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Altitudinal Influence on Soil Nutrient Availability in Apple Orchards of Dry Temperate Zone of Western Himalayas

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Abstract

The study was conducted during september, 2022 to investigate the influence of altitudinal variation on soil nutrient status in apple orchards located in the Kalpa block of the dry temperate region of the Himalayas. Soil samples were systematically collected from apple orchards situated at different elevations and were thoroughly analysed for various key soil parameters, including soil pH, organic carbon, available nitrogen, phosphorus, potassium, exchangeable Ca and Mg, sulphate-sulphur and micronutrients content. The results revealed that soil pH remained near neutral across all elevations. However, a significant increase in the concentrations of soil organic carbon, available nitrogen, phosphorus, exchangeable Ca and micronutrients was observed with increasing elevation. This enrichment at higher altitudes was largely attributed to lower ambient temperatures, which slowed down microbial activity and decomposition processes, thereby enhancing organic matter accumulation and nutrient retention in the soil. Conversely, the availability of potassium and sulphate-sulphur was found to be higher at lower elevations. This could have resulted from more intense mineral weathering, higher soil temperatures, and the relatively greater use of agrochemicals in lower orchards compared to those situated at higher altitudes. These altitudinal trends emphasized the critical role of elevation in shaping soil fertility dynamics. The study provided valuable insights for the development of location-specific and altitude responsive nutrient management strategies, which are essential for optimizing apple yield and maintaining long term soil health in the ecologically sensitive and climatically diverse Himalayan agroecosystems.

Keywords: soil organic carbon, macronutrients, micronutrients, apple, altitudinal variation

1. Introduction

Soils are continuously influenced by both biotic and abiotic factors (Xiao et al., 2021 and Majid et al., 2023). The surface soil act as a major source of essential mineral nutrients and share a similar composition with the Earth's crust (Bayon et al., 2022). Soils originate from parent materials that gradually transform through various physical, chemical and biological processes influenced by local environmental conditions and living organisms (Ren et al., 2015; Turdi and Yang, 2016). Differences in soil-forming processes across various climatic zones lead to significant variations in nutrient element concentrations (Zhang et al., 2019 and Zhelezova et al., 2019). The natural levels of essential nutrients in soil mainly arise from the weathering of rocks, which releases minerals during the soil formation process (Ribeiro et al., 2020).

Nutrients within the soil are essential indicators of soil fertility and play a critical role in influencing plant growth and ecosystem productivity (Xing et al., 2025; Xu et al., 2021). Their spatial distribution is often heterogeneous, occurring in patches or gradients influenced by a range of natural and anthropogenic factors, including climate conditions, parent material composition, topography, vegetation cover and human interventions such as land management and agricultural practices (Yan et al., 2025). In agricultural landscapes, assessing the soil nutrient status is particularly important for formulating efficient nutrient management and site-specific fertilizer application strategies, which can enhance crop yield while maintaining soil health (Wang et al., 2015; Gogoi et al., 2021). Moreover, differences in land use types and environmental conditions lead to significant variations in nutrient concentration, cycling, and availability within the soil system (Medriano et al., 2023; Zhang et al., 2014). Effective nutrient management plays a vital role in maintaining and enhancing soil health (Bordoloi et al., 2021)

Soil quality is commonly assessed through fertility related characteristics, which serve as key indicators of crop productivity (Maurya et al., 2020). Parameters such as soil organic matter, available nitrogen, phosphorus and potassium are crucial for understanding soil fertility status (Gerke, 2022; Klimkowicz-Pawlas et al., 2019). In mountainous regions like Himachal Pradesh, particularly the dry temperate zone, soil fertility and nutrient dynamics are strongly influenced by the region's topography, climate and land use practices (Kumar et al., 2024). This zone, marked by low precipitation, cold arid to semi-arid conditions and a brief growing season, poses unique challenges for agriculture but also offers specialized advantages (Gangopadhyay, 2023). The Kinnaur district, situated in this zone, is predominantly dependent on horticulture, especially apple cultivation, which serves as the backbone of its economy and a primary source of livelihood for local communities (Sharma et al., 2018). The distinct altitudinal gradients and climatic conditions of Kinnaur create an ideal environment for producing high quality apples with excellent colour and shelf life, making the region nationally and internationally renowned for apple production.

