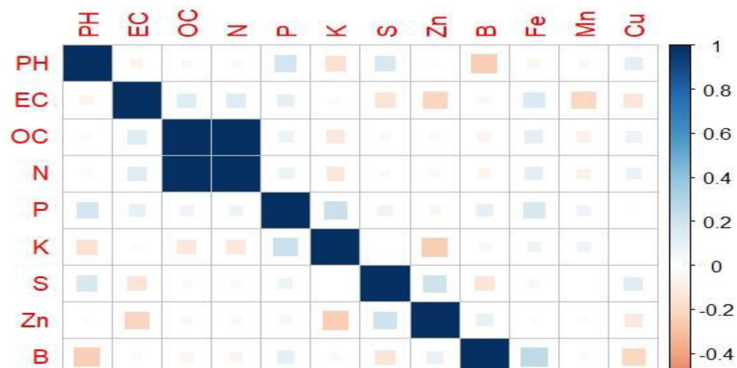
Descriptive	pH	EC	OC	N	P	K	S	Zn	B	Fe	Mn	Cu

Mean	8.11	0.75	0.26	149.0	10.8	145.38	8.60	0.68	0.94	3.51	4.89	0.35
S. D	0.19	0.17	0.08	48.60	4.9	40.46	0.97	0.54	0.30	0.86	1.18	0.19
Median	8.155	0.81	0.26	145.6	9	136.08	8.64	0.505	0.95	3.34	5.03	0.28
Mode	8.21	0.81	0.16	89.6	9	134.4	8.9	0.24	1.18	3.17	4.17	0.28
Max	8.38	0.97	0.51	285.6	27	301.28	10.48	2.09	1.57	5.75	6.68	1.22
Min	7.23	0.21	0.15	84	4.5	101.92	6.55	0.14	0.32	2.19	2.29	0.11
Range	1.15	0.76	0.36	201.6	22.5	199.36	3.93	1.95	1.25	3.56	4.39	1.11

3.2. Statistical Analysis: Key measures such as mean, standard deviation (S.D), median, mode, maximum, minimum, and range are included to summarize the soil's nutrient variability and distribution.

Table 2: Descriptive Statistics of Soil Properties and Nutrients

3.2.1 Pearson Correlation Matrix: Correlation matrix that illustrates the relationships between various variables, including "pH, EC (electrical conductivity), OC (organic carbon), N (nitrogen), P (phosphorus), and other elements or nutrients such as potassium (K), sulfur (S), zinc (Zn), boron (B), iron (Fe), manganese (Mn), and copper (Cu)". Each variable is perfectly correlated with itself, which is why the diagonal values in the matrix are all 1.000. The off-diagonal values show the pairwise correlation coefficients, which reflect the strength and direction of the linear relationship between two variables.Positive values indicate a direct correlation, whereas negative values imply an inverse correlation. For instance, the correlation between pH and EC is about -0.0597, indicating a very weak negative relationship. On the other hand, the correlation between nitrogen (N) and organic carbon (OC) is nearly 0.9999, suggesting a very strong positive relationship. This matrix offers useful insights into the interactions and influence of these variables on each other.



Variable	PH	EC	OC	N	P	K	S	Zn	B	Fe	Mn	Cu
PH	1											
EC	-0.05	1										
OC	0.03	0.13	1									
N	0.03	0.13	0.99	1								
P	0.18	0.1	0.07	0.07	1							
K	-0.15	0.02	-0.12	-0.12	0.21	1						
S	0.16	-0.14	0.03	0.03	0.07	0.002	1					
Zn	0.01	-0.21	-0.03	-0.03	-0.04	-0.24	0.2	1				
B	-0.24	-0.03	-0.05	-0.05	0.1	0.03	-0.13	0.09	1			
Fe	-0.05	0.15	0.11	0.11	0.16	0.07	0.04	-0.01	0.25	1		
Mn	-0.04	-0.2	-0.07	-0.07	0.07	0.06	0.009	0.02	-0.03	-0.05	1	
Cu	0.11	-0.13	0.08	0.08	-0.01	0.004	0.12	-0.11	-0.2	-0.15	0.16	1

