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Geostatistical modeling and soil fertility assessment for sugarcane crop in tropical region of Maharashtra

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Abstract

The analysis of the spatial variability of soil properties is important for precision agriculture, land use planning and environmental modelling. A geostatistical assessment was undertaken in the sugarcane-growing soils of Ambad Taluka, Jalna District, to understand the spatial patterns of key soil fertility attributes, including pH, electrical conductivity (EC), organic carbon, and available nitrogen, phosphorus, and potassium. A total of 3500 geo-referenced surface soil samples (0-22 cm) were collected on a survey-number basis and analyzed for these parameters. The resulting geodatabase was interpolated using kriging, selecting semivariogram models based on the minimum root mean square error. The exponential model provided the best fit for pH, EC, organic carbon, available phosphorus, and potassium, while available nitrogen followed a spherical model. Most soil nutrients showed moderate spatial dependence (nugget-to-sill ratio 25-75%), whereas nitrogen and phosphorus were characterized by strong spatial dependence (ratio <25%). Spatial maps revealed widespread deficiencies of available nitrogen and phosphorus, contrasted by predominantly high potassium levels across the study area. These insights offer a valuable foundation for implementing site-specific nutrient management strategies in sugarcane production systems.

Keywords: Spatial distribution, soil fertility, geostatistical modelling

Introduction

Sugarcane (*Saccharum officinarum* L.) is one of India's most important commercial crops, forming the backbone of the rural economy and supporting millions of farming families. In Maharashtra and other major sugarcane-growing states, the crop occupies a central place in agricultural planning; however, the average productivity has not shown significant improvement over the past decade. This stagnation is closely linked to the progressive deterioration of soil fertility, which remains a key determinant of crop performance. Multiple interacting factors—such as erratic climatic conditions, continuous monocropping, over-exploitation of soils, indiscriminate fertilizer use, declining soil organic carbon, excessive irrigation, poor-quality water, and inadequate drainage have collectively contributed to soil health degradation across sugarcane landscapes.

Spatial variability is an inherent and dynamic feature of soil. It may be both vertical (within a pedon) and horizontal (across the landscape). Soil variability is the outcome of many processes acting and interacting across a continuum of spatial and temporal scales and is inherently scale dependent. Variability may also occur as a result of land use and management strategies. As other environmental variables, soil water and soil texture changes in space and time. For farmers and sugar industries alike, enhancing sugarcane yield is essential for improving economic returns. Yet, considerable field-to-field variation in soil fertility often restricts the potential to achieve uniform productivity. This spatial heterogeneity of soils underscores the need for site-specific nutrient management (SSNM), a core principle of precision agriculture that ensures balanced and efficient nutrient application suited to local soil conditions (Sharma *et al.*, 2020)^[33]. Sugar mills generally operate over large command areas typically 5,000 to 7,000 hectares and although many have established soil testing laboratories, conventional soil sampling and analysis remain time-consuming, labour-intensive, and financially demanding. Despite the distribution of thousands of soil health cards each year, a large proportion of farmers still adopt blanket fertilizer doses, often resulting in nutrient imbalance, unnecessary input costs, and sub-

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optimal yields.

In this context, the ability to predict and map the spatial variability of soil fertility parameters at a finer scale becomes critically important. Geospatial technologies and geostatistical modelling offer efficient tools for generating continuous surface information on soil properties using limited point-based data. Studies across diverse agroecosystems have demonstrated that spatial variability maps derived using these techniques are invaluable for diagnosing nutrient constraints, delineating management zones, and formulating soil test-based fertilizer prescriptions (Khan *et al.*, 2020; Santra *et al.*, 2017; Reza *et al.*, 2016; Shit *et al.*, 2016; Marchetti *et al.*, 2012; Dayani & Mohammadi, 2010) [14, 31, 29, 34, 7]. Such maps also support long-term soil fertility monitoring and enable farmers to adopt nutrient-smart practices tailored to the inherent variability within their fields (Prasad *et al.*, 2020) [27].

Given that systematic assessments of spatial nutrient variability are limited for sugar mill command areas in semi-arid Maharashtra, there is a pressing need to document soil fertility patterns and understand their geostatistical behaviour for precision nutrient advisory development. Therefore, the present study was undertaken in the operational area of Samarth SSK, Ambad Taluka, Jalna District, Maharashtra, with the objectives to: (i) assess the spatial variability of key soil fertility parameters, (ii) identify suitable geostatistical models for predicting nutrient distribution, and (iii) generate high-resolution, cadastral-level nutrient management advisories to support sustainable sugarcane production. This investigation provides a scientific basis for transitioning from blanket fertilizer recommendations to field-specific nutrient management within sugar mill zones, ultimately contributing to improved soil health and enhanced sugarcane productivity.