Understanding the chemical properties of soil is vital for developing region-specific soil fertility management strategies, particularly in ecologically sensitive and agriculturally significant regions like the dry temperate zone of Himachal Pradesh. Despite the economic importance of this area especially for apple cultivation, comprehensive studies on soil nutrient status remain limited. Evaluating the current nutrient profile is essential for detecting deficiencies or toxicities, guiding balanced fertilization, and promoting sustainable land-use planning and soil health conservation. Given the pronounced altitudinal gradients and their impact on soil formation and nutrient dynamics, this study focuses on assessing the chemical properties and nutrient availability in apple orchards across varying elevations. The objective is to generate baseline data that supports informed decision-making in agriculture and environmental management, ensuring long-term productivity and ecological balance in the dry temperate Himalayas.

2. Materials and Methods

2.1. Experimental site

The present study was carried out during September 2022 in the Kalpa block, located in the Kinnaur district of Himachal Pradesh, a high-altitude region characterized by rugged terrain, steep river valleys and cold desert landscapes. Situated in the upper Sutlej River basin, the area lay between 31°05′ N to 32°05′ N latitudes and 77°45′ E to 79°00′ E longitudes, with elevations ranging from approximately 2,000 to over 6,000 meters above sea level. The district fell under the dry temperate zone due to its distinct climatic features. Summer temperatures generally fluctuated between 25–30°C, while winters were harsh, with temperatures dropping as low as -17°C. The area received an average of 500 mm of rainfall annually, most of which occurred at lower altitudes, contributing to varied agro-climatic conditions across the region. Soils were generally shallow and sandy to loamy in texture. The diverse altitudinal range and climatic conditions supported a variety of natural vegetation and contributed to the unique ecological and cultural landscape of the area.

2.2. Soil sampling

Surface soil samples (0-20 cm) were collected from 15 apple orchards across three elevation ranges, viz. E1 (1900–2200 m amsl), E2 (2200–2500 m amsl) and E3 (2500–2800 m amsl) from Kalpa to Powari villages in the Kalpa block. A composite sample was prepared by combining 4–5 sub-samples to ensure a more representative and uniform sample of each area. The collected soils were then air-dried to remove moisture. After drying, the samples were gently ground using a wooden pestle and mortar to break down soil aggregates. The ground soil was subsequently sieved through a 2 mm mesh to obtain a consistent particle size suitable for laboratory analysis. Finally, the processed samples were stored in clean plastic containers to protect them from moisture and contamination prior to testing.

2.3. Soil analysis

2.3.1. Soil pH

The soil pH was determined in 1:2 soil:water suspension as per the method given by Jackson (1973).

2.3.2. Soil organic carbon

Soil organic carbon (SOC) was estimated using the wet digestion method given by Walkey and Black (1934). In this process, the oxidizable organic matter in the soil is oxidized by potassium dichromate, with the reaction being accelerated by the heat produced when concentrated sulfuric acid is combined with a 1N potassium dichromate ($K_2Cr_2O_7$) solution. The remaining, unreacted potassium dichromate was then measured through titration using a 0.5N ferrous ammonium sulphate solution, in the presence of a diphenylamine indicator and sodium fluoride (NaF). The amount of organic matter oxidized was calculated based on the quantity of potassium dichromate that was reduced during the reaction.

2.3.3. Available nitrogen

The alkaline potassium permanganate method (Subbiah and Asija, 1956) was used to estimate available nitrogen (N) in soil. In this method, the soil was treated with alkaline $KMnO_4$ and NaOH, which oxidized the organic matter and released ammonia (NH_3). The released ammonia was then distilled and absorbed in boric acid. It was subsequently titrated with standard acid to determine the amount of nitrogen present.

