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SOIL PHYSICOCHEMICAL CHARACTERISTICS AND THEIR ROLE IN SUSTAINABLE NUTRIENT MANAGEMENT

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ABSTRACT

The physicochemical soil properties are the factors that determine nutrient retention, transformation and availability, and soil depth and agricultural management can significantly change these relationships. This study aimed to characterize soil physicochemical properties and nutrient status across soil depths, evaluate the effects of nitrogen application and crop rotation, and identify major physicochemical drivers of nutrient variation. One hundred and eight observations were analysed on 27 experimental plots at three nitrogen rates, three crop rotations, three blocks and four depths. Descriptive statistics, repeated-measures analysis, factorial models, Spearman correlation analysis, principal component analysis, and cluster-robust multivariable regression were used to evaluate the cation exchange capacity, pH, soil organic matter, water-stable aggregates, bulk density, nitrate nitrogen, ammonium nitrogen, total inorganic nitrogen, Bray-extractable phosphorus and potassium. All measured characteristics were highly influenced by soil depth, with the highest concentrations of soil organic matter and nutrients found in the top layer of soil. Crop rotation significantly influenced CEC, pH, WAS, NO3, and K, while nitrogen rate significantly affected NO3. There were especially high positive correlations between soil organic matter and the NH4s and TIN, and soil organic matter was an independent predictor of both nutrients. pH, bulk density and CEC were also identified as nutrient-specific variables by multivariable models. The three main components accounted for 72.11 % of the total variance. The results confirm the need for nutrient-management strategies using soil depth, cropping and nutrient application, and physicochemical conditions rather than nutrient concentrations alone.

Keywords: soil physicochemical properties, nutrient availability, soil organic matter, nitrogen management, crop rotation

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1.Introduction

Soil physicochemical properties are basic aspects of soil fertility, soil nutrient availability and the ability of agricultural soils to support crop production. The soil properties, including pH, cation exchange capacity (CEC), soil organic matter (SOM), aggregation and soil bulk density, govern nutrient retention, mobility, root accessibility, and overall soil functioning. These interactions can determine the availability of nutrients in the root zone or their ability to be fixed or lost. Hence, soil quality evaluation must be done by taking into account soil physical and chemical properties as interdependent rather than separate (Tale & Ingole, 2015). These qualities also change depending on land management and environmental conditions, causing soil nutrient supporting capacity (Kokeb, 2015) differences. Sustainable nutrient management strives to get the right amount of nutrients in place, while minimizing nutrient losses and degradation of soil quality. The use of fertilization may be useful to help make nutrients available and to increase crop productivity, but its usefulness will be limited by soil and cropping conditions. Therefore, the integrated management of soil and crops is crucial to ensure both sustainable agriculture and agricultural productivity (Shah & Wu, 2019). Management can influence at the same time soil structure, nutrient pools and biological processes. Moisture regime and organic amendments, for instance, have been linked with changes in physicochemical properties of soil and microbial nutrient turnover (Bhanwaria et al., 2022).

