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The authors' details and affiliations are provided below, following the reference section

Assessment of soil fertility levels under horticultural land use soils of Kaushambi District of Uttar Pradesh, India

Krishna Kumar Singh, Anil Kumar, Dheerendra Kumar, Sarvesh Kumar, Shubha Tripathi, Kushal Sachan, Vineet Dheer, Rajat Yadav, Suryabhan, Anurag Kumar Singh, Veerendra Singh and Abhishek Kumar Yadav

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Abstract

The present study assessed the physico-chemical properties and nutrient status of soils under horticultural land-use systems in Manjhanpur and Sirathu blocks of Kaushambi district across three soil depths (0-15, 15-30, and 30-60 cm). Soil reaction in both regions ranged from slightly to moderately alkaline, with mean pH values increasing gradually with depth (7.32 to 7.51 in Manjhanpur; 7.33 to 7.51 in Sirathu). Electrical conductivity remained low across all depths (0.34 to 0.49 dS/m in Manjhanpur; 0.34 to 0.48 dS/m in Sirathu), indicating non-saline conditions. Organic carbon content declined with depth, showing higher accumulation in surface layers (0.36 to 0.33% in Manjhanpur and 0.39 to 0.40% in Sirathu), reflecting the effect of organic matter inputs and biological activity. Exchangeable Ca, Mg, and Na increased with soil depth in both blocks, with higher mean Ca (2.26-2.57 meq/100 g) and Mg (0.66-0.73 meq/100 g) observed in deeper horizons. Primary nutrient concentrations also followed a depth-wise decreasing trend. In Manjhanpur, mean nitrogen decreased from 200.44 to 175.97 kg/ha with increasing depth, while phosphorus (16.48 to 14.29 kg/ha) and potassium (201.26 to 171.35 kg/ha) showed similar reductions. Comparable patterns were recorded in Sirathu, where nitrogen declined from 186.13 to 162.91 kg/ha, phosphorus from 14.95 to 12.87 kg/ha, and potassium from 208.94 to 177.53 kg/ha. Sulphur levels were higher in surface soils of both regions, ranging from 11.03 to 7.22 kg/ha in Manjhanpur and 11.79 to 7.97 kg/ha in Sirathu. Micronutrient availability (Fe, Mn, Cu, Zn, and B) exhibited significant spatial and vertical variability but consistently decreased with depth. In Manjhanpur surface soils, mean Fe, Mn, Cu, Zn, and B were 9.55, 8.18, 0.79, 0.73, and 0.68 mg/kg respectively, declining notably in subsurface layers. Similarly, Sirathu showed higher micronutrient levels at 0-15 cm (Fe 8.68 mg/kg; Mn 8.05 mg/kg; Cu 0.77 mg/kg; Zn 0.71 mg/kg; B 0.67 mg/kg) compared with deeper horizons.

Overall, the study highlights that horticultural soils of both blocks are moderately fertile, alkaline, non-saline, and characterized by decreasing organic carbon and nutrient content with soil depth. These findings underscore the need to adopt depth-specific nutrient management and soil conservation strategies to sustain productivity under horticultural land-use systems.

Keywords: Horticultural land use, organic carbon, fertility, soil depth

1. Introduction

Global agriculture productivity and sustainability depend heavily on soil fertility. Soil nutrient availability is vital to crop yields, ecological balance, and agricultural sustainability (Brady and Weil, 2017) [2]. Soil fertility depends on its physical and chemical qualities, including its ability to retain water and nutrients, maintain pH levels, and support microbial activity and root penetration. With the expansion of agricultural methods and the rising demand for high-quality products, soil fertility assessment and maintenance are essential for sustainable crop production. Indian and worldwide agricultural production relies on horticultural crops like fruits and vegetables. These crops need more macronutrients (nitrogen, phosphorus, potassium, calcium, magnesium, and sulphur) and micronutrients than cereal crops. Horticultural production systems are susceptible to soil fertility fluctuations because nutrient deficits affect fruit quality, yield, and market acceptability. Thus, horticultural land use requires detailed soil fertility assessment for

Corresponding Author:
Krishna Kumar Singh
Research Scholar, Department of
Soil Science and Agricultural
Chemistry, Chandra Shekhar Azad
University of Agriculture and
Technology, Kanpur, Uttar
Pradesh, India

location-specific fertilizer management and crop performance.