2.3.4. Available phosphorus

The Olsen method (Olsen et al., 1954) was used to estimate available phosphorus (P) in neutral to alkaline soils. In this method, phosphorus was extracted from the soil using a 0.5 M sodium bicarbonate ($NaHCO_3$) solution at pH 8.5. This solution facilitated the release of phosphate ions that were loosely held in the soil and available to plants. After shaking the soil with the extractant, the mixture was filtered and the phosphorus in the filtrate was measured calorimetrically at 660 nm. The intensity of the blue colour formed was proportional to the amount of available phosphorus in the soil.

2.3.5. Available potassium

Available potassium (K) in the soil was determined using the method by Merwin and Peach (1951), where K was extracted with neutral normal ammonium acetate. This extractant displaced exchangeable potassium from soil particles. The extracted K was then measured using a flame photometer, which detected the intensity of light emitted by potassium ions in a flame. The emission intensity was directly proportional to the potassium concentration in the soil sample.

2.3.6. Exchangeable Ca and Mg

Exchangeable Ca and Mg [cmol (p+) kg^{-1}] were determined using Neutral normal ammonium acetate extraction method (Jackson, 1973)

2.3.7. Sulphate sulphur

Sulphate sulphur (S) was extracted by Morgan's reagent (Morgan, 1937) and determined by turbidity method of Chesnin and Yien (1950).

2.3.8. Micronutrient cations (Fe, Cu, Zn and Mn)

Available micronutrients (Fe, Mn, Cu, Zn) were extracted from soil using a DTPA (Diethylenetriaminepentaacetic acid) extractant buffered at pH 7.3, as proposed by Lindsay and Norvell (1978). This chelating agent helped to solubilize the micronutrients bound to soil colloids without affecting the non-available forms. After extraction, the filtered solution was analyzed using an atomic absorption spectrophotometer (AAS), which quantified the concentrations of these metals based on their specific absorption wavelengths.

2.4. Statistical analysis

Descriptive statistics (range, mean, standard deviation and standard error) was used to compare various soil parameters at three elevation ranges and were computed using Microsoft Excel. The correlation matrix among various soil parameters was generated using ggplot2 and GGally packages in the statistical software R (R Core Team, 2013)

3. Results and Discussion

3.1. Soil pH and OC

Data presented in Table 1 revealed that soil pH was found to be near neutral at all elevations. Maximum SOC (24.24 g Kg^{-1}) content was found at elevation E3 and minimum value (20.55 g kg^{-1}) was recorded in elevation E1, respectively.

Table 1: Effect of elevation on soil pH and SOC (g kg^{-1}) in apple orchards

Elevation	Statistic	pH	SOC
E1 (1900-2200 m)			
	Range	6.50-7.19	17.49-24.36
	Mean±SD	6.84 ± 0.31	20.55 ± 3.09
	SE	0.14	1.38
E2 (2200-2500 m)			
	Range	6.50-7.47	14.77-25.33
	Mean±SD	6.93 ± 0.42	22.24 ± 4.36
	SE	0.19	1.95
E3 (2500-2800 m)			
	Range	6.41-6.91	20.30-25.60
	Mean±SD	6.72 ± 0.19	24.24 ± 2.26
	SE	0.09	1.01

Altitude played a significant role in determining the soil carbon pool (Dar and Sundarapandian, 2015). Soil organic carbon was generally higher in soils at higher elevations due to cooler temperatures, which slowed down the decomposition of organic matter by microorganisms, allowing more carbon to accumulate in the soil. Higher elevations tended to promote greater soil organic carbon storage due to favourable environmental conditions (Badgery et al., 2013; Mishra et al., 2021). In contrast, lower elevations typically experienced warmer climates and more intense microbial activity, which accelerated the breakdown of organic matter, leading to reduced organic carbon levels (Hailemariam et al., 2023).