Materials and Methods

Study Area

The soil fertility survey was conducted in the operational area of Samarth SSK Sugar Mill, located in Ambad Taluka, Jalna District, Maharashtra, with the aim of generating detailed soil fertility maps and facilitating site-specific nutrient management. The study area lies geographically between 19.61°N latitude and 75.79°E longitude, covering a typical sugarcane-growing region of Marathwada. The region experiences a tropical climate, characterized by distinct wet and dry seasons. According to the Köppen-Geiger climate classification, Ambad Taluka falls under the Aw category, indicating a tropical savanna climate where winter months receive significantly lower rainfall compared to the summer monsoon season.

The mean annual temperature of the region is approximately 26.1°C, providing a warm environment conducive for sugarcane cultivation. Annual precipitation averages around 824 mm, with most of the rainfall occurring during the southwest monsoon months (June-September). The length of growing period in the area is 152 days. The soils have a Typic Tropoustic moisture regime. The soil temperature regime is hyperthermic. The soils of the area are Vertisols and associated black soils typically developed on alluvium derived from weathering of Deccan Basalt, which influences the chemical and physical properties, including pH, nutrient availability, and cation exchange capacity. Majority percentage of cultivated land in kharif is under cotton (*Gossypium spp.*), Soybean (*Glycin max*), pigeon pea (*Cajanus cajan*), greengram (*Phaseolus aurens*) as principal crops. Chickpea (*Cicer arietinum*) is dominant crop in rabi season under residual soil moisture and/or with some protective irrigations. The natural vegetation of the area

comprises of dry deciduous tree species and grasses. The dominant tree species are babul (*Accacia arabica*), ber (*Ziziphus jujube*), palas (*Butea frondosa*), neem (*Azadiracta indica*), rui (*Calotropis gigantea*), kans (*Saccharum spontaneum*) and dub (*Cynodon dactylon*).

This combination of climatic conditions, soil parent material, and cropping patterns makes Ambad Taluka a representative site for studying spatial variability in soil fertility and assessing the potential for precision nutrient management in sugarcane systems. Understanding these characteristics is crucial for optimizing fertilizer use, improving crop productivity, and sustaining soil health under intensive sugarcane cultivation.

Soil Sampling and Analysis

Soil samples were collected systematically from the operational area of Samarth SSK Sugar Mill using a survey-number-wise approach, targeting the 0 - 22 cm soil depth, which represents the plough layer and is most relevant for nutrient availability to sugarcane. A total of 3,500 composite soil samples were collected, with each composite representing the overall fertility status of the corresponding plot. This approach ensures that spatial variability within individual fields is adequately captured while maintaining efficiency in sample processing.

Collected samples were processed following standard laboratory procedures. Soil pH, a critical parameter influencing nutrient availability and chemical reactions, was determined in a 1:2.5 soil-to-water suspension, while electrical conductivity (EC), an indicator of soil salinity, was measured in the soil supernatant (Jackson, 1993) [11]. Soil organic carbon (OC), which plays a key role in soil fertility, structure, and nutrient retention, was analyzed using the wet digestion method (Walkley and Black, 1934). Available nitrogen (N) was estimated by the alkaline potassium permanganate method (Subbaiah and Asija, 1956) [40], available phosphorus (P) by the Olsen bicarbonate method (Olsen *et al.*, 1954) [23], and available potassium (K) by the neutral normal ammonium acetate extraction method (Jackson, 1973) [11].

The measured soil test values were then interpreted to derive fertilizer recommendations based on the soil fertility rating and guidelines provided by the State Agriculture University (Table 1). This approach enables site-specific nutrient management, facilitating optimal fertilizer application tailored to the specific soil conditions of each field, and ultimately contributing to improved sugarcane productivity and sustainable soil management.

Geostatistical Analysis of Soil Parameters

To assess the spatial variability of soil fertility parameters across Ambad Taluka, thematic maps of soil chemical properties were developed using Geographic Information System (GIS) techniques in ArcGIS version 10.1 (ESRI, Redlands, USA). Digital shapefiles of Ambad Taluka, obtained from the Maharashtra Remote Sensing Application Centre (MRSAC), Nagpur, served as the base maps. These shapefiles were derived from IRS P6 LISS IV satellite imagery with a high spatial resolution of 5.8 meters, ensuring precise delineation of cadastral boundaries. Additionally, ancillary data sources, including Google Earth imagery, were integrated to enhance mapping accuracy and spatial reference.

Survey-number-wise soil analytical data were overlaid on the base maps to create a point map, representing the exact locations of collected soil samples. Using this georeferenced dataset, surface thematic maps for key soil properties including soil pH, electrical conductivity (EC), organic carbon (OC), and

macronutrients (N, P, K) were generated.