In India, pH, electrical conductivity (EC), organic carbon, available macronutrients (nitrogen, phosphorus, potassium, and sulphur), and micronutrients (zinc, copper, iron, manganese, and boron) are the twelve essential soil health parameters identified by the Indian Council of Agricultural Research (ICAR). These factors provide a complete picture of soil fertility and crop output. Soil fertility evaluation uses soil testing, plant analysis, and nutrient indexing to assess soil nutrients. Uttar Pradesh's Kaushambi district has rich agricultural potential. Fertile soils and diversified farming patterns make the district a major producer of wheat, rice, arhar, urad, and chana.

Kaushambi district is known for its Allahabad guava, a high-value fruit with enormous potential for horticultural growth. The horticultural sector in this region grows mango, guava, banana, and other fruit crops, which boost the agricultural economy and nutritional security. Comprehensive soil fertility assessment is needed to guide sustainable management methods in Kaushambi district due to a lack of systematic data on soil fertility status under horticultural land use. Intensive farming practices over several cropping seasons and improper fertilizer application have raised soil fertility concerns in many districts of Uttar Pradesh (Singh *et al.*, 2017)^[12].

Continuous mono-cropping without scientific crop rotation and diminishing soil organic matter concentration have lowered nutrient availability and soil productivity. These problems bring attention to a rigorous soil fertility study to assess nutrient levels, identify limiting nutrients, and generate evidence-based fertility management recommendations. Soil organic matter controls nutrient retention, water holding capacity, soil structure, and nutrient cycling microorganism activity, making it a key indication of soil quality. Soil fertility is assessed by assessing total nutrient reserves and plant-available nutrients (Lal, 2016)^[8]. Total nutrient content indicates long-term nutrient availability, but available nutrient determination determines crop nutrient needs and informs fertilizer recommendations.

This study evaluates soil fertility in Kaushambi district horticultural land use soils. This study will establish baseline soil fertility data, identify nutrient deficits and imbalances, and present scientific evidence for district-specific horticultural crop nutrient management plans. This thorough evaluation should improve soil health, environmental quality, and horticultural enterprise productivity and sustainability in the region. The findings of this research will help farmers, extension workers, and policymakers make informed soil and crop management decisions in horticulture systems in Kaushambi district.

Brady, N. C., & Weil, R. R. (2017)^[2]. *The Nature and Properties of Soils* (15th ed.). Pearson.

Lal, R. (2016)^[8]. Soil organic matter and water retention. *Agronomy Journal*, 108(3), 1072-1078.

Singh, A. K., Singh, S. P., & Maurya, S. (2017).^[12] Horticultural development and guava production in Uttar Pradesh. *Indian Horticulture Journal*, 7(2), 45-50.

2. Methods and Materials

2.1 Study sites

Kaushambi district is located in the Lower Gangetic Plain region of Uttar Pradesh. It is bounded by Pratapgarh district to the North, Chitrakoot to the South, Fatehpur to the West, and Prayagraj (Allahabad) to the East. The district covers a geographical area of about 1,903.17 square kilometres. It extends between 25°15'30" to 25°47'45" N latitude and 81°10' to 81° 55' E longitude, with an average elevation of approximately 120 meters above mean sea level. The region

forms part of the alluvial plains of the Ganga and Yamuna river systems, characterized by fertile soils that support intensive agricultural activities. For the purpose of this study, the entire research area was segmented into two distinct blocks, namely Manjhanpur and Sirathu, each comprising five different sites selected from the respective villages, viz., Afzalpur wari, Rala, Udihin Buzurg, Terahra, Shelraha East, Agiyouna, Chak Sahanpur, Edilpur, Chhimirachha and Ukhaiya Khas.

2.2 Collection of Soil Samples and Laboratory Analysis

Soil samples were collected at depths of 0-15 cm, 15-30 cm, and 30-60 cm at the site. The soil samples were air-dried, ground up with the help of a wooden pestle and mortar, sieved through a 2-mm mesh, labeled, and stored at the Soil Laboratory of the Department of Soil Science and Agricultural Chemistry, C.S. Azad University of Agriculture and Technology, Kanpur 208002, UP, India, in compliance with standard laboratory protocols.