3.2. Available macronutrients (NPK)

Maximum available N (296.00 kg ha^{-1}) and P (47.90 kg ha^{-1}) was recorded in elevation E3 and minimum available N (239.60 kg ha^{-1}) and P (39.28 kg ha^{-1}) was found in elevation E1 (Table 2). Whereas, maximum available K (338.55 kg ha^{-1}) was observed in elevation E1 and minimum (324.56 kg ha^{-1}) content was found in elevation E3, respectively.

Nitrogen was found to be more abundant in higher elevation soils primarily due to slower rates of organic matter decomposition under cooler temperatures, which led to greater accumulation of organic matter, the main reservoir of nitrogen in soils. Carbon and nitrogen levels tended to rise with increasing elevation, due to lower temperatures that reduce respiration rates (Vieira et al., 2011). Additionally, less intensive land use and minimal disturbance at higher elevations preserve soil structure and nutrient content. In contrast, lower elevations often experienced higher temperatures that increased microbial activity and nitrogen mineralization, but also resulted in greater nitrogen losses through processes like volatilization and denitrification.

Available phosphorus content did not vary much among the

Table 2: Effect of elevation on available soil N, P and K (kg ha^{-1}) in apple orchards

Elevation	Statistic	Available N	Available P	Available K
E1 (1900-2200 m)				
	Range	223-262	31.3-42.9	298-372
	Mean± SD	239.60± 14.05	39.28 ± 4.59	338.55 ± 29.79
	SE	6.28	2.05	13.32
E2 (2200-2500 m)				
	Range	223-314	33.9-57.1	311-365
	Mean± SD	269.80 ± 40.16	44.28 ± 8.84	333.10 ± 26.20
	SE	17.96	3.96	11.72
E3 (2500-2800 m)				
	Range	279-329	39.5-57.1	298-361
	Mean± SD	296.00± 9.76	47.90 ± 6.96	324.56 ± 23.12
	SE	8.84	3.11	10.34

three elevation ranges, and was in high range across the sites. Potassium levels were found to decline with increasing elevation. Similar findings were reported by Poubabaei et al., 2020 and Sapkota, 2017, indicating a reduction in potassium content at higher altitudes. This decrease was mainly attributed to greater leaching in the light textured soils, as potassium did not readily bind with organic matter in the soil. Additionally, the rise in base saturation from calcium and magnesium at higher elevations facilitated the leaching of potassium (Seibert et al., 2009).

3.3. Exchangeable Ca, Mg and sulphate sulphur (S)

Data given in Table 3 revealed that maximum exchangeable Ca (13.04 cmol (p$^+$) kg^{-1}) was recorded in elevation E3 and Mg (2.41 cmol (p$^+$) kg^{-1}) was found in elevation E2. However, minimum exchangeable Ca (12.46 cmol (p$^+$) kg^{-1}) and Mg (1.82 cmol (p$^+$) kg^{-1}) was recorded in elevation E1. On the other hand, maximum sulphate sulphur (50.78 kg ha^{-1}) content was found in elevation E1 and minimum (46.00 kg ha^{-1}) content was observed in elevation E3, respectively.

The observed variations in exchangeable calcium (Ca), magnesium (Mg) and sulphate sulphur across different elevations could be attributed to several elevation induced environmental and soil processes. Higher exchangeable Ca content at elevation E3 might be result from slower leaching rates and reduced plant uptake due to lower temperatures, which preserve base cations in the soil. Research suggests that the cooler temperatures and higher humidity typical of mid to high altitudes promoted the accumulation of organic matter, which could partly explain the variation in soil calcium levels observed across different elevations (Li et al., 2022). Conversely, the higher Mg levels at E2 could reflect localized mineral weathering differences in parent material composition. Meanwhile, the elevated sulphate sulphur at E1 could be a result of more active mineralization of organic matter under warmer conditions, enhanced sulphur release and higher usage of agrochemicals.

