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The Evolution of Physico - Chemical Characteristics of Coffee - Based Soils in Bastar Division, Chhattisgarh

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ABSTRACT
This study evaluates the progression of physico-chemical properties of coffee-based soils in the Bastar Division of Chhattisgarh, India, and a burgeoning non-traditional coffee cultivation area. Soil samples were obtained from coffee farms of varying ages and management practices at two depths (0–15 cm and 15–30 cm). Conventional laboratory techniques were employed to assess soil texture, pH, electrical conductivity, bulk density, organic carbon, total nitrogen, available phosphorus, available potassium, and DTPA-extractable micronutrients (Fe, Mn, Zn, and Cu). The spatial variability of essential soil parameters was assessed by geostatistical interpolation utilizing Geographic Information System (GIS) technology. Findings demonstrated that coffee-based agroforestry systems markedly improved soil organic carbon and nutrient availability in comparison to younger plantings and monoculture systems. The soils were primarily moderately acidic to nearly neutral, conducive to coffee growing, however significant geographical diversity in phosphorus and micronutrient levels was noted. Elevated organic carbon concentrations in mature plants indicated a gradual enhancement in soil structure and nutrient cycling. The research underscores the promise of coffee-based agroforestry in enhancing soil quality and advocates for site-specific nutrient management to ensure sustainable coffee production in the Bastar region.
Keywords*: Coffee-based soils, Physico-chemical characteristics, Soil fertility; GIS, Bastar Division, Chhattisgarh.*

INTRODUCTION

Soil is an essential natural resource that regulates agricultural productivity, ecosystem stability, and biogeochemical cycling. Essential physico-chemical soil characteristics—such as texture, pH, organic carbon content, and nutrient availability—significantly affect soil fertility and crop yield [1]. Alterations in land use and management techniques can substantially affect these qualities, particularly in perennial plantation systems where soil–plant interactions develop progressively over time [2]. Coffee (Coffea spp.) is a significant agricultural crop grown in several tropical regions. In India, coffee growing has historically been centered in the Western Ghats; nevertheless, its proliferation into non-traditional areas has intensified due to advantageous climatic conditions, diversification of land utilization, and economic prospects for smallholders. The Bastar Division of Chhattisgarh is a rising region where coffee is progressively advocated inside agroforestry systems. The Bastar region features undulating topography, extensive forest coverage, and lateritic to red soils, typically categorized as Entisols, Inceptisols, and Alfisols. These soils typically possess low to moderate fertility and demonstrate significant regional heterogeneity in organic carbon and nutrient levels [5,6]. In these delicate agro-ecosystems, sustainable land-use techniques are crucial to avert soil deterioration and guarantee long-term productivity. Coffee-based agroforestry systems are acknowledged for their capacity to improve soil quality via ongoing litter inputs, increased root biomass, diminished erosion, and heightened microbial activity [4,7]. Research from conventional coffee cultivation areas has indicated elevated soil organic carbon levels, enhanced nutrient cycling, and superior soil physical characteristics in shaded coffee systems relative to monocropping practices [2,3]. The accumulation of organic matter in agroforestry boosts soil structure, water retention, and the availability of macro- and micronutrients [1]. Despite the growing significance of coffee cultivation in Bastar, thorough scientific investigations into the evolution of physico-chemical soil parameters within coffee-based systems in this non-traditional location are still few. Current research in central India has predominantly concentrated on forest soils and annual cropping systems, with very little studies on plantation crops like coffee [8]. Furthermore, numerous studies depend on point-based soil data and fail to sufficiently consider spatial variability, which is essential for site-specific nutrient management [9]. Recent advancements in Geographic Information Systems (GIS) and geostatistical methodologies offer powerful instruments for analyzing and visualizing the spatial variability of soil parameters [10]. GIS-based soil fertility mapping facilitates the identification of nutrient-deficient areas and enhances precision soil management, especially in varied landscapes such as Bastar. This study seeks to assess the changes in physico-chemical properties of coffee-based soils in the Bastar Division of Chhattisgarh, considering various plantation ages and management approaches, while incorporating GIS-based spatial analysis. The results are anticipated to facilitate sustainable coffee cultivation and soil health management in non-traditional coffee-growing areas of India.