The soil samples were analysed for soil physico-chemical properties viz., soil pH and electrical conductivity (EC) was recorded in 1:2.5 soil to water suspension (Jackson, 1973)^[6], the organic carbon (OC) determined by Walkley and Black, 1934^[15] method, Exchangeable bases were collected using neutral normal ammonium acetate and the exchanged ion measured following the procedure outlined in Hesse (1970)^[5]. The Ca⁺⁺ and Mg⁺⁺ were determined by complex metric titration, involving ethylene diamine tetra acetic acid (EDTA) and Na⁺ was determined.

The macronutrients like available nitrogen and phosphorus were by alkaline potassium permanganate method (Subbiah and Asija, 1956)^[13] and Spectrophotometer follow by the method (Olsen, *et al.*, 1954)^[11], respectively. Available potassium was determined by a flame photometer with neutral normal ammonium acetate as an extractant (Hanway and Heidel, 1952)^[3]. The available Sulphur content of the soil samples was determined by the turbidimetric method (Black, 1965)^[1]. Micronutrients viz., available zinc, Fe, Cu and Mn (DTPA extractable) were determined by using Atomic Absorption Spectrophotometer (Lindsay and Norvell, 1978)^[9]. The available Boron is estimated by Azomethine-H method by John *et al.*, 1975^[7].

2.3 Data Analysis

The data underwent descriptive statistical analysis, including minimum, maximum, mean, and standard deviation and coefficient of variation utilizing SPSS.

3. Results and Discussion

3.1 Physical Properties of Soil in Manjhanpur and Sirathu Block

The physico-chemical properties of soil (from 0 to 60 cm) in horticultural land use regions of Manjhanpur and Sirathu block is provided in table-1. The measurements are categorized into different depth ranges (0-15 cm, 15-30 cm, and 30-60 cm). The properties measured include soil pH, electrical conductivity (EC), soil organic carbon (OC) and exchangeable cations (calcium, magnesium and sodium). The table additionally presents data including the minimum, maximum, mean, standard deviation (SD), and coefficient of variation (CV) for every characteristic and depth range.

The physico-chemical characterization of soils in the horticultural land use regions of Manjhanpur and Sirathu Block revealed systematic variations across the 0-60 cm profile. Soil pH values ranged from 7.02 to 7.89 across both locations, with

mean values increasing progressively with soil depth, reaching 7.51 in both regions at the 30-60 cm depth. This slight alkalinity is consistent with the optimal range for most horticultural crops, where a pH range of 5.5 to 7.5 is generally considered desirable. However, pH above 7.5 can reduce the availability of micronutrients including iron, manganese, copper, and zinc through precipitation and reduced solubility. The depth-wise increase in pH suggests accumulation of basic cations in the subsoil, a phenomenon well-documented in soil profile development.

Electrical conductivity (EC) values ranged from 0.27 to 0.59 dS/m across all samples, well below the critical salinity threshold of 4.0 dS/m where crop growth is significantly impaired. Mean EC values in Manjhanpur ranged from 0.38 to 0.49 dS/m, while Sirathu Block showed mean values from 0.34 to 0.48 dS/m. The relatively low EC values indicate that dissolved salt concentration is not a limiting factor for horticultural production in these regions. EC serves as an important indirect indicator of nutrient availability, soil texture, and water-holding capacity; thus, the uniform low EC across depths suggests consistent management practices and stable soil conditions.

Organic carbon (OC) content remained relatively stable across the soil profile, with mean values ranging from 0.33 to 0.40% in Manjhanpur and 0.39 to 0.40% in Sirathu Block. While these values represent moderate organic carbon levels, the minimal variation across depths differs from typical patterns where

organic matter concentration decreases significantly with depth. This stable distribution suggests that horticultural practices in these regions may maintain consistent organic matter inputs across the profile through regular organic amendments and residue management. Organic carbon is critical for soil structure, water retention, nutrient cycling, and providing reserves of essential nutrients, particularly nitrogen, phosphorus, and sulphur.