SOM plays a particularly important role since it not only has a nutrient storage function, but also affects several physical and chemical properties of the soil. Organic matter influences the availability of nutrients, aggregation, exchange characteristics, moisture relations and biological activity, thus having a close relationship with overall nutrient status (Bashir et al., 2021). The soil physicochemical conditions are also related to mineral composition, pore structure, water relations, acidity and nutrient exchange, which all play a role in the regulation of nutrient transformations and availability (Naga Raju et al., 2016). Nutrient concentrations should thus be considered along with the physicochemical properties that determine nutrient distribution. These relationships are very variable with respect to soil depth. There is a vertical variation of organic inputs, root activity, water movement, mineral processes and management disturbances within the soil profile. Soil profile assessment is crucial in evaluating soil conditions, as differences in soil properties between soil depths can have significant effects on physicochemical properties (Tumayro & Tesgaye, 2021). There is also vertical variation in the physical and chemical properties of the soil, which has also been recorded in different soil profiles (Joshi & Negi, 2015). Nutrient status based on surface measurements may thus be misleading, especially when organic matter and nutrients are well stratified. The cycling of nutrients is tightly linked to the carbon cycle, as decomposition, stabilization and mineralization of organic matter affect the availability and nutrient pool of nutrients (Powlson et al., 2015). SOM also plays a role in soil structure, soil water dynamics, nutrient availability and other soil functions (Murphy, 2015). Therefore, soil fertility is not solely based on the nutrients present in the soil but also on the interactions between nutrient availability, organic matter, soil reaction, biological processes and management conditions (Javed et al., 2022). Simultaneous changes in more than one soil indicator as a response to environmental changes can create wider soil patterns as well (Sheng et al., 2018). These interrelated processes can be impacted by agricultural management. Nitrogen fertilization affects soil nitrogen availability directly, while crop rotation might have indirect effects on nutrient uptake, residue inputs, soil organic matter dynamics and soil structural conditions. Soil depth and nitrogen rate in combination with crop rotation can thus be used to gain a fuller knowledge of nutrient distribution in managed soils. This is especially important when assessing nutrient status based on the physicochemical properties rather than its descriptive characteristics.

Most of the knowledge is available for individual soil properties, but there is relatively little information available to connect the physicochemical properties of soils with nutrient status, soil depth, nitrogen application and crop rotation. Nutrient measurements alone are not sufficient to establish the actual correlation that exists between soil and nutrient variability, and simple correlations are not sufficient to establish if a correlation exists after considering other soil and management factors. These limitations can be overcome by incorporating depth-wise comparisons, management effects, association analysis, multivariate modelling, and multivariate characterization in a synthesis to support evidence of sustainable nutrient management.

The present study was aimed at characterizing the soil physicochemical properties with depth, assessing the impact of application rates of nitrogen and crop rotation on soil characteristics and highlighting the most significant physicochemical factors controlling soil nutrient status through correlations, multivariable modelling and principal component analysis. The objectives serve as an overarching approach to soil nutrient distribution, and as a means to more informed nutrient-management approaches.

2. Methodology

2.1 Research Design

The soil physicochemical properties and their relationship with the nutrient status were assessed in a quantitative analytical design under various soil depths and soil management. A total of 108 observations were made from 27 experimental plots, which included three application rates of nitrogen (0, 202, and 269 kg ha-1), three crop rotations (CCC, Cs, and Sc), and three blocks and four soil depths (0–15, 15–30, 30–60, and 60–90 cm). Physicochemical variables comprised Soil Organic Matter (SOM), Cation Exchange Capacity (CEC), Soil pH (pH), Water-Stable Aggregates (WAS) and Bulk Density (BD). Nutrient variables included in the analysis were Bray-extractable phosphorus (Bray-P), potassium (K), nitrate nitrogen (NO3), ammonium nitrogen (NH4s), and total inorganic nitrogen (TIN).

2.2 Data Source

The data on which this article is based were drawn from research data reported by Villamil (2022) that was publicly available. The observations were soil measurements at four depths, under various nitrogen fertilization and crop rotation treatments. Relevant soil physicochemical and nutrient variables were chosen for analysis.

2.3 Data Preparation and Descriptive Analysis

The data were checked for missing values, duplicate observations, experimental balance and inconsistencies. All 108 observations were retained for analysis. The descriptive statistics were mean, standard deviation (SD), median, interquartile range (IQR), range and coefficient of variation (CV). The distributional characteristics were determined by skewness, kurtosis, the Shapiro-Wilk test and IQR criterion for potential outliers. NO3, NH4s, TIN, Bray-P and K were highly skewed and so were log1p transformed for inferential analysis but reported as original data for descriptive purposes.