Table 6: Correlation Matrix of Soil Properties and Nutrient

3.2.2 Principal Component Analysis for soil quality index:

Principal Component Analysis (PCA) is a statistical tool used to identify the most significant variables influencing soil quality from a large dataset. By reducing dimensionality, PCA isolates principal components (PCs) that explain the maximum variance in soil properties like pH, organic carbon, nutrients ("N", "P", "K"), and trace elements ("Zn", "Fe", etc.). These PCs are then weighted and combined into a Soil Quality Index, (SQI), allowing for a comprehensive evaluation of soil health. For instance, PCs with high loadings of organic matter and essential nutrients are often prioritized, as they directly correlate with soil fertility and productivity. Studies like (Andrews et al., 2004) highlight the use of PCA in deriving indices that reflect soil functionality, guiding sustainable land management practices.There are six principal components (PC1 to PC6) on various chemical components (PH, EC, OC, N, P, K, S, Zn, B, Fe, Mn, Cu). Loadings represent the contribution of each principal component to the variation in the chemical components. Higher absolute values indicate stronger contributions, while the sign indicates the direction (positive or negative). PH, EC, OC, N: Strong positive loading on PC1, indicating these components are heavily influenced by this principal component. P, K, S, Mn: Show a mix of strong positive and negative influences across PCs, with PC3 and PC4 reflecting significant variation. Zn, B, Fe: High loadings on PC3 and PC2 suggest strong associations with these components. Cu: Negative influence on PC2 and PC6, indicating its variability is captured by these PCs. Figure 3 presents the PCA biplot, displaying both the PC scores of the samples and the variable loadings.

Component	**PC1**	**PC2**	**PC3**	**PC4**	**PC5**	**PC6**
pH	0.08	-0.3	-0.10	-0.20	-0.52	0.40
EC	0.20	0.3	-0.18	0.23	-0.37	-0.006
OC	0.65	-0.04	0.05	0.009	0.18	-0.007
N	0.65	-0.04	0.05	0.009	0.18	-0.007
P	0.11	0.13	-0.31	-0.55	-0.17	0.35
K	-0.11	0.24	-0.51	-0.20	0.15	-0.37
S	0.03	-0.31	0.06	-0.45	-0.18	-0.62
Zn	-0.07	-0.17	0.59	-0.29	0.01	0.0003
B	-0.06	0.43	0.28	-0.25	0.25	0.163
Fe	0.15	0.38	0.06	-0.37	-0.06	-0.13
Mn	-0.12	-0.18	-0.18	-0.23	0.54	0.35
Cu	0.06	-0.40	-0.33	0.009	0.24	-0.08

Table 3: Principal Component Analysis (PCA) Loadings for Soil Properties and Nutrients