Semivariogram Modeling

Ordinary Kriging, a widely used geostatistical interpolation technique, was employed to predict soil property values at unsampled locations. Kriging leverages the semivariogram model to account for spatial dependence, assigning weights to known sample points based on their spatial correlation to provide accurate estimates across the landscape. This approach enabled the generation of continuous, high-resolution soil fertility maps, facilitating site-specific nutrient management in sugarcane cultivation. The geostatistical analysis provides valuable insights into spatial heterogeneity, supports precision fertilization, and helps optimize overall crop management strategies.

This study employed ordinary kriging, a linear geostatistical interpolation technique, to estimate soil property values at unsampled locations by computing a weighted average of nearby observed values (Kriging, 1951)^[15]. The kriging estimate at an unknown location $Z(k)$ is given by:

$$Z_{(k)} = \sum_{i=1}^n y_i \cdot Z_i$$

where Z_i represents known values at sampled points, and y_i are the weights assigned to each sample, determined based on spatial correlation patterns. In geostatistics, the semivariogram quantifies spatial dependence, measuring how similarity between paired observations decreases with distance (Matheron, 1963; Webster and Oliver, 2001)^[18, 43]. The semi variance $\gamma(h)$ is calculated as:

$$\gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [z(x_i) - z(x_i + h)]^2 \quad (1)$$

where $z(x_i)$ is the value at location x_i , h is the lag distance, and $N(h)$ is the number of sample pairs separated by distance h . Semivariogram models, such as spherical and exponential, were fitted to the data to describe the spatial structure and optimize kriging weights. Key parameters—nugget (C_0), sill ($C + C_0$), and range (a) were derived, representing measurement error or micro-scale variability, total variance, and the distance over which spatial correlation persists, respectively (Lopez-Granados *et al.*, 2002)^[17].

Statistical analyses of soil parameters included computation of mean, standard deviation, coefficient of variation, skewness, and kurtosis, alongside evaluation of normality using histograms and QQ plots. Prediction accuracy of kriging was validated using error metrics such as mean error (ME), root mean square error (RMSE), root mean square standardized error (RMSSE), and average standard error (ASE). The formulae for ME and RMSE are:

$$ME = \frac{\sum_{i=1}^N [z(x_i) - \hat{z}(x_i)]}{N} \quad (2)$$

$$RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^N [z(x_i) - \hat{z}(x_i)]^2} \quad (3)$$

The semivariogram parameters and kriging weights provided a robust framework for spatial interpolation of soil fertility parameters, allowing the generation of thematic maps for site-specific nutrient management in the sugarcane-growing areas of

Ambad Taluka.

Across the soil parameter, the spherical and exponential models were found to be best fitted. The semivariogram models used are shown in Equations (4) and (5):

Spherical model

$$\gamma(h) = C_0 + C \left[1.5 \frac{h}{a} - 0.5 \left(\frac{h}{a} \right)^3 \right], \text{ if } 0 \leq h \leq a = C_0 + C \quad (4)$$

Otherwise

Exponential model:

$$\gamma(h) = C_0 + C \left[1 - \exp \left\{ -\frac{h}{\tau} \right\} \right] \quad (5)$$

Using the model semivariogram, basic spatial parameters such as nugget (C_0), sill ($C + C_0$) and range (a) was calculated which describes overall structure and inputs used for interpolation. Nugget is the variance at zero distance, sill ($g(h)$) is the lag distance between measurement at which one value for a variable does not influence neighboring values and range is the lag distance between measurements at which one value for a variable does not influence neighbouring values and range is the distance at which values of one variable become spatially independent of another (Lopez-Granados *et al.* 2002)^[17]. Soil dependency of soil parameters (the ratio of nuggets to sill variances) is expressed as percentage.

Nutrient Index

The Nutrient Index (NI) was calculated to assess the overall fertility status of surface soils in the study area, following the method proposed by Ramamoorthy and Bajaj (1969)^[28]. This index integrates the distribution of nutrient levels across soil samples, providing a quantitative measure of soil nutrient sufficiency. The formula used is:

$$NI = \frac{NLX1 + NmX2 + NHX3}{NT}$$

Where N_L , N_m and N_H are numbers of samples falling in low, medium and high classes of nutrient status and N_T is total no. of samples analyzed for a given area.

Table 2: Rating chart for nutrient index

Nutrient Index	Value
Low	< 1.67
Medium	1.67-2.33
High	>2.33

Results and Discussion

Soil Reaction (pH)

Soil pH is one of the fundamental indicators of soil fertility because it directly governs the availability of macro- and micronutrients, influences microbial activity, and regulates several chemical and physical processes in the soil (Brady & Weil, 2017; Fageria *et al.*, 2011)^[5, 9]. It also reflects long-term pedogenic factors such as the nature of parent material, climatic conditions, and leaching intensity, which together shape soil development (Wild, 1993; Xu *et al.*, 2020)^[44, 45].