2.4 Soil Depth and Management Effects

Analysis of the differences among the four soil depths was made by repeated measures analysis, as the data were obtained from common plots. All data were analysed on their original scale except for those data which were log1p transformed (NO3, NH4s, TIN, Bray-P, and K). Paired t-tests or Wilcoxon signed-rank tests as appropriate, with Holm adjustment for multiple comparisons, were performed for significant depth effect. Factorial models with crop rotation, nitrogen rate, crop rotation by nitrogen rate and block were used for assessing the management effects. Analysis was done at the plot level to maintain the experimental design. The size of the observed management effects was estimated using partial eta squared (ηp^2).

2.5 Physicochemical–Nutrient Associations and Principal Component Analysis

Spearman rank correlation coefficients (ρ) were used to assess the relationship between CEC, pH, SOM, WAS, and BD with the nutrient variables, NO3, NH4s, TIN, Bray-P and K. To control for multiple comparisons, the Benjamini–Hochberg false-discovery-rate (FDR) procedure was used. To describe the multivariate structure of the soil variables, Principal component analysis (PCA) was carried out. Before analysis, variables were standardised; log1p-transformed values for NO3, NH4s, TIN, Bray-P and K were used, and components with at least 70% of the cumulative variance were retained. Principal gradients and differences between soil depths were characterized by component loadings and scores.

2.6 Multivariable Modelling and Sensitivity Analysis

Multivariable regression models were created for each of the following models: NO3, NH4s, TIN, Bray-P, and K, and the main predictors were CEC, pH, SOM, WAS, and BD, with adjustment variables of soil depth, nitrogen rate, and crop rotation. Cluster-robust standard errors were estimated at the plot level to account for dependence among observations from the same experimental plot. Variance inflation factors (VIFs) were used to assess multicollinearity. Some model diagnostics were used: residual normality, Breusch–Pagan test, Ramsey RESET test, Cook's distance and leverage statistics. Sensitivity analyses were performed by refitting the models without influential observations for the outcomes identified using Cook's distance. A p-value of < 0.05 was considered statistically significant.

3. Results

3.1 Overall Soil Physicochemical and Nutrient Characteristics

There were 108 soil observations on 27 experimental plots over three nitrogen-rate treatments, three crop rotations, three blocks, and four sampling depths to create the analytical dataset. Observations were recorded at all plots at each depth, and there were no missing values for the analytical variables. Table 1 shows the overall physicochemical and nutrient characteristics of the soil samples. Cation exchange capacity (CEC) averaged 18.93 ± 1.70, while soil pH averaged 6.60 ± 0.46. Soil organic matter (SOM) averaged 2.82 ± 1.03, water-stable aggregates (WAS) averaged 72.39 ± 8.36, and bulk density (BD) averaged 1.37 ± 0.10. Nutrient concentrations showed significantly greater variation than most of the physicochemical properties. NO3 exhibited the greatest relative variability (CV = 138.85%), followed by NH4s (118.60%), total inorganic nitrogen (TIN; 95.32%), Bray-P (83.64%), and K (55.59%). However, the lowest level of variation was found for pH (CV = 6.91%).

Table 1. Descriptive statistics of soil physicochemical and nutrient variables

Variable	n	Mean ± SD	Median (IQR)	Range	CV (%)
CEC	108	18.93 ± 1.70	19.06 (17.71–20.08)	14.09–22.56	8.96
pH	108	6.60 ± 0.46	6.70 (6.50–6.80)	4.30–7.40	6.91
SOM	108	2.82 ± 1.03	3.05 (1.81–3.67)	1.00–4.89	36.47
WAS	108	72.39 ± 8.36	73.38 (66.60–79.43)	49.73–86.79	11.55
BD	108	1.37 ± 0.10	1.37 (1.30–1.42)	1.11–1.65	7.38
NO3	108	4.53 ± 6.28	2.33 (1.26–5.41)	0.20–46.41	138.85
NH4s	108	7.85 ± 9.31	5.12 (1.70–9.78)	0.06–43.34	118.60
TIN	108	12.37 ± 11.79	7.57 (3.80–17.52)	0.89–57.01	95.32
Bray-P	108	13.58 ± 11.36	10.00 (6.00–14.25)	2.00–72.00	83.64
K	108	104.91 ± 58.32	88.50 (65.50–111.50)	29.00–397.00	55.59