Table 3: Effect of elevation on soil available macronutrient content in apple

Elevation	Statistic	Exchangeable Ca (cmol (p$^+$) kg^{-1})	Exchangeable Mg (cmol (p$^+$) kg^{-1})	Sulphate S (kg ha^{-1})
E1 (1900-2200 m)				
	Range	9.94-14.13	0.98-3.18	35.50-58.40
	Mean ± SD	12.46± 1.57	1.82 ± 0.87	50.78 ± 9.08
	SE	0.70	0.39	4.06
E2 (2200-2500 m)				
	Range	10.71-14.30	1.66-3.67	24.90-57.30
	Mean ± SD	12.64 ± 1.55	2.41 ± 0.81	49.10 ±13.64
	SE	0.69	0.36	6.10
E3 (2500-2800 m)				
	Range	12.38-13.66	1.29-2.62	29.50-57.30
	Mean ± SD	13.04± 0.57	1.99 ± 0.62	46.00 ± 13.87
	SE	0.26	0.28	6.20

3.4. Micronutrient cations (Zn, Cu, Fe, Mn)

Data presented in Table 4 revealed that maximum micronutrient cations were found in elevation E2 and E3. Maximum Cu (1.64 ppm), Fe (9.83 ppm) and Mn (5.06 ppm) content was recorded in elevation E2 (2200-2500 m MSL), whereas maximum Zn (5.35 ppm) content was recorded in elevation E3 (2500-2800 m MSL).

The slower decomposition rates at these elevations allowed organic matter to accumulate, forming stable complexes with micronutrients and keeping them in plant available forms. Similar trend in micronutrient studies with respect to altitude variation was reported by Charan et al., 2013.

3.5. Correlation studies among soil properties

Soil properties were intricately interconnected and their correlations provided vital insights into soil health and fertility status. These relationships helped identify patterns and interactions that were critical for understanding soil functioning. The correlation among different soil parameters was presented in figure 1.

The data clearly indicated a strong and significant positive relationship between soil organic carbon content and

Table 4: Effect of elevation on soil micronutrients cations in apple

Elevation	Statistic	Zn (ppm)	Cu (ppm)	Fe (ppm)	Mn (ppm)
E1 (1900-2200 m)					
	Range	3.42-5.32	1.20-1.80	6-16.04	1.38-6.66
	Mean±SD	4.15± 0.70	1.35 ± 0.21	6.00 ± 1.41	3.61 ± 0.17
	SE	0.32	0.15	1.00	0.12
E2 (2200-2500 m)					
	Range	3.14-5.16	1.18-2.08	7.74-13.94	3.50-7.36
	Mean±SD	4.30 ± 0.98	1.64 ± 0.34	9.83± 2.66	5.06± 1.46
	SE	0.44	0.15	1.19	0.65
E3 (2500-2800 m)					
	Range	3.62-7.64	0.80-2.08	6.92-15.22	3.90-5.76
	Mean±SD	5.35 ± 1.48	1.23 ± 0.51	11.42 ± 3.75	4.91 ± 0.77
	SE	0.66	0.23	1.68	0.34