Exchangeable calcium (Ca) and magnesium (Mg) showed distinct depth-related patterns. Mean calcium content increased systematically with depth, from 2.26 meq/100 g in the 0-15 cm layer to 2.57 meq/100 g in the 30-60 cm layer in Manjhanpur, and from 2.31 to 2.66 meq/100 g in Sirathu Block. Magnesium values ranged from 0.66 to 0.73 meq/100 g in Manjhanpur and 0.63 to 0.70 meq/100 g in Sirathu Block, showing relatively minor depth variations. These exchangeable cations are essential for plant nutrition and maintain soil structure through cation exchange reactions. The adequate levels of exchangeable bases indicate sufficient capacity for nutrient retention and slow release of nutrients to plants, as exchangeable cations occupy the negatively charged adsorption sites on clay minerals and organic matter colloids. The desirable ranges for exchangeable cations in soil are calcium 65-80% of cation exchange capacity, magnesium 10-15%, and potassium 1-5%. The present data suggests adequate base saturation for horticultural crop production (Havlin *et al.*, 2014)^[4].

Table 1: Physico-chemical properties of soil (from 0 to 60 cm) in horticultural land use regions of Manjhanpur and Sirathu Block

	Soil Depth (cm)	Manjhanpur						Sirathu					
		pH	EC (dS/m)	OC (%)	Exchangeable cations (meq/100 g)			pH	EC (dS/m)	OC (%)	Exchangeable cations (meq/100 g)		
					Ca	Mg	Na				Ca	Mg	Na
Minimum	0-15	7.02	0.34	0.32	2.13	0.62	0.79	7.12	0.27	0.34	2.18	0.60	0.74
	15-30	7.08	0.44	0.30	2.18	0.60	0.77	7.16	0.36	0.35	2.24	0.61	0.72
	30-60	7.23	0.36	0.30	2.38	0.69	0.81	7.32	0.38	0.35	2.52	0.63	0.78
Maximum	0-15	7.73	0.42	0.40	2.35	0.71	0.92	7.55	0.41	0.45	2.38	0.66	0.82
	15-30	7.82	0.55	0.38	2.48	0.73	0.90	7.63	0.53	0.47	2.61	0.70	0.86
	30-60	7.89	0.58	0.39	2.74	0.77	1.01	7.71	0.59	0.48	2.80	0.76	0.96
Mean	0-15	7.32	0.38	0.36	2.26	0.66	0.85	7.33	0.34	0.39	2.31	0.63	0.78
	15-30	7.39	0.49	0.33	2.32	0.66	0.84	7.39	0.45	0.40	2.41	0.65	0.79
	30-60	7.51	0.47	0.34	2.57	0.73	0.92	7.51	0.48	0.40	2.66	0.70	0.87
Standard Deviation	0-15	0.261	0.027	0.028	0.067	0.029	0.037	0.139	0.051	0.040	0.059	0.022	0.027
	15-30	0.265	0.036	0.025	0.110	0.044	0.042	0.145	0.059	0.042	0.146	0.026	0.043
	30-60	0.264	0.062	0.029	0.130	0.025	0.074	0.136	0.074	0.042	0.099	0.051	0.067
Coefficient of Variation (%)	0-15	0.036	0.071	0.078	0.030	0.043	0.043	0.019	0.147	0.103	0.026	0.0348	0.0347
	15-30	0.036	0.073	0.077	0.047	0.066	0.050	0.020	0.133	0.105	0.060	0.040	0.055
	30-60	0.035	0.133	0.087	0.051	0.034	0.081	0.018	0.153	0.105	0.037	0.073	0.077

Exchangeable sodium (Na) content ranged from 0.79 to 1.01 meq/100 g in Manjhanpur and 0.74 to 0.96 meq/100 g in Sirathu Block, remaining well below the critical level of sodicity. These low sodium values are consistent with the low EC values observed, indicating absence of salt-induced soil degradation in these horticultural systems.