In Ambad Taluka, the spatial distribution pattern of pH (Fig. 1) revealed that the soils range from slightly alkaline to strongly alkaline, with values between 7.1 and 9.1, and an average pH of 7.86 (Table 3). Such alkaline conditions are characteristic of black soils (Vertisols) derived from basaltic parent rock, which

are inherently rich in basic cations such as Ca^{2+} and Mg^{2+} (Bhaskar *et al.*, 2014; Patil & Dasog, 2018) [4, 26]. The pH data exhibited a normal distribution, and the coefficient of variation ($\text{CV} < 15\%$) indicated low variability across the landscape, suggesting relative uniformity in soil reaction likely governed by the region's homogeneous parent material and limited leaching. The reclassified soil pH map, based on AIS & LUS (1971) [2] guidelines, further showed that 81.9% (57,858.4 ha) of the area falls under the alkaline category. An additional 13.5% (9,540.5 ha) is moderately alkaline, while only 4.6% (3,253.3 ha) exhibits

slightly alkaline characteristics (Table 4). Alkaline soils are frequently reported in semi-arid tropical regions of India due to low rainfall, accumulation of carbonates, limited weathering, and poor drainage, which restrict the removal of basic cations from the soil profile (Singh *et al.*, 2018; Sharma & Singh, 2017) [1, 32].

Similar pH trends in black soil regions were also documented by Arain *et al.* (2011) [3] and Panhwar *et al.* (2003) [25] who reported dominant alkaline conditions influenced by parent material and regional climatic patterns.

Table 3: Descriptive statistics of soil fertility parameter of Ambad tehsil

Soil properties	Minimum	Maximum	Mean	SD	CV	Skewness	Kurtosis	Distribution pattern
pH	7.1	9.1	7.86	0.31	3.94	-0.25	3.07	Normal
Electrical Conductivity (dSm^{-1})	0.1	1.0	0.43	0.16	37.20	0.74	3.39	Normal
Organic Carbon (%)	0.11	1.49	0.32	0.16	50	2.78	18.14	Normal
Available N (kg ha^{-1})	13.5	193.5	58.86	24.97	47.51	1.62	6.36	Normal
Available P (kg ha^{-1})	4.35	54.50	13.87	10.28	74.11	2.09	6.31	Normal
Available K (kg ha^{-1})	202.0	995.0	446.5	137.4	30.77	0.95	4.03	Normal

Table 4: Frequency distribution of soil properties of Ambad tehsil

Soil property	Unit	Rating	Class	Area (ha)	Area (%)
Soil Reaction (PH)		7.1-7.5	Slightly Alkaline	3253.3	4.60
		7.6-8.3	Moderately Alkaline	9540.5	13.50
		8.4-9.0	Alkaline	57858.4	81.89
Electrical Conductivity (EC)	dSm^{-1}	<0.4	Low	25661.2	36.32
		0.4-0.6	Medium	44115.0	62.43
		0.6-1.0	High	876.1	1.23
Organic Carbon (OC)	%	<0.2	Very low	2339.18	3.31
		0.21-0.40	Low	51566.9	72.98
		0.41-0.60	Moderate	13022.1	18.43
		0.61-0.80	Moderately high	3663.1	5.18
		0.81- 1.00	High	55.6	0.08
Available Nitrogen	Kg ha^{-1}	>1.0	Very high	5.2	0.01
		<140	Very low	66936.9	94.7
		141-280	Low	3685.6	5.21
Available phosphorus	Kg ha^{-1}	281-420	Moderate	29.76	0.04
		0-7	Very low	35713.92	50.55
		7-14	Low	12632.19	17.88
		14-21	Moderate	7089.6	10.03
		21-28	Moderately high	5321.63	7.53
		28-35	High	2805.35	3.97
Available potassium	Kg ha^{-1}	>35	Very high	7089.88	10.03
		201-250	Moderately high	1806.9	2.55
		251-300	High	6998.9	9.90
		>300	Very high	61846.4	87.53

Electrical Conductivity (EC)

Soil electrical conductivity (EC) is an important indicator of soil salinity and overall soil health, as it influences nutrient availability and crop productivity. In Ambad Taluka, the measured EC values ranged from 0.10 to 1.0 dS m^{-1} , with a mean value of 0.43 dS m^{-1} (Table 3), which is well below the threshold for salinity risk ($<1 \text{ dS m}^{-1}$), indicating that salinity is not a limiting factor for crop growth in the study area.