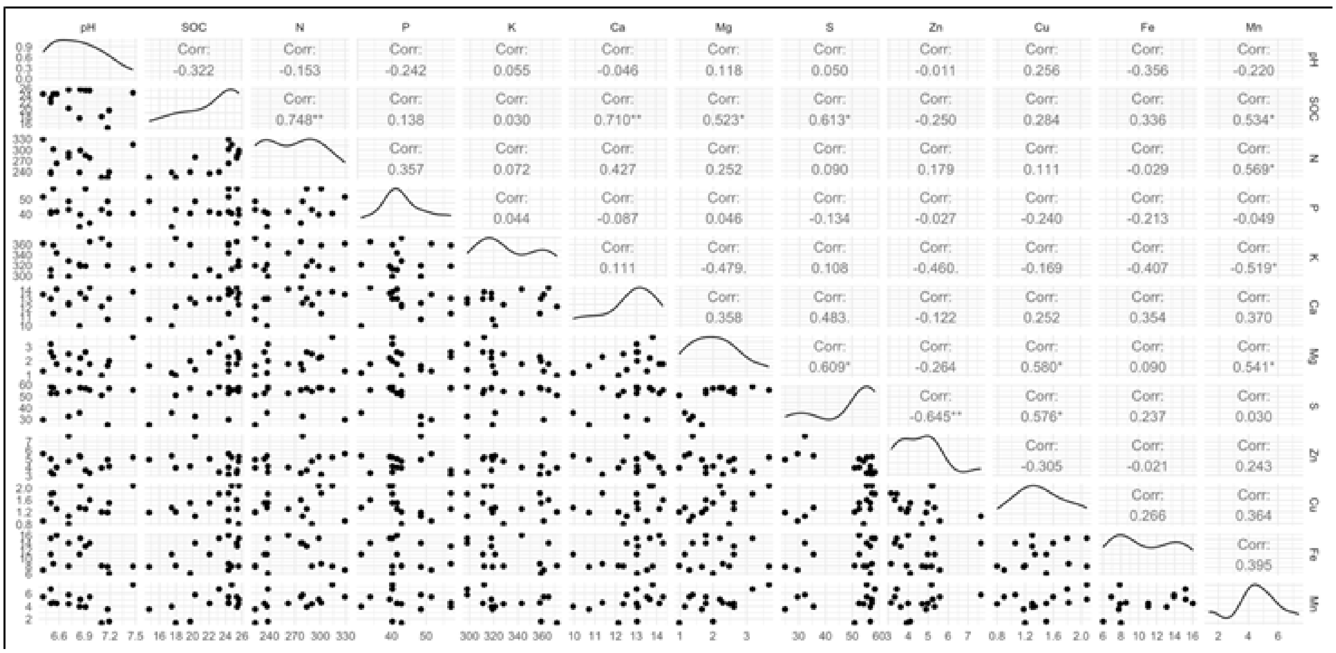

Figure 1: Correlation (r-values) among different soil parameters

available nitrogen (r=0.74**) and Ca (r=0.71**) content in soil, suggesting that as organic carbon levels increase, the availability of nitrogen and calcium in the soil also improved. This relationship likely reflected the role of organic matter in enhancing nitrogen retention and mineralization. Among the micronutrients assessed, zinc demonstrated a negative and significant correlation with sulphur (r=-0.64**) content in the soil, indicating an inverse relationship between the two nutrients. This suggested that as the availability of sulphur increases, the concentration of zinc tended to decrease and vice versa. Such interactions were likely attributed to antagonistic effects during nutrient uptake or competition for adsorption sites in the soil matrix. Understanding this negative correlation was crucial for developing balanced fertilization strategies, as the excessive application of one nutrient could potentially suppress the availability or uptake of the other, ultimately impacting crop growth and productivity.

4. Conclusion

The study conducted in the dry temperate zone of Western Himalayas revealed a clear altitudinal gradient in soil nutrient availability. Soil organic carbon, available nitrogen, phosphorus and micronutrients increased with elevation, likely due to cooler temperatures, reduced microbial decomposition and greater organic matter accumulation at higher altitudes. Conversely, potassium content was found to be higher at lower elevations, which may have been attributed to higher mineral weathering rates in warmer, lower-altitude zones. These findings highlighted the importance of considering elevation in nutrient management strategies for sustainable apple cultivation in the region.

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6. References

Badgery, W.B., Simmons, A.T., Murphy, B.M., Rawson, A., Andersson, K.O., Lonergan, V.E., 2013. Relationship between environmental and land-use variables on soil carbon levels at the regional scale in central New South Wales, Australia. Soil Research 51, 645–656.

Bayon, G., Bindeman, I.N., 2022. Long-term evolution of terrestrial weathering and its link to earth's oxygenation. Earth and Planetary Science Letters 584, 117490.

Bordoloi, A., Sarmah, A.C., Pathak, P.K., 2021. Soil nutrient in different tea gardens of Tinsukia district of Assam. International Journal of Economic Plants 8(3), 143–148.

Charan, G., Bharti, V.K., Yadhav, S.E., Kumar, S., Acharya, S., Kumar. P., Gogoi, D., Srivastava, R.B., 2013. Altitudinal variations in soil physicochemical properties at cold desert high altitude. Journal of Soil Science and Plant Nutrition 13(2), 267–277.