3.2 Nutrient Content of horticultural land use

3.2.1 Primary Macronutrients

Available nitrogen (N) demonstrated a pronounced depth-related decline, with mean values of 200.44 kg/ha at 0-15 cm depth decreasing to 175.97 kg/ha at 30-60 cm depth in Manjhanpur, and from 186.13 kg/ha to 162.91 kg/ha in Sirathu Block. This

pattern reflects the concentration of biological activity, organic matter mineralization, and nutrient cycling in the surface soil horizon. The decline in available nitrogen with depth is well-established in the literature, as nitrogen availability is predominantly derived from the oxidative breakdown of soil organic matter through microbial processes, which are most active in biologically dynamic surface layers. The coefficients of variation for nitrogen remained relatively low (1.7-2.4%), indicating consistent nitrogen distribution across the sampling area within each depth increment.

Available phosphorus (P) content displayed similar depth-dependent trends, with mean values declining from 16.48 kg/ha at 0-15 cm to 14.29 kg/ha at 30-60 cm in Manjhanpur, and from

14.95 kg/ha to 12.87 kg/ha in Sirathu Block. These phosphorus levels are moderate to low, suggesting that phosphorus could potentially limit horticultural productivity if not supplemented through management. The concentration of phosphorus in surface layers reflects the immobility of phosphorus in the soil matrix and its association with the most active organic matter pools (Nayak *et al.*, 2015)^[10].

Available potassium (K) ranged from mean values of 201.26 kg/ha at 0-15 cm to 171.35 kg/ha at 30-60 cm in Manjhanpur, and from 208.94 kg/ha to 177.53 kg/ha in Sirathu Block. While potassium also declined with depth, the decline was less pronounced than for nitrogen and phosphorus, likely due to potassium's presence in both mineral and exchangeable forms, providing longer-term nutrient reserves from weathering processes. These potassium levels indicate adequate short-term nutrient availability for most horticultural crops (Vimalashree and Sathish, 2024)^[14].

The pronounced decline in all three primary macronutrients with increasing soil depth emphasizes the critical importance of surface soil management and the localization of the most fertile, biologically active soil layers in the upper 15 cm of the profile (Wang *et al.*, 2024)^[16].

3.2.2 Secondary Nutrients and Micronutrients

Sulphur (S) content was relatively low, with mean values ranging from 7.22 to 11.03 kg/ha in Manjhanpur and 7.97 to 11.79 kg/ha in Sirathu Block. The decline in available sulphur with depth (from 11.03 kg/ha to 7.22 kg/ha in Manjhanpur) reflects the importance of organic matter mineralization in sulphur availability. These sulphur levels are moderately low and consistent with widespread sulphur deficiency problems documented across Indian agricultural soils, where deficiency can reach 45-65% depending on region and depth. Adequate sulphur is essential for synthesis of sulphur-containing amino acids and for crop quality, particularly in oilseed and pulse crops.

Micronutrient analysis revealed substantial variations in distribution patterns. Iron (Fe) content ranged from mean values of 9.55 mg/kg at 0-15 cm to 5.93 mg/kg at 30-60 cm in Manjhanpur, and from 8.68 mg/kg to 5.72 mg/kg in Sirathu Block. The pronounced decline in iron with depth likely reflects the pH-dependent availability of iron and its strong association

with organic matter and organic complexation. At the slightly alkaline pH values observed (7.3-7.5), iron availability decreases significantly, and iron becomes more tightly bound to organic matter and mineral surfaces.

Manganese (Mn) ranged from mean values of 8.18 mg/kg at 0-15 cm to 5.95 mg/kg at 30-60 cm in Manjhanpur, and from 8.05 mg/kg to 5.82 mg/kg in Sirathu Block, exhibiting similar depth-dependent trends to iron. Like iron, manganese availability is strongly pH-dependent, with availability decreasing substantially as pH increases above 7.0.

Copper (Cu) levels were relatively low, with mean values ranging from 0.79 mg/kg at 0-15 cm to 0.52 mg/kg at 30-60 cm in Manjhanpur, and from 0.77 mg/kg to 0.50 mg/kg in Sirathu Block. These low copper values suggest that copper could potentially become a limiting micronutrient in these horticultural soils, particularly considering that copper may form strong complexes with soil organic matter, reducing its availability. Low organic matter and sandy soil conditions typically result in low copper availability.