For clarity in mapping, the EC values were grouped into three categories: <0.4, 0.4-0.6, and 0.6-1.0 dS m^{-1} . The spatial analysis revealed that the majority of the area (44,114.99 ha; 62.43% of total geographical area, TGA) falls within the 0.4-0.6 dS m^{-1} range. Approximately 25,661.18 ha (36.32% of TGA) were classified in the <0.4 dS m^{-1} category, while very small pockets (876.07 ha; 1.24% of TGA) located mainly in the central and southern parts of the study area exhibited slightly higher EC values (0.6-1.0 dS m^{-1}) (Fig. 1, Table 4).

These findings are in agreement with earlier studies by Prasad *et*

al. (2020) [27], which reported low to moderate EC levels in soils of similar agro-climatic conditions. The overall low EC levels suggest that soil salinity does not pose a constraint to sugarcane cultivation in Ambad Taluka.

Soil Organic Carbon (OC)

Soil organic carbon (SOC) is one of the most important indicators of soil fertility and soil health because it regulates the cycling, storage, and availability of key nutrients, especially nitrogen, phosphorus, sulfur, and various micronutrients (Stevenson, 1982) [39]. Adequate SOC improves soil aggregate stability, enhances water infiltration and retention, reduces bulk density, and strengthens the soil's resilience against erosion and degradation (Smith & Elliott, 1990; Lal, 2004) [37, 16]. In addition, SOC plays a vital role in sustaining microbial activity and enzymatic processes that drive nutrient mineralization and soil biological functioning.

In the present study, SOC values in Ambad Taluka ranged from

0.11 to 1.49%, with a mean value of 0.32%, and exhibited a normal distribution pattern (Table 3). These values indicate overall poor soil organic matter status, which is a common feature in semi-arid tropical regions of India.

One of the major reasons for low SOC in this region is the limited use of organic manures, such as farmyard manure, compost, and green manures. Due to increasing fertilizer dependency, most farmers apply chemical fertilizers without supplementing organic sources, leading to gradual depletion of soil carbon stocks over time (Ghosh *et al.*, 2012) [10]. Another key factor is trash burning, particularly in sugarcane-based production systems. Farmers often burn sugarcane trash to ease land preparation, which results in the loss of large quantities of organic residues that could otherwise contribute to carbon buildup in soils (Sandhu *et al.*, 2019) [30]. Burning residues accelerates carbon oxidation and eliminates potential additions to soil organic matter pools, thereby contributing significantly to SOC decline.

Spatial analysis of SOC distribution revealed distinct carbon deficiency zones across the Taluka. The majority of the area 51,566.9 ha (73% of TGA) fell under the low SOC category. Soils with moderate SOC occupied 13,022.1 ha (18.4%), while moderately high SOC was observed in 3,663.1 ha (5.18%). Very low SOC occurred in 2,339.2 ha (3.31%), and only marginal areas were classified as high (55.6 ha; 0.08%) and very high SOC (5.2 ha; 0.01%) (Table 4; Fig. 2).

The widespread deficiency of SOC observed in this study is consistent with reports from other black soil regions of India, where low biomass return, monocropping, residue burning, and limited manure application collectively lead to SOC depletion (Singh *et al.*, 2014; Meena *et al.*, 2006) [35, 36, 19, 20].

Available Nitrogen (N)

Nitrogen is a fundamental macronutrient that controls vegetative growth, tillering, chlorophyll formation, and overall biomass production, making it one of the most yield-limiting nutrients in sugarcane. In the present study, available nitrogen in the soils of Ambad Taluka ranged from 13.5 to 195.5 kg ha⁻¹, with a mean of 58.86 kg ha⁻¹ (Table 3), and exhibited very low variability (CV = 0.42%), indicating that nitrogen deficiency is widespread across the region. Spatial mapping showed that 94.7% of the total geographical area (66,936.9 ha) fell under the very low nitrogen category, while 5.21% (3,685.5 ha) was classified as low, and only a negligible area (29.8 ha; 0.04%) recorded moderate nitrogen levels (Table 4; Fig. 2). The dominance of low nitrogen is largely attributed to heavy nitrogen losses through volatilization under alkaline soil conditions, leaching of nitrate beyond the root zone during irrigation or rainfall, and denitrification in intermittently waterlogged microsites. Another major reason is the common practice of applying nitrogen fertilizers in a single large dose, which leads to severe mismatch between fertilizer supply and crop demand, thereby reducing nitrogen use efficiency. These findings agree with the observations of Sharma *et al.* (2020) [33] and Khalid *et al.* (2012) [13], who reported similar nitrogen depletion trends under tropical agricultural conditions. In sugarcane, nitrogen requirement is highly stage-specific; therefore, for efficient utilization, 10% of the recommended dose should be applied at planting, followed by 40% at 6-8 weeks to promote rapid tiller formation, another 10% at 12-14 weeks during early internode development, and the remaining 40% at the grand growth stage (around 120 days after planting), along with 50% of phosphorus and potassium. Such split application ensures synchronized nutrient release with crop demand, minimizes losses, and improves nitrogen use

efficiency in sugarcane production systems.