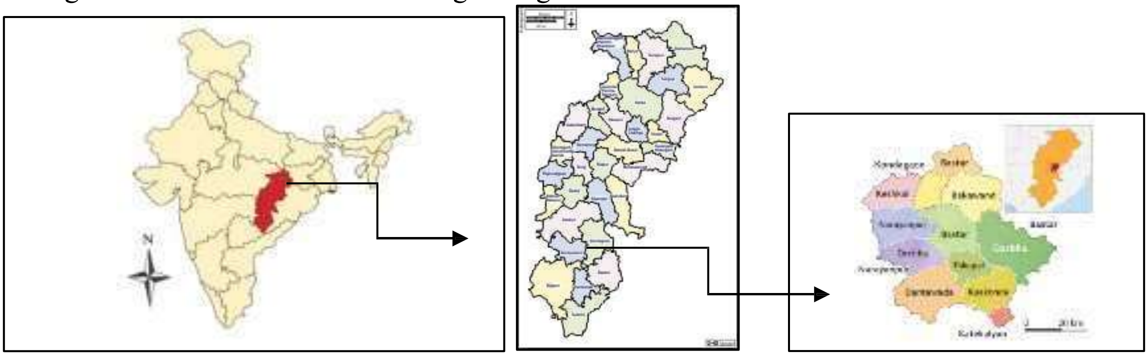

Figure 1 Bastar division of Chhattisgarh maps

MATERIALS AND METHODS

Study area

The research was carried out in the Bastar Division, situated in the southern region of Chhattisgarh, India. The area features rolling terrain, extensive woodland, and a tropical climate influenced by monsoons. The mean annual precipitation varies from 1200 to 1600 mm, predominantly occurring during the southwest monsoon season. The mean yearly temperature ranges from 18 °C in winter to approximately 35 °C in summer. The soils in the research region are primarily red and lateritic, classed chiefly as Entisols, Inceptisols, and Alfisols. Coffee farming in the region predominantly occurs beneath shade trees under agroforestry systems.

Soil sampling design

Soil sampling was conducted in coffee plantations of varying ages and management approaches, encompassing young plantations (≤5 years), medium-aged plantations (6–15 years), and older plantations (>15 years). The study encompassed both coffee monoculture and coffee-based agroforestry systems. Composite soil samples were obtained at two depths: 0–15 cm (surface layer) and 15–30 cm (subsurface layer). At each sampling location, five to seven sub-samples were collected using a zig-zag pattern and amalgamated to create one composite sample per depth. The geographic coordinates of each sampling site were documented with a handheld Global Positioning System (GPS). The gathered samples were air-dried, meticulously crushed, and subjected to a 2-mm filter for physico-chemical examination.

Laboratory analysis

Standard laboratory protocols were adhered to for the investigation of physicochemical soil parameters. The hydrometer method was employed to ascertain soil texture. The soil pH was determined in a 1:2.5 soil-to-water suspension with a digital pH meter, and the electrical conductivity (EC) was assessed in the same extract using a conductivity meter.

The core sampler method was employed to ascertain bulk density. Soil organic carbon was quantified via the Walkley–Black wet oxidation technique. The Kjeldahl digestion method was employed to ascertain total nitrogen content. Available phosphorus was quantified via the Olsen method, whereas available potassium was extracted using neutral normal ammonium acetate and assessed with a flame photometer. Micronutrients including iron (Fe), manganese (Mn), zinc (Zn), and copper (Cu) were extracted with DTPA solution and measured via atomic absorption spectrophotometry (AAS). All analyses were performed with suitable quality control methods, encompassing reagent blanks and standard reference samples.

Spatial analysis and GIS mapping

The spatial variability of specific soil parameters was examined utilizing Geographic Information System (GIS) methodologies. The GPS-tracked sampling sites were loaded into GIS software to establish a spatial database. Exploratory spatial data analysis was conducted, succeeded by geostatistical interpolation employing the ordinary kriging method to produce continuous spatial distribution maps for essential soil properties, including organic carbon, available phosphorus, available potassium, and micronutrients. Semivariogram models were calibrated and validated by cross-validation methods to guarantee predictive accuracy.