Zinc (Zn) content ranged from mean values of 0.73 mg/kg at 0-15 cm to 0.43 mg/kg at 30-60 cm in Manjhanpur, and from 0.71 mg/kg to 0.49 mg/kg in Sirathu Block. The low zinc values, particularly at depth, align with the well-documented pattern that zinc is one of the most frequently deficient micronutrients in crop production, and zinc deficiency has been extensively reported in Indian soils at levels affecting horticultural crop quality.

Boron (B) content ranged from mean values of 0.68 mg/kg at 0-15 cm to 0.45 mg/kg at 30-60 cm in Manjhanpur, and from 0.67 mg/kg to 0.41 mg/kg in Sirathu Block. These boron levels are relatively low, and boron deficiency can be exacerbated by soil pH above 8.5, though at the neutral to slightly alkaline pH of these soils (7.3-7.5), boron availability is not severely restricted.

The decline in micronutrient concentrations with increasing soil depth is consistent with global findings that micronutrients are concentrated in surface soil layers where biological cycling is most active. This pattern reflects the predominantly organic origin of many available micronutrients through the mineralization of soil organic matter. The relatively low values of copper and zinc, in particular, suggest that micronutrient deficiency management should be a consideration for horticultural crop production in these regions

Table 2.a: Nutrient content of soils (from 0 to 60 cm) in horticultural land use regions of Manjhanpur

	Soil Depth (cm)	Primary Nutrients (kg/ha)			Micronutrients (mg/kg)					
		N	P	K	S	Fe	Mn	Cu	Zn	B
Minimum	0-15	193.51	14.75	192.86	9.75	8.48	6.61	0.64	0.59	0.55
	15-30	190.00	14.52	189.36	9.67	7.75	6.98	0.55	0.65	0.62
	30-60	171.46	12.98	165.47	6.92	5.73	5.80	0.49	0.39	0.41
Maximum	0-15	207.80	18.67	212.18	12.70	11.05	9.89	0.95	0.81	0.75
	15-30	200.94	18.07	205.39	10.87	8.58	7.51	0.62	0.72	0.69
	30-60	180.78	15.96	179.29	7.59	6.27	6.13	0.64	0.46	0.50
Mean	0-15	200.44	16.48	201.26	11.03	9.55	8.18	0.79	0.73	0.68
	15-30	195.30	16.08	196.20	10.15	8.09	7.20	0.59	0.69	0.65
	30-60	175.97	14.29	171.35	7.22	5.93	5.95	0.52	0.43	0.45
Standard Deviation	0-15	4.310	1.330	6.776	0.785	0.694	0.988	0.101	0.060	0.056
	15-30	3.403	1.273	6.197	0.361	0.279	0.181	0.023	0.024	0.022
	30-60	2.984	1.123	5.398	0.249	0.174	0.109	0.044	0.023	0.029
Coefficient of Variation (%)	0-15	0.022	0.081	0.034	0.071	0.073	0.121	0.128	0.082	0.082
	15-30	0.017	0.079	0.032	0.036	0.034	0.025	0.040	0.034	0.034
	30-60	0.017	0.079	0.032	0.034	0.029	0.018	0.085	0.053	0.065

Table 2.b: Nutrient content of soils (from 0 to 60 cm) in horticultural land use regions of Sirathu