Note: SD, standard deviation; IQR, interquartile range; CV, coefficient of variation; CEC, cation exchange capacity; SOM, soil organic matter; WAS, water-stable aggregates; BD, bulk density; TIN, total inorganic nitrogen.

3.2 Depth-Wise Variation in Soil Characteristics and Nutrient Status

Soil depth showed a great variation in all 10 characteristics measured. The mean and test results for repeated measurements are presented in Table 2. SOM exhibited the strongest depth effect ($F = 880.36$, $p < 0.001$), decreasing progressively from 3.87 ± 0.37 at 0–15 cm to 1.37 ± 0.16 at 60–90 cm. TIN similarly decreased from 23.06 ± 12.75 to 5.17 ± 8.14 across the soil profile ($F = 114.55$, $p < 0.001$). Surface soil also contained the highest NO3 (8.62 ± 10.07), NH4s (14.38 ± 9.49), Bray-P (26.44 ± 14.88), and K (188.70 ± 54.98). In addition, significant depth effects were found for CEC, pH, WAS and BD (all < 0.01). WAS followed a non-monotonic profile, increasing from 64.80 ± 5.33 at 0–15 cm to 79.39 ± 5.25 at 30–60 cm before decreasing at 60–90 cm.

Table 2. Depth-wise variation in soil physicochemical and nutrient characteristics

Variable	0–15 cm	15–30 cm	30–60 cm	60–90 cm	F	df	p-value
CEC	19.39 ± 2.15	19.33 ± 1.30	18.01 ± 1.38	19.01 ± 1.53	5.46	3, 78	0.0019
pH	6.40 ± 0.75	6.55 ± 0.30	6.69 ± 0.26	6.78 ± 0.23	6.43	3, 78	<0.001
SOM	3.87 ± 0.37	3.50 ± 0.38	2.53 ± 0.38	1.37 ± 0.16	880.36	3, 78	<0.001
WAS	64.80 ± 5.33	76.96 ± 5.71	79.39 ± 5.25	68.40 ± 7.07	52.05	3, 78	<0.001
BD	1.37 ± 0.12	1.45 ± 0.08	1.30 ± 0.08	1.37 ± 0.07	21.01	3, 78	<0.001
NO3	8.62 ± 10.07	5.19 ± 5.01	2.61 ± 1.99	1.69 ± 1.45	39.88	3, 78	<0.001
NH4s	14.38 ± 9.49	8.58 ± 8.16	4.85 ± 7.75	3.59 ± 8.18	106.42	3, 78	<0.001
TIN	23.06 ± 12.75	13.77 ± 9.00	7.46 ± 7.91	5.17 ± 8.14	114.55	3, 78	<0.001
Bray-P	26.44 ± 14.88	10.70 ± 7.29	6.04 ± 1.95	11.15 ± 2.66	85.12	3, 78	<0.001
K	188.70 ± 54.98	93.81 ± 12.12	59.93 ± 15.02	77.19 ± 16.80	206.10	3, 78	<0.001

Note: Values are mean ± SD. Repeated-measures tests for NO3, NH4s, TIN, Bray-P, and K were conducted using log1p-transformed values; descriptive values are presented on their original scales.

The depth profiles of the physicochemical and nutrient variables have been standardized and the results are presented in Figure 1. The standardized representation shows clear vertical zonation, especially in the surface enrichment of SOM and nutrient variables and their general decrease in the deeper horizons. Figure 1A shows that SOM declined consistently with increasing soil depth, while pH increased and WAS reached its highest standardized level at 30–60 cm. Figure 1B indicates that NO3, NH4s, TIN, Bray-P, and K were mostly found in the 0-15 cm soil depth with generally lower standardized levels at deeper soil depths.