Statistical analysis

Descriptive statistics, encompassing mean, standard deviation, minimum, and maximum values, were calculated for all soil characteristics and Management system on soil physicochemical parameters. Statistical studies were conducted utilizing conventional statistical tools, with significance assessed at the 5% probability threshold.

RESULTS AND DISCUSSION

Table 1: Chemical Properties of Soils in Bastar Division (0–15 cm depth)

District's Name	Block's Name	pH	EC (dS m^{-1})	Organic Carbon (%)	N (kg ha^{-1})	P (kg ha^{-1})	K (kg ha^{-1})
Bastar	Bastar	6.1	0.12	0.58	210	12.5	285
Bastar	Tokapal	5.9	0.11	0.55	195	10.8	270
Bastar	Lohandiguda	6.0	0.10	0.62	220	13.6	295
Bastar	Darbha	6.2	0.09	0.78	245	18.6	315
Kondagaon	Kondagaon	6.1	0.13	0.60	230	14.2	295
Kondagaon	Keshkal	6.0	0.12	0.59	220	13.5	305
Dantewada	Dantewada	5.7	0.14	0.52	185	9.8	260
Dantewada	Gidam	5.9	0.15	0.50	170	8.4	250
Dantewada	Katekalyan	5.6	0.16	0.48	165	7.9	240
Bijapur	Bijapur	5.6	0.14	0.49	175	8.6	255
Sukma	Sukma	5.4	0.17	0.46	160	7.2	235
Sukma	Chhindgarh	5.2	0.18	0.44	155	6.8	230
Narayanpur	Narayanpur	5.9	0.13	0.56	205	11.6	280

Table 2: Chemical Properties of Soils in Bastar Division (15–30 cm depth)

District's Name	Block's Name	pH	EC (dS m^{-1})	Organic Carbon (%)	N (kg ha^{-1})	P (kg ha^{-1})	K (kg ha^{-1})
Bastar	Bastar	6.0	0.10	0.46	185	9.8	265
Bastar	Tokapal	5.8	0.10	0.43	170	8.6	250
Bastar	Lohandiguda	5.9	0.09	0.48	190	10.2	275
Bastar	Darbha	6.1	0.08	0.60	210	14.5	295
Kondagaon	Kondagaon	6.0	0.11	0.47	200	11.6	280
Kondagaon	Keshkal	5.9	0.10	0.45	195	11.2	285
Dantewada	Dantewada	5.6	0.12	0.40	160	7.2	240
Dantewada	Gidam	5.7	0.13	0.38	150	6.8	230
Dantewada	Katekalyan	5.5	0.14	0.36	145	6.2	220
Bijapur	Bijapur	5.5	0.13	0.37	155	6.9	235
Sukma	Sukma	5.3	0.15	0.35	140	5.8	215
Sukma	Chhindgarh	5.2	0.16	0.34	135	5.5	210
Narayanpur	Narayanpur	5.8	0.11	0.44	180	9.4	260

Table 3: Physical Properties of Soils in Bastar Division (0–15 cm depth)

District's Name	Block's Name	Bulk Density (g cm^{-3})	Particle Density (g cm^{-3})	Porosity (%)	Soil Moisture (%)	Texture Class
Bastar	Bastar	1.32	2.62	49.6	18.4	Sandy loam
Bastar	Tokapal	1.35	2.63	48.7	17.9	Sandy loam
Bastar	Lohandiguda	1.30	2.60	50.0	19.2	Loam
Bastar	Darbha	1.26	2.58	51.2	20.6	Loam
Kondagaon	Kondagaon	1.34	2.62	48.9	18.1	Sandy loam
Kondagaon	Keshkal	1.33	2.61	49.0	18.8	Loam
Dantewada	Dantewada	1.38	2.64	47.7	16.5	Sandy clay loam
Dantewada	Gidam	1.40	2.65	47.2	16.0	Sandy clay loam
Dantewada	Katekalyan	1.42	2.66	46.6	15.6	Clay loam
Bijapur	Bijapur	1.41	2.65	46.8	15.9	Clay loam
Sukma	Sukma	1.45	2.67	45.7	14.8	Clay
Sukma	Chhindgarh	1.44	2.66	45.9	15.0	Clay
Narayanpur	Narayanpur	1.36	2.63	48.3	17.5	Sandy loam