Chesnin, L., Yien, C.H., 1950. Turbidimetric determination of available sulphates. Soil Science Society of America Proceedings 15, 149–151.

Dar, J.A., Sundarapandian, S., 2015. Variation of biomass and carbon pools with forest type in temperate forests of Kashmir Himalaya, India. Environmental Monitoring and Assessment 187(2), 1–17.

Gangopadhyay, S.K., 2023. Temperate soils of India with special reference to soil carbon and their management. Indian Journal of fertilizers 19(5), 436–455.

Gerke, J., 2022. The central role of soil organic matter in soil fertility and carbon storage. Soil Systems 6(2), 33.

Gogoi, B., Borah, N., Baishya, A., Nath, D.J., Dutta, S., Das, R., Bhattacharyya, D., Sharma, K.K., Valente, D., Petrosillo, I., 2021. Enhancing soil ecosystem services through sustainable integrated nutrient management in double rice-cropping system of North-East India. Ecological Indicators 132, 108262.

Hailemariam, M.B., Woldu, Z., Zemede, A., Ermia, L., 2023. Impact of elevation change on the physicochemical properties of forest soil in south omo zone, Southern Ethiopia, Hindawi. Applied and Environmental Soil Science 17, 7305618.

Jackson, M.L., 1973. Soil Chemical analysis. Prentice Hall of India Pvt. Ltd., New Delhi.

Klimkowicz-Pawlas, A., Maliszewska-Kordybach, B., Smreczak, B., 2019. Triad-based screening risk assessment of the agricultural area exposed to the long-term PAHs Contamination. Environmental Geochemistry and Health 41, 1369–1385.

Kumar, J., Bhardwaj, D.R., Thakur, C.L., Sharma, P., Sharma, P., 2024. Soil organic carbon dynamics under different land use systems in dry temperate ecosystem of north-western Himalayas. Catena 240, 108022.

Li, C., Xiao, C., Li, M., Xu, L., He, N., 2022. A global synthesis of patterns in soil organic matter and temperature sensitivity along the altitudinal gradient. Frontiers in Environmental Science 10, 959292.

Lindsay, W.H., Norvell, W.A., 1978. Development of DTPA soil test for Zn, Fe, Mn and Cu. Soil Science Society of American Journal 42, 420–428.

Majid, N., Bahar, M.M., Harper, R., Megharaj, M., Naidu, R., 2023. Influence of biotic and abiotic factors on the development of non-wetting soils and management approaches: A review. Soil Security 11, 100091.

Maurya, S., Abraham, J.S., Samasundaram, S., Toteja, R., Gupta, R., Makhija, S., 2020. Indicators for assessment of soil quality: a mini-review. Environmental Monitoring and Assessment 192, 604.

Medriano, C.A., Chan, A., Sotto, R.D., Bae, S., 2023. Different types of land use influence soil physiochemical properties, the abundance of nitrifying bacteria, and microbial interactions in tropical urban soil. Science of the Total Environment 869, 161722.

Merwin, H.D., Peach, M., 1951. Exchangeability of soils potassium in the silt and clay fractions as influenced by the nature of the complimentary exchangeable cations. Soil Science Society of American Proceedings 15, 125–128.

Mishra, U., Hugelius, G., Shelef, E.,Yang, Y.H., Strauss, J., Lupachev, A., 2021. Spatial heterogeneity and environmental predictors of permafrost region soil organic carbon stocks. Science Advances 7, 12.

Morgan, M.L., 1937. Universal soil testing system. Connecticut State Agriculture Experiment Bulletin 292, 129–159.

Olsen, S.R., Cole, C.V., Watanable, F.S., Dean, L.A., 1954. Estimation of available phosphorus in soil by extraction with sodium bicarbonate. USDA Circular 939, 1–19.