Available Phosphorus (P)

Phosphorus is a vital macronutrient in sugarcane cultivation, particularly due to its role in promoting early root development, enhancing tillering, and improving overall vigour of the crop. In the soils of Ambad Taluka, the available phosphorus content ranged from 4.35 to 54.5 kg ha⁻¹, with a mean of 13.87 kg ha⁻¹ (Table 3), and the data exhibited low variability (CV = 0.73%), indicating relatively uniform phosphorus deficiency across the study area. Spatial distribution analysis showed that more than half of the total geographical area (35,580.9 ha) fell under the low phosphorus category, while an additional 17.9% (12,632.2 ha) was classified as very low, reflecting widespread scarcity of plant-available P (Fig. 3). Moderate and very high phosphorus categories each occupied substantial portions of land (7,147.6 ha and 7,089.8 ha, respectively), whereas moderately high (5,321.6 ha) and high P areas (2,880.4 ha) represented smaller but notable pockets of phosphorus sufficiency (Table 4). The predominance of low phosphorus levels can be attributed to the high calcium carbonate content of the region's soils, which leads to fixation of phosphorus in the form of insoluble calcium phosphate, significantly reducing its availability to plants. Furthermore, limited use of phosphorus fertilizers, poor adoption of soil test-based recommendations, and inadequate application of organic manures exacerbate P deficiency, as organic inputs help solubilize fixed phosphorus and improve P availability through microbial activity. These observations align with the findings of Memon *et al.* (1992) [21] and Sharma *et al.* (2020) [33], who also reported phosphorus scarcity in calcareous soils due to fixation and suboptimal fertilizer management practices.

Available Potassium (K)

Potassium is the third major nutrient essential for sugarcane growth, contributing to enzyme activation, water regulation, stress tolerance, and sugar translocation within the stalks. In the soils of Ambad Taluka, available potassium ranged from 202 to 995 kg ha⁻¹, with a mean value of 446.5 kg ha⁻¹ (Table 3), and showed low variability (CV = 0.30%), indicating uniformly high potassium status across the study area. Spatial distribution revealed that a vast majority of the area (61,846.4 ha; 87.53% of TGA) belonged to the very high potassium category, while the high class accounted for 6,998.6 ha (9.9%). Only a small fraction of the land 1,806.9 ha (2.55%) fell under the moderately high category, and none of the soils were classified as low or very low in potassium availability (Table 4). The abundance of available potassium can be attributed to the dominance of K-bearing minerals such as mica (biotite), illite, and K-feldspars in the basaltic parent material, which undergo weathering and continuously release potassium into the soil. Moreover, the recycling of crop residues and upward movement of potassium through capillary rise during dry spells further enrich the surface soil with exchangeable K. Frequent drought occurrences in Marathwada, typically every three years, may also enhance the importance of potassium, as it plays a pivotal role in osmotic regulation and improves plant resilience under moisture stress. Similar trends of elevated potassium in black soils derived from basalt have been reported by Spark *et al.* (1987) and Khadka *et al.* (2019) [12]. Despite the high natural K reserves, balanced fertilization is still necessary to avoid nutrient imbalance, particularly in intensive sugarcane cultivation systems.

Soil Nutrient Index (SNI)

The Soil Nutrient Index (SNI) is a reliable indicator used to

assess the overall fertility status of an area by integrating the distribution of soil samples across low, medium, and high nutrient categories. It provides a composite value that reflects the nutrient sufficiency or deficiency at the landscape level. In the context of Ambad Taluka, the SNI helps classify the status of available N, P, K, and other nutrients, thereby identifying areas requiring corrective nutrient management. The index is calculated using a weighted approach, where low, medium, and high nutrient classes are assigned scores of 1, 2, and 3, respectively. The resulting index value categorizes the nutrient status as low (<1.67), medium (1.67-2.33), or high (>2.33). This

quantitative classification is useful for recommending site-specific nutrient management strategies and aligning fertilizer application with soil fertility needs. Moreover, the SNI serves as a guiding tool for identifying nutrient-deficient zones, prioritizing extension activities, and planning balanced fertilization programs. Earlier studies by Ramamoorthy and Bajaj (1969) ^[28] and Kanwar (1976) emphasized the effectiveness of nutrient indexing for large-scale fertility evaluation, which further supports its application in the present study area.