Table 4: Physical Properties of Soils in Bastar Division (15–30 cm depth)

District Name	Block's Name	Bulk Density (g cm^{-3})	Particle Density (g cm^{-3})	Porosity (%)	Soil Moisture (%)	Texture Class
Bastar	Bastar	1.38	2.63	47.5	16.8	Sandy loam
Bastar	Tokapal	1.40	2.64	47.0	16.2	Sandy loam
Bastar	Lohandiguda	1.36	2.62	48.1	17.5	Loam
Bastar	Darbha	1.32	2.60	49.2	18.6	Loam
Kondagaon	Kondagaon	1.39	2.63	47.1	16.9	Sandy loam
Kondagaon	Keshkal	1.37	2.62	47.7	17.2	Loam
Dantewada	Dantewada	1.44	2.66	45.9	15.1	Sandy clay loam
Dantewada	Gidam	1.46	2.67	45.3	14.8	Sandy clay loam
Dantewada	Katekalyan	1.48	2.68	44.8	14.2	Clay loam
Bijapur	Bijapur	1.47	2.67	45.0	14.6	Clay loam
Sukma	Sukma	1.50	2.69	44.2	13.9	Clay
Sukma	Chhindgarh	1.49	2.68	44.4	14.0	Clay
Narayanpur	Narayanpur	1.41	2.64	46.6	16.0	Sandy loam

Figure: 1 & 2. GIS-based block-wise spatial distribution of soil of available pH and available Zn in Bastar Division, Chhattisgarh.


Figure: 3 & 4 .GIS-based block-wise spatial distribution of soil of available Mn and available Cu in Bastar Division, Chhattisgarh.


Figure: 5 & 6.GIS-based block-wise spatial distribution of soil of available Fe and Nitrogen in Bastar Division, Chhattisgarh.

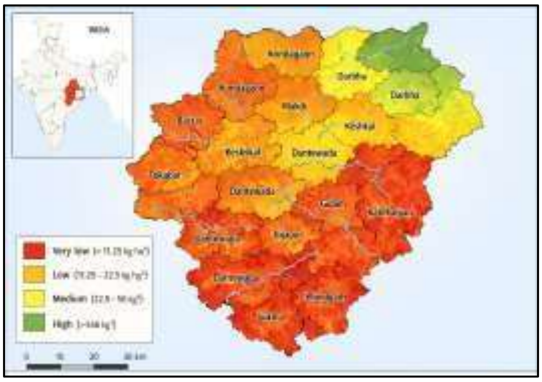


Figure: 7& 8.GIS-based block-wise spatial distribution of soil of available Phosphorus and Potassium in Bastar Division, Chhattisgarh.

Soil texture and bulk density

The soils in the study area were predominantly sandy clay loam to clay loam in texture at both surface (0–15 cm) and subsurface (15–30 cm) depths. The textural composition exhibited slight variation within plantation age groups, indicating the predominance of parent material over management activities. Bulk density values were comparatively lower in older coffee-based agroforestry systems than in younger plantings, especially in the surface layer. The diminished bulk density in mature plantations is due to increased organic matter buildup, ongoing litter deposition, and enhanced soil aggregation beneath shade trees. Comparable tendencies have been observed in long-term coffee agroforestry systems, wherein organic inputs enhance soil physical structure and porosity.

Soil pH and electrical conductivity

The soil pH in the coffee fields varied from mildly acidic to almost neutral, conditions deemed advantageous for coffee cultivation. Surface soils typically demonstrated somewhat reduced pH values relative to deeper layers, likely attributable to organic acid generation from litter breakdown and root activity. Coffee-based agroforestry plots had comparatively steady pH levels in contrast to monoculture plantings, suggesting a buffering effect from organic matter inputs.