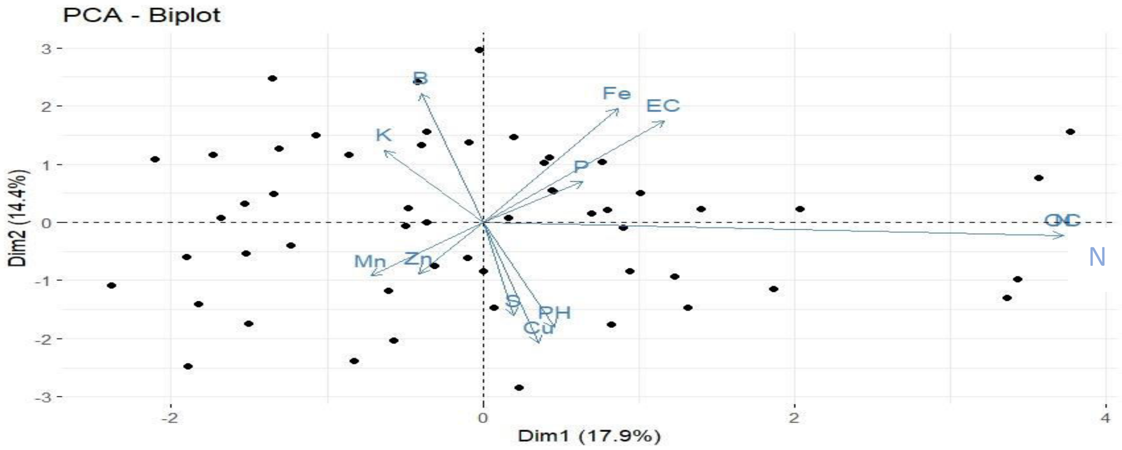


Fig. 3. PCA Biplot

This PCA scatter plot visualizes high-dimensional data using two principal components: Dim 1 (17.85% variance) and Dim 2 (14.39%), together capturing 32.24% of total variance. OC and N strongly influence Dim 1, while B, Fe, and EC impact Dim 2. Arrows indicate variable relationships—acute angles show positive correlations, right angles indicate none, and opposite directions suggest negative correlations (e.g., OC vs. Mn). The clustering of Zn, Mn, and S suggests similar relationships, warranting further exploration.

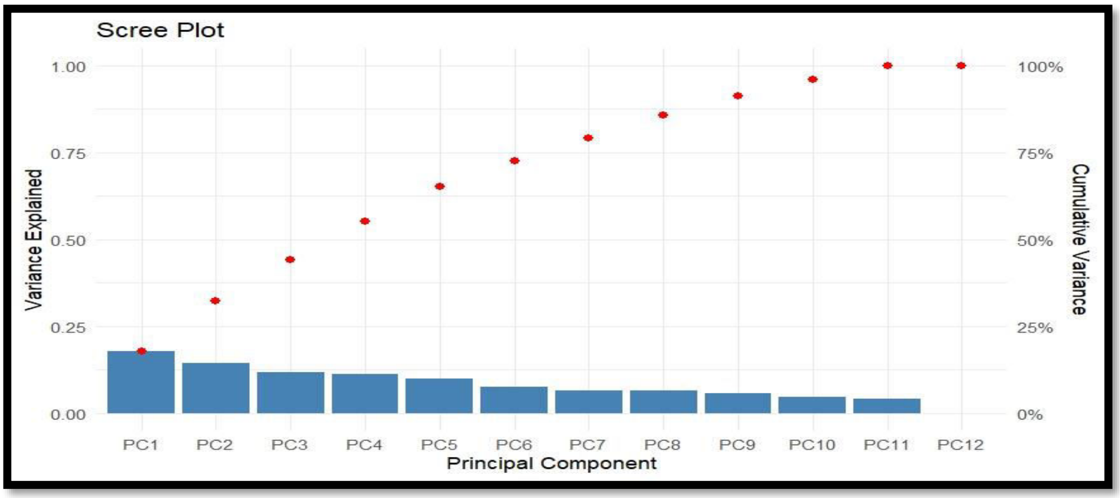


Fig. 4 scree Plot Explained Variance and Cumulative Variance by Principal Components

The Scree plot shows the variance explained by each principal component (PC), where PC1 accounts for the highest variance, followed by subsequent components. The red line represents the cumulative variance explained, which increases as more components are included. This plot aids in identifying the number of principal components needed to capture a substantial amount of the variance in the dataset.