Table 6: Nutrient index of Ambad Tehsil

Parameter	% distribution of samples					Nutrient index	Nutrient index class
	Very low	low	Medium	high	Very high		
Organic carbon (%)	25	48	15	1	0.4	1.72	Medium
Available N (kg ha ⁻¹)	85	1	0.02	0	0	1.01	Low
Available P (kg ha ⁻¹)	23	56	4.37	1.68	9.37	1.30	Low
Available K (kg ha ⁻¹)	0	0	3	11	85	2.86	High

Semivariogram Modeling and Spatial Variability

Semivariogram modelling was carried out to understand the spatial structure and continuity of soil properties across Ambad Taluka. The initial descriptive statistics indicated high variability (CV ≥ 35%) for most soil parameters, except pH and available potassium, which exhibited low to moderate variability as per the classification of Warrick (1998). This inherent variability necessitated the use of geostatistical tools to quantify the spatial dependence of soil attributes and to generate reliable interpolation surfaces.

For each soil parameter, experimental semivariograms were developed and fitted with theoretical models based on the lowest RMSE and highest model performance. Out of the six soil properties, pH, EC, organic carbon, available phosphorus, and available potassium were best fitted by the exponential model under ordinary kriging, indicating gradual spatial change and a smooth increase in semivariance with distance. In contrast, available nitrogen followed the spherical model, implying a clearer sill and a well-defined spatial continuity structure (Table 5).

The range values representing the distance beyond which samples become spatially independent varied considerably among soil properties. Larger ranges were observed for pH (7859.3 m) and available phosphorus (7590.5 m), suggesting these properties are mainly governed by intrinsic soil-forming factors such as parent material, mineralogical composition, and long-term pedogenic processes. Since these characteristics do not change abruptly, their spatial influence extends over larger distances.

On the other hand, relatively shorter ranges were recorded for EC (6189.08 m), organic carbon (6643.18 m), available nitrogen (132.41 m), and available potassium (6647.1 m). These shorter ranges reflect a smaller zone of influence, implying that these properties vary more abruptly across the landscape. Such short-distance variability is commonly associated with extrinsic factors such as heterogeneous fertilizer application, residue management, tillage operations, and localized soil degradation processes. For example, available nitrogen showed an extremely short range, likely due to the highly mobile and dynamic nature of N in the soil, coupled with farmers' practice of applying

nitrogenous fertilizers in large quantities at a single time, leading to patchy distribution.

The nugget-to-sill ratio, used to categorize spatial dependence (Cambardella *et al.*, 1994) ^[6], revealed that available nitrogen and phosphorus exhibited moderate spatial dependence, indicating that both intrinsic and extrinsic factors influence their spatial patterns. Strong spatial dependence was observed for parameters with nugget-sill ratios below 0.25, implying that their variability is largely governed by natural soil-forming processes rather than management-induced variability.

Interpretation of the spatial variability maps further supported these findings. The pH map indicated that about 81.89% of the area falls under alkaline conditions (pH 8.4 - 9.0), which is consistent with soils derived from basaltic parent material, known for their basic reaction due to the dominance of Ca- and Mg-bearing minerals (Bhaskar *et al.*, 2014) ^[4]. Electrical conductivity showed that 62.43% of the area lies in the medium range (0.4 - 0.6 dS m⁻¹), suggesting moderate salt accumulation influenced by irrigation practices and soil texture.

Organic carbon displayed a strong predominance of low values (72.98% of the area), reflecting low biomass return, trash burning in sugarcane fields, and accelerated carbon oxidation due to high temperature. Available nitrogen showed extremely low levels across 94.07% of the landscape, in agreement with its short range and moderate spatial dependence, driven by episodic fertilizer use and rapid N transformations. Available phosphorus mapped to 50.55% of the area falling under the very low category, likely due to phosphorus fixation in calcareous soils and insufficient application strategies. Conversely, available potassium was very high in 87.53% of the area, attributed to the abundance of K-rich primary minerals such as biotite mica and K-feldspars in the basaltic parent material, consistent with observations by Vasu *et al.* (2017) ^[41].