Electrical conductivity (EC) measurements were minimal at all locations, signifying non-saline conditions. Elevated EC values in mature plantations may indicate the progressive accumulation of exchangeable bases and nutrient inputs via organic amendments and trash recycling. Nonetheless, all readings remained comfortably under the safe threshold for coffee cultivation, indicating no risk of salinity development in the studied area.

Dynamics of soil organic carbon

The level of soil organic carbon (SOC) had a distinct upward trend with the age of the plantation and was significantly greater in coffee-based agroforestry systems compared to younger or monoculture plants. Surface soils (0–15 cm) exhibited significantly elevated SOC levels in comparison to subsurface soils, underscoring the influence of surface litter deposition and less soil disturbance. The elevated soil organic carbon in mature plantations signifies a continual enhancement in soil quality and carbon sequestration capacity. The ongoing addition of leaf litter, trimmed biomass, and root leftovers in agroforestry systems enhances stable carbon reservoirs and promotes soil aggregation. These findings align with previous research in coffee-growing areas, indicating elevated SOC stocks in shaded coffee systems relative to open or annual cropping systems. This enhancement is especially significant in the Bastar Division, where soils typically possess low to moderate organic matter content.

Macronutrient availability (N, P, and K)

The total nitrogen content exhibited a pattern analogous to that of organic carbon, with elevated values noted in mature agroforestry plantings. This equation illustrates the robust connection between soil organic matter and nitrogen mineralization. Juvenile plantings demonstrated relatively decreased nitrogen concentrations, indicating the necessity for additional fertilizer control in the initial phases of coffee cultivation.

Available phosphorus exhibited significant regional and vertical heterogeneity. In numerous surface soils, accessible phosphorus levels were low to moderate, likely due to phosphorus fixation in acidic soil conditions and the intrinsic low phosphorus status of Bastar soils. While several older farms saw minor enhancements in accessible phosphorus, the findings indicate that phosphorus continues to be a potentially limiting resource for coffee cultivation in the area. This underscores the significance of site-specific phosphorus control as opposed to generalized fertilizer recommendations.

The potassium content varied from medium to high in most plants, with notably greater levels in older crops. The rise in accessible potassium may be linked to the recycling of potassium-rich litter and less leaching losses in shaded systems. Potassium is essential for coffee bean development and stress resilience, and its sufficient presence in agroforestry systems promotes the sustainability of coffee cultivation in the area.

Micronutrient status (Fe, Mn, Zn, and Cu)

DTPA-extractable micronutrients demonstrated significant regional diversity throughout the research area. The concentrations of iron (Fe) and manganese (Mn) were often sufficient to elevated, especially in surface soils, due to the influence of acidic soil reactions and parent material. Zinc (Zn) and copper (Cu) exhibited low to moderate availability in certain areas, particularly in younger plantations, suggesting possible micronutrient limitations.

The elevated availability of micronutrients in mature plantations may be associated with increased organic matter content, which facilitates micronutrient chelation and diminishes fixation. Organic wastes and root exudates in agroforestry systems enhance the mobility and availability of micronutrients for plants. These findings underscore the significance of integrated nutrient management strategies, including organic amendments, for sustaining balanced micronutrient levels in coffee soils.

Spatial variability and GIS-based interpretation

GIS-based geostatistical maps demonstrated clear geographical patterns in soil organic carbon, accessible phosphorus, potassium, and some micronutrients. Regions with long-established coffee-based agroforestry systems consistently demonstrated elevated soil organic carbon (SOC) levels and superior nutrient status, whereas nutrient-deficient areas were predominantly linked to younger plants and freshly converted lands. The regional study revealed the variability of soil fertility even within small geographical regions, emphasizing the inadequacy of consistent fertilizer recommendations. The identification of low-fertility areas by GIS mapping establishes a scientific foundation for targeted soil management, facilitating the efficient utilization of inputs and enhancing the sustainability of coffee farming in Bastar.