3.3. Digital soil maps using IDW (Inverse Distance Weighted) Geo-statistics helps quantify the spatial variation of nutrients and estimate values at unsampled locations (Ahmed et al., 2014). Two commonly used geostatistical methods for predicting soil variables at unsampled points are inverse distance weighting (IDW) and Kriging. IDW generates maps by identifying neighbouring points and assigning them weights based on a power function. When the power of IDW is increased, the influence of more distant points becomes stronger. In contrast, using a lower power result in more evenly distributed weights among neighbouring points (Poshtmasari et al., 2012). One key advantage of IDW is its simplicity and efficiency, particularly when points are evenly spaced. However, it can be susceptible to outliers and can introduce errors when data points are unevenly distributed or clustered (Balakrishnan et al., 2011). For Binauli Block, the following soil nutrient prediction maps were created using the IDW method, providing insights into spatial nutrient distribution across the region.

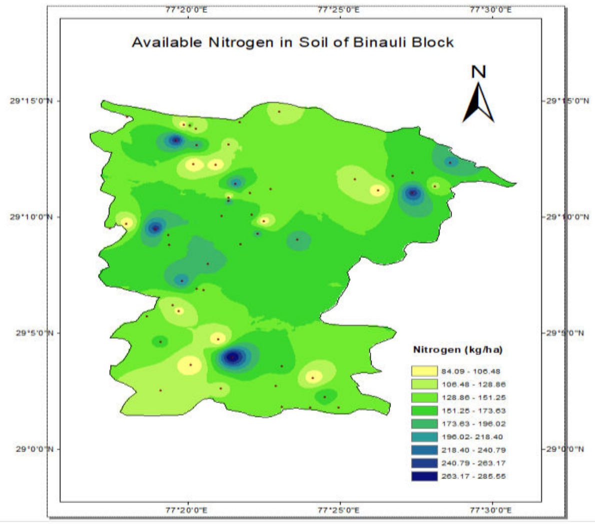


Fig. 5 Available Nitrogen and Predictive Mapping

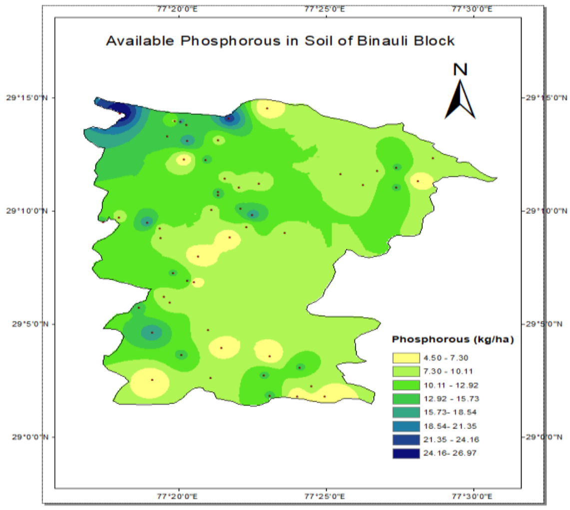


Fig. 6 Available Phosphorous and Predictive Mapping

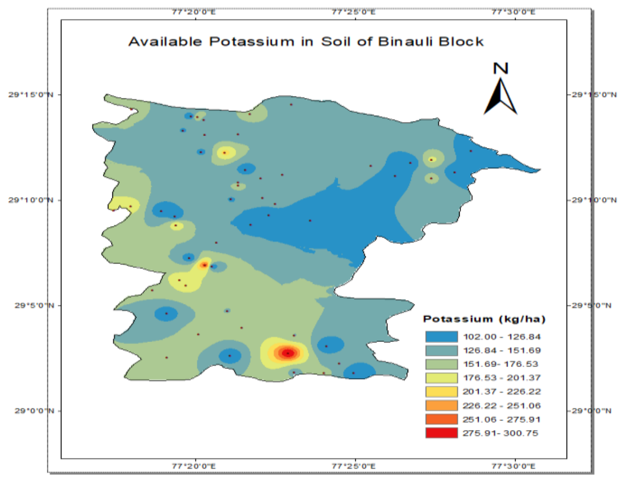


Fig. 7 Available Potassium and Predictive Mapping

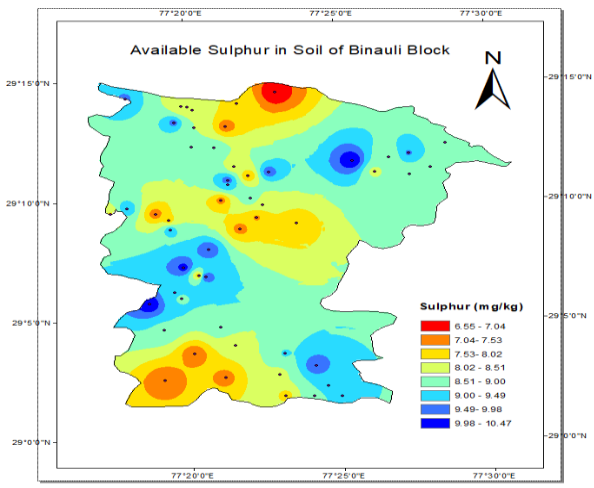


Fig. 8 Available Sulphur and Predictive Mapping

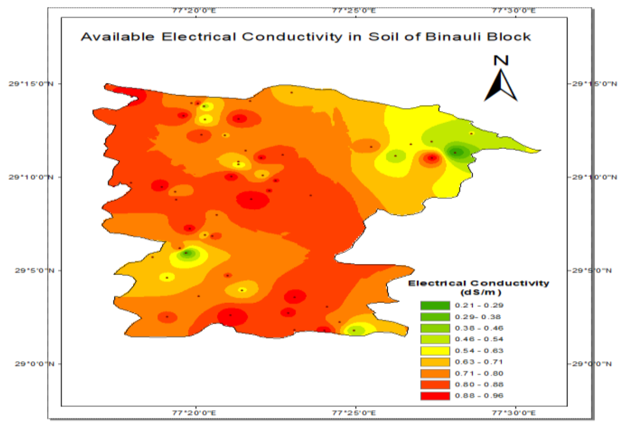


Fig. 9 Available Electrical Conductivity and Predictive Mapping

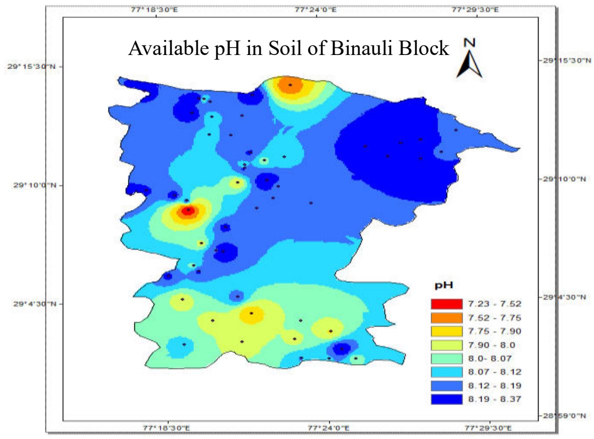


Fig. 10 Available pH and Predictive Mapping

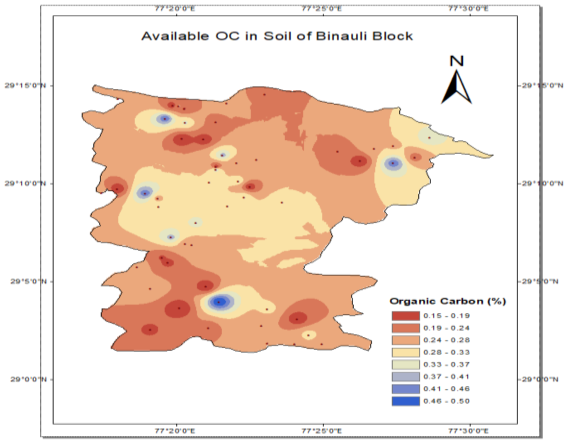


Fig. 11 Available Organic Carbon and Predictive Mapping

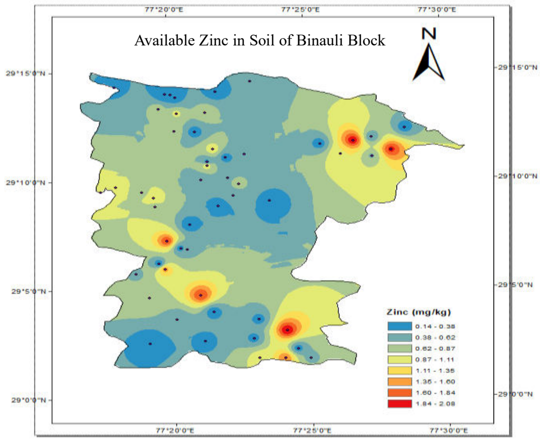


Fig. 12 Available zinc and Predictive Mapping

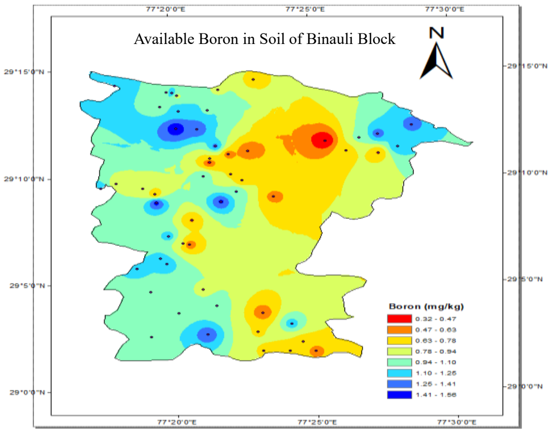


Fig. 13 Available Boron and Predictive Mapping

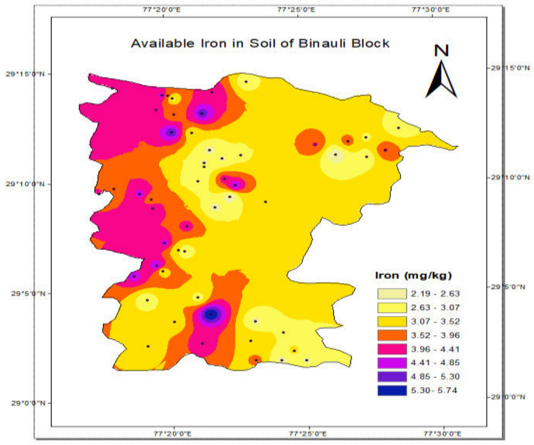


Fig. 14 Available Iron and Predictive Mapping

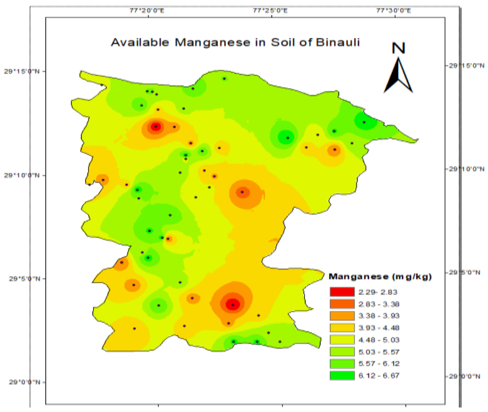


Fig.15Available Manganese and Predictive Mapping

Conclusion:

This study provides a comprehensive understanding of the soil nutrient dynamics in the research area and serves as a baseline for developing sustainable land management strategies. By addressing the identified deficiencies and adopting precision agriculture techniques, it is possible to improve soil fertility, improve crop yield, and support lasting agricultural sustainability. Adoption of site-specific nutrient management practices, including the balanced application of fertilizers andorganic amendments, to address deficiencies in nitrogen, phosphorus, sulphur, iron, and copper. Implementation of soil conservation techniques such as crop rotation, cover cropping, and residue management to enhance organic carbon levels and overall soil health. Regular soil testing and GIS-based monitoring to track changes in soil properties and nutrient availability, ensuring timely corrective measures.

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