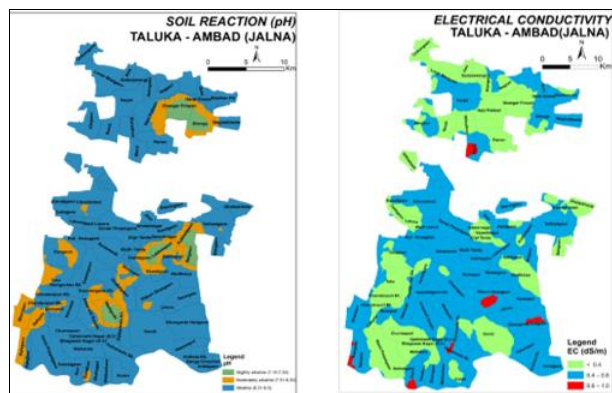
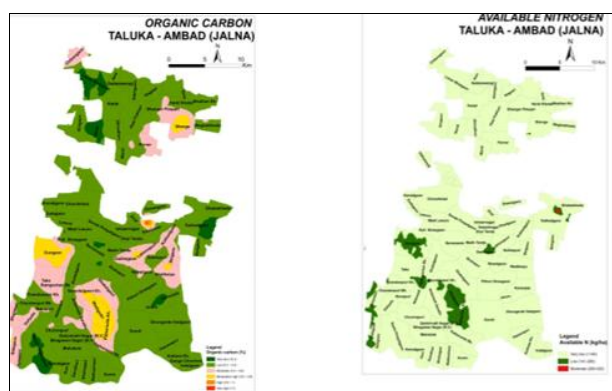
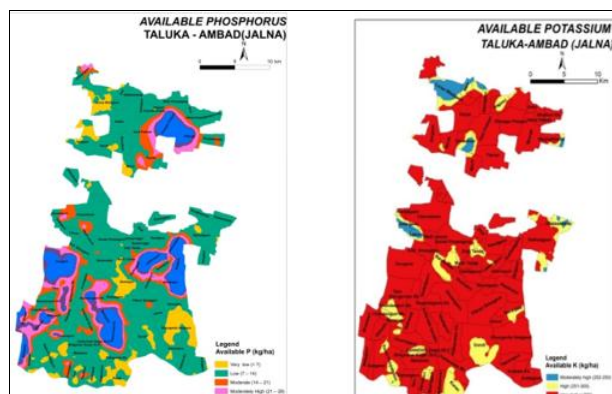
Overall, the semivariogram analysis highlights that soil chemical properties in Ambad Taluka are shaped by a combination of natural pedogenic factors and anthropogenic interventions. Understanding these spatial patterns is crucial for designing site-specific nutrient management strategies and enhancing fertilizer-use efficiency in the region.

Table 5: Geostatistics of the best-fitted semivariogram models for soil fertility parameter Ambad tehsil

Soil properties	Kriging type	Fitted model	Lag distance (m)	Range (m)	Nugget (Co)	Partial Sill(C)	Sill (Co+C)	N: S Ratio (%)	Spatial Class	RMSE**	RMSE std
pH	Ordinary	Exponential	654	7859.3	0.047	0.03	0.10	47	Moderate	0.23	0.99
Electrical Conductivity (dSm ⁻¹)	Ordinary	Exponential	602.63	6189.0	0.020	0.007	0.027	74	Moderate	0.151	0.153
Organic Carbon (%)	Ordinary	Exponential	864.4	6643.1	0.010	0.02	0.03	33	Moderate	0.13	1.11
Available N (kg ha ⁻¹)	Ordinary	Spherical	870.21	9792.6	219.41	821.80	1041.21	21	Strong	1.10	18.01
Available P(kg ha ⁻¹)	Ordinary	Exponential	632	7590.5	17.37	119.9	137.27	12	Strong	6.16	1.07
Available K (kg ha ⁻¹)	Ordinary	Exponential	2316.99	6647.1	0.01	0.02	0.03	33	Moderate	0.13	1.11

*Nugget/sill ratio (%) = $[C0/(C0 + C)*100]$. **Strong =% nugget <25%; moderate =% nugget 25-75%;

random =% nugget > 75% (Cambardella *et al.*, 1994)^[6]

**Fig 1:** Spatial variability map of soil pH and Electrical conductivity**Fig 2:** Spatial variability map of soil organic carbon and Available nitrogen**Fig 3:** Spatial variability map of Available phosphorus and potassium

Conclusion

Soil fertility is a critical determinant of sugarcane growth and productivity, making regular monitoring of soil health essential for understanding the spatial variability of nutrient status. The present study revealed that soil pH and electrical conductivity (EC) exhibited relatively long ranges in semivariogram

modeling, reflecting their intrinsic nature and stability against short-term human interventions. EC values remained within safe limits ($<1 \text{ dS m}^{-1}$), indicating no salinity-related constraints for plant growth, a finding particularly relevant in black soils with high buffering capacity.

In contrast, soil organic carbon and major nutrients displayed high variability over short distances, largely influenced by extrinsic factors such as fertilizer management, tillage, and crop residue handling. Geostatistical modeling of these parameters provides a robust approach to assess spatial variability and facilitates site-specific nutrient management, which can enhance sugarcane productivity while sustaining soil fertility.

Cross-validation of soil properties using the kriging interpolation method demonstrated reliable predictions with minimal errors. The application of GIS techniques for spatial interpolation of unsampled locations offers an effective, time-efficient, and cost-effective tool for managing soil fertility over extensive sugarcane-growing areas. This approach can also support the development of soil health cards for operational areas of sugar mills, enabling more informed and targeted nutrient management strategies.

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Declarations

Conflict of interest: The author declare that they have no conflict of interest.

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