Implications for sustainable coffee cultivation

The consolidated findings indicate that coffee-based agroforestry systems enhance the physico-chemical development of soils throughout time. Enhancements in organic carbon, nutrient accessibility, and soil physical properties augment soil resilience and sustained productivity. In a non-traditional coffee-growing region such as Bastar, these systems provide a sustainable land-use alternative that enhances agricultural output while promoting environmental conservation.

CONCLUSION

The study offers a thorough evaluation of the development of physico-chemical properties of coffee-based soils in the Bastar Division of Chhattisgarh, a rising non-traditional coffee cultivation area in India. The findings unequivocally indicate that coffee-based agroforestry systems positively impact soil quality by enhancing organic carbon levels, nutrient accessibility, and the general physical state of the soil over time. Soils beneath mature coffee plantations demonstrated elevated organic carbon levels, enhanced nitrogen status, and superior availability of potassium and micronutrients in comparison to younger plantations and monocropping systems. Despite the soil response being mildly acidic to nearly neutral and conducive to coffee growing, geographic diversity in phosphorus and micronutrient availability was seen throughout the research area, highlighting the necessity for site-specific nutrient management. GIS-based spatial analysis accurately identified nutrient-deficient areas, underscoring the inadequacy of consistent fertilizer recommendations in the varied soils of the Bastar region. The study substantiates that coffee-based agroforestry constitutes a sustainable land-use approach that improves soil health, facilitates efficient nutrient cycling, and sustains the long-term production of coffee plants in Bastar. It is advisable to implement soil testing-based and location-specific management strategies to guarantee the sustainable growth of coffee cultivation in analogous non-traditional agro-ecological areas.

Prospective Outlook

The results of this study give multiple opportunities for more research on coffee-based soil systems in unconventional coffee cultivation areas, including the Bastar Division of Chhattisgarh. Prolonged observation of identical coffee plantations is necessary to confirm the identified patterns in soil physico-chemical parameters and to delineate definitive cause-and-effect linkages between management strategies and the evolution of soil quality. Longitudinal research would yield more robust evidence regarding carbon sequestration capability and nutrient dynamics in coffee-based agroforestry systems.

Future study ought to incorporate biological indicators of soil health, such as microbial biomass carbon, enzymatic activities, and soil respiration, to enhance physico-chemical evaluations and yield a comprehensive understanding of soil dynamics. Correlating soil quality metrics with coffee yield, bean quality, and biochemical characteristics will enhance the significance of soil management advice for farmers and policymakers.

Advanced spatial modeling tools, including as machine learning-based digital soil mapping and remote sensing, can enhance the predictive accuracy of soil fertility maps and facilitate precision fertilizer management. Furthermore, comparative analyses of organic, integrated, and conventional nutrient management strategies in coffee farms would facilitate the identification of sustainable and climate-resilient management practices. Ultimately, extending such studies to additional non-traditional coffee-growing areas of India would facilitate regional comparisons and enhance national policies for sustainable coffee production and soil conservation amid shifting climatic conditions.

REFERENCES

1. Bationo, A., Waswa, B., Kihara, J., & Kimetu, J. (2007). *Advances in integrated soil fertility management in sub-Saharan Africa*. Springer. https://doi.org/10.1007/978-1-4020-5760-1
2. Beer, J., Muschler, R., Kass, D., & Somarriba, E. (1998). Shade management in coffee and cacao plantations. *Agroforestry Systems, 38*(1–3), 139–164. https://doi.org/10.1023/A:1005956528316
3. Behera, S. K., & Singh, D. (2019). Soil nutrient variability and fertility mapping using GIS in tropical regions. *Journal of the Indian Society of Soil Science, 67*(2), 123–134.
4. Bouyoucos, G. J. (1962). Hydrometer method improved for making particle size analyses of soils. *Agronomy Journal, 54*(5), 464–465. https://doi.org/10.2134/agronj1962.00021962005400050028x
5. Brady, N. C., & Weil, R. R. (2017). *The nature and properties of soils* (15th ed.). Pearson Education.
6. FAO. (2019). *Measuring and modelling soil carbon stocks and stock changes in livestock production systems*. Food and Agriculture Organization of the United Nations.
7. Hengl, T., de Jesus, J. M., Heuvelink, G. B. M., Gonzalez, M. R., Kilibarda, M., Blagotić, A., Kempen, B. (2017). SoilGrids250m: Global gridded soil information based on machine learning. *PLOS ONE, 12*(2), e0169748. https://doi.org/10.1371/journal.pone.0169748