	Soil Depth (cm)	Primary Nutrients (kg/ha)			Micronutrients (mg/kg)					
		N	P	K	S	Fe	Mn	Cu	Zn	B
Minimum	0-15	179.23	13.69	201.60	11.02	7.01	7.23	0.71	0.66	0.63
	15-30	174.55	13.27	197.14	10.03	7.78	7.00	0.57	0.67	0.62
	30-60	157.84	11.86	172.27	7.75	5.55	5.03	0.48	0.46	0.38
Maximum	0-15	193.20	16.77	216.98	12.50	9.83	8.82	0.83	0.74	0.71
	15-30	186.44	16.23	210.04	10.61	8.36	7.54	0.64	0.73	0.67
	30-60	168.08	14.34	183.35	8.25	5.93	6.14	0.54	0.53	0.43
Mean	0-15	186.13	14.95	208.94	11.79	8.68	8.05	0.77	0.71	0.67
	15-30	180.43	14.48	203.27	10.32	8.04	7.28	0.61	0.69	0.65
	30-60	162.91	12.87	177.53	7.97	5.72	5.82	0.50	0.49	0.41
Standard Deviation	0-15	4.385	0.991	4.455	0.488	0.891	0.537	0.044	0.028	0.025
	15-30	3.934	0.958	3.907	0.216	0.200	0.200	0.023	0.018	0.016
	30-60	3.492	0.843	3.387	0.192	0.131	0.311	0.021	0.022	0.018
Coefficient of Variation (%)	0-15	0.024	0.066	0.021	0.041	0.103	0.067	0.057	0.040	0.036
	15-30	0.022	0.066	0.019	0.021	0.025	0.027	0.038	0.026	0.025
	30-60	0.021	0.066	0.019	0.024	0.023	0.053	0.041	0.046	0.045

4. Conclusion

The assessment of soil fertility under horticultural land use in the Kaushambi district revealed that the soils are moderately fertile, slightly to moderately alkaline, and non-saline, with favourable levels of exchangeable bases. Organic carbon and major nutrients—including nitrogen, phosphorus, and potassium, were concentrated in the surface horizons and declined with depth, reflecting the influence of organic matter dynamics and biological activity. Micronutrients such as Fe, Mn, Cu, Zn, and B also showed higher availability in the upper soil layers, indicating their strong association with organic matter and pH-dependent solubility. Although nutrient levels were generally adequate, the consistently low concentrations of sulphur, zinc, and copper highlight the need for targeted nutrient supplementation. Overall, the study establishes a valuable baseline of soil fertility status and underscores the importance of depth-specific nutrient management, organic matter enhancement, and balanced fertilization to sustain horticultural productivity and soil health in the region.

Competing Interest

The authors have no competing interest.

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Author's Details

Krishna Kumar Singh

Research Scholar, Department of Soil Science and Agricultural Chemistry, Chandra Shekhar Azad University of Agriculture and Technology, Kanpur, Uttar Pradesh, India

Anil Kumar

Professor, Department of Soil Science and Agricultural Chemistry, Chandra Shekhar Azad University of Agriculture and Technology, Kanpur, Uttar Pradesh, India

Dheerendra Kumar

Research Scholar, Department of Soil Science and Agricultural Chemistry, Chandra Shekhar Azad University of Agriculture and Technology, Kanpur, Uttar Pradesh, India

Sarvesh Kumar

Professor, Department of Soil Conservation and Water Management, Chandra Shekhar Azad University of Agriculture and Technology, Kanpur, Uttar Pradesh, India

Shubha Tripathi

Research Scholar, Department of Soil Science and Agricultural Chemistry, Chandra Shekhar Azad University of Agriculture and Technology, Kanpur, Uttar Pradesh, India

Kushal Sachan

Research Scholar, Department of Soil Science and Agricultural Chemistry, Chandra Shekhar Azad University of Agriculture and Technology, Kanpur, Uttar Pradesh, India

Vineet Dheer

Teaching Associate, Department of Agronomy, Chandra Shekhar Azad University of Agriculture and Technology, Kanpur, Uttar Pradesh, India

Rajat Yadav

Research Scholar, Department of Agronomy, Chandra Shekhar Azad University of Agriculture and Technology, Kanpur, Uttar Pradesh, India

Suryabhan

Research Scholar, Department of Agronomy, Chandra Shekhar Azad University of Agriculture and Technology, Kanpur, Uttar Pradesh, India

Anurag Kumar Singh

Teaching associate, College of Agriculture, Chandra Shekhar Azad University of Agriculture and Technology, Kanpur, Uttar Pradesh, India

Veerendra Singh

Senior Research Fellow, Division of Environmental Soil Science, Indian Institute of Soil Science, Bhopal, Madhya Pradesh, India

Abhishek Kumar Yadav

Research Scholar, Department of Entomology, Chandra Shekhar Azad University of Agriculture and Technology, Kanpur, Uttar Pradesh, India