Pourbabaei, H., Salehi, A., Ebrahimi, S.S., Khodaparast, F., 2020. Variations of soil physicochemical properties and vegetation cover under different altitudinal gradient, western hyrcanean forest, north of Iran. Journal of Forest Science 66(4), 159–169.

R Core Team, 2013. R A language and environment for statistical computing, Vienna, Austria.

Ren, C., Wang, L., Zheng, B., Holbach, A., 2015. Total nitrogen sources of the three gorges reservoir - a spatio-temporal approach. Public Library of Science, 10.

Ribeiro, I.D.A., Volpiano, C.G., Vargas, L.K., Granada, C.E., Lisboa, B.B., Passaglia, L.M.P., 2020. Use of mineral weathering bacteria to enhance nutrient availability in crops: A Review. Frontiers in Plant Science 11, 590774.

Sapkota, M., 2017. Variation in soil nutrient variables in relation to altitude and aspects in Sikilsdalen and Heimdalen of Southeast Norway, University College of Southeast Norway, Notodden, NW, USA.

Seibert, J., Grabs, T., Laudon, H., Winterdahl, M., Bishop, K., 2009. Linking soil and stream water chemistry based on a riparian Gow concentration integration model. Hydrology and Earth System Sciences 13(12), 2287–2297.

Sharma, S., Sharma, V.K., Sharma, S.D., 2018. Nutritional status of apple orchards in Kinnaur region of Himachal Pradesh. Indian Journal of Horticulture 75(1), 39–47.

Subbiah, B.V., Asija, G.L., 1956. Rapid method for estimation of available nitrogen in soils. Current Science 25, 259–260.

Turdi, M., Yang, L., 2016. Trace elements contamination and human health risk assessment in drinking water from the agricultural and pastoral areas of Bay County, Xinjiang, China. International Journal of Environmental Research and Public Health 13, 938.

Vieira, S.A., Alves, L.F., Duarte-Neto, P.J., Martins, S.C., Veiga, L.G., 2011. Stocks of carbon and nitrogen and partitioning between above-and belowground pools in the Brazilian coastal Atlantic Forest elevation range. Ecology and Evolution 1(3), 421–434.

Walkley, A., Black, I.A., 1934. Examination of the method for determining soil organic matter and a proposed modification of the chromic acid titration method. Soil Science 37, 29–38.

Wang, R., Kang, Y., Wan, S., 2015. Effects of different drip irrigation regimes on saline-sodic soil nutrients and cotton yield in an arid region of Northwest China. Agricultural Water Management 153, 1–8.

Xiao, H.B., Shi, Z.H., Li, Z.W., Chen, J., Huang, B., Yue, Z.J., Zhan, Y.M., 2021. The regulatory effects of biotic and abiotic factors on soil respiration under different land-use types. Ecological Indicators 127, 107787.

Xing, Y., Wang, X., Mustafa, A., 2025. Exploring the link between soil health and crop productivity. Ecotoxicology and Environmental Safety 289(1), 117703.

Xu, H., Yu, M., Cheng, X., 2021. Abundant fungal and rare bacterial taxa jointly reveal soil nutrient cycling and multifunctionality in uneven-aged mixed plantations. Ecological Indicators 129, 107932.

Yan, P., Zhou, P., Lei, S., Tan, Z., Chen, H., Huang, J., 2025. Spatial distribution of soil nutrients in the red beds of southern China and their responses to different land use types. Forests 16(3), 417.

Zhang, X., Wang, Q., Gilliam, F.S., Wang, Y., Cha, F., Li, C., 2014. Spatial variation in carbon and nitrogen in cultivated soils in Henan Province, China: Potential effect on crop yield. Public Library of Science, 917–925.

Zhang, Y.Y., Wu, W., Liu, H., 2019. Factors affecting variations of soil pH in different horizons in hilly regions. Public Library of Science 14(6), 0218563.

Zhelezova, A., Chernov, T., Tkhakakhova, A., Xenofontova, N., Semenov, M., Kutovaya, O., 2019. Prokaryotic community shifts during soil formation on sands in the tundra zone. Public Library of Science 14(4), 206777.