8. Isaaks, E. H., & Srivastava, R. M. (1989). *An introduction to applied geostatistics*. Oxford University Press.
9. ISRIC–World Soil Information. (2023). *WoSIS analytical method descriptions*. ISRIC.
10. Jackson, M. L. (1973). *Soil chemical analysis*. Prentice Hall of India.
11. Jenny, H. (1941). *Factors of soil formation: A system of quantitative pedology*. McGraw-Hill.
12. Kumar, S., Lal, R., & Lloyd, C. D. (2012). Assessing spatial variability of soil properties using geostatistics. *Geoderma, 171–172*, 54–64. https://doi.org/10.1016/j.geoderma.2011.12.002
13. Kumar, S., Singh, R., & Sharma, J. P. (2018). Soil fertility evaluation under agroforestry systems in central India. *Agroforestry Systems, 92*, 147–159. https://doi.org/10.1007/s10457-017-0113-2
14. Lal, R. (2015). Restoring soil quality to mitigate soil degradation. *Sustainability, 7*(5), 5875–5895.
15. https://doi.org/10.3390/su7055875
16. Lal, R., Kimble, J. M., Follett, R. F., & Stewart, B. A. (2007). *Soil carbon sequestration and the greenhouse effect*. Soil Science Society of America.
17. Lindsay, W. L., & Norvell, W. A. (1978). Development of a DTPA soil test for zinc, iron, manganese, and copper. *Soil Science Society of America Journal, 42*(3), 421–428. https://doi.org/10.2136/sssaj1978.03615995004200030009x
18. Mandal, B., Majumder, B., Bandyopadhyay, P. K., Hazra, G. C., Gangopadhyay, A., Samantaray, R. N., Mishra, A. K., Chaudhury, J., Saha, M. N., & Kundu, S. (2007). Soil organic carbon pools under different cropping systems. *Soil and Tillage Research, 92*(1–2), 173–183. https://doi.org/10.1016/j.still.2006.03.005
19. Nair, P. K. R. (2011). Agroforestry systems and environmental quality: Introduction. *Journal of Environmental Quality, 40*(3), 784–790. https://doi.org/10.2134/jeq2011.0076
20. Olsen, S. R., Cole, C. V., Watanabe, F. S., & Dean, L. A. (1954). *Estimation of available phosphorus in soils by extraction with sodium bicarbonate*. USDA Circular No. 939.
21. Rayment, G. E., & Lyons, D. J. (2011). *Soil chemical methods: Australasia*. CSIRO Publishing.
22. Singh, K. P., Beena, N., & Kumar, R. (2024). Soil properties and carbon dynamics under coffee-based agroforestry systems in Bastar region of Chhattisgarh, India. *Environmental Development and Sustainability*. https://doi.org/10.1007/s10668-023-04230-9
23. Sparks, D. L. (Ed.). (1996). *Methods of soil analysis: Part 3—Chemical methods*. Soil Science Society of America.
24. Van Noordwijk, M., & Hairiah, K. (2006). Carbon stocks in Indonesian agroforestry systems. *Forest Ecology and Management, 224*(1–2), 63–71. https://doi.org/10.1016/j.foreco.2005.12.005
25. Walkley, A., & Black, I. A. (1934). An examination of the Degtjareff method for determining soil organic matter. *Soil Science, 37*(1), 29–38. https://doi.org/10.1097/00010694-193401000-00003
26. Webster, R., & Oliver, M. A. (2007). *Geostatistics for environmental scientists* (2nd ed.). Wiley. https://doi.org/10.1002/9780470517277