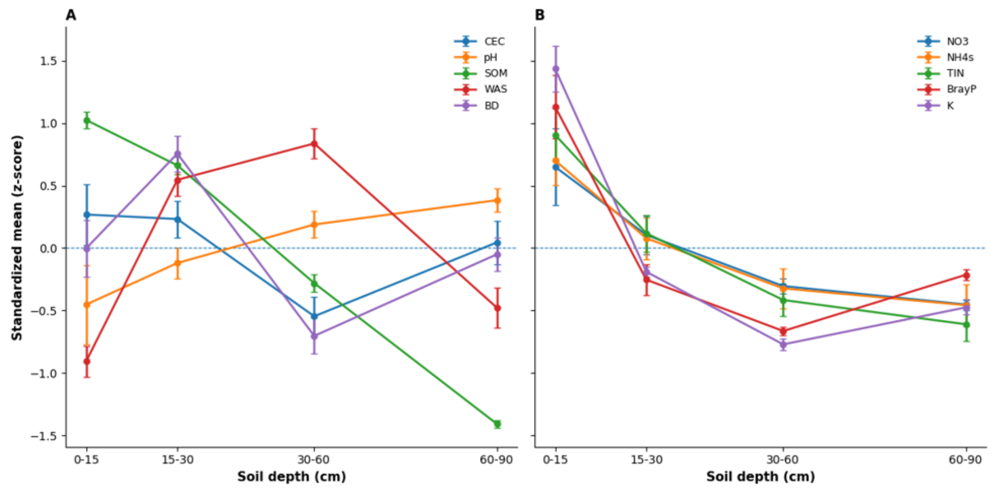

Figure 1. Depth-wise variation in soil physicochemical characteristics and nutrient status. (A) Standardized depth profiles of CEC, pH, SOM, WAS, and BD. (B) Standardized depth profiles of NO3, NH4s, TIN, Bray-P, and K.

3.3 Effects of Nitrogen Rate and Crop Rotation

The effects of management were highly variable by the measured soil characteristics. The effects of N rate, crop rotation and their interaction on physicochemical and nutrient variables are shown in Table 3. Crop rotation significantly affected CEC ($p = 0.0038$, partial $\eta^2 = 0.501$), pH ($p < 0.001$, partial $\eta^2 = 0.606$), WAS ($p = 0.0135$, partial $\eta^2 = 0.416$), NO3 ($p = 0.0087$, partial $\eta^2 = 0.447$), and K ($p = 0.0073$, partial $\eta^2 = 0.460$). Nitrogen rate had a significant main effect on NO3 ($p = 0.0033$, partial $\eta^2 = 0.511$). Significant nitrogen rate × rotation interactions were detected for CEC ($p = 0.0369$, partial $\eta^2 = 0.453$) and NO3 ($p = 0.0056$, partial $\eta^2 = 0.579$). There were no significant main or interaction effects for NH4s or TIN.

Table 3. Effects of nitrogen rate, crop rotation, and their interaction on soil characteristics

Variable	N rate p	N rate ηp²	Rotation p	Rotation ηp²	N rate × rotation p	N rate × rotation ηp²
CEC	0.8054	0.027	0.0038	0.501	0.0369	0.453
pH	0.1121	0.239	<0.001	0.606	0.2318	0.281
SOM	0.7800	0.031	0.0547	0.305	0.9715	0.030
WAS	0.4792	0.088	0.0135	0.416	0.1720	0.314
BD	0.0851	0.265	0.1312	0.224	0.9703	0.031

NO3	0.0033	0.511	0.0087	0.447	0.0056	0.579
NH4s	0.8699	0.017	0.4629	0.092	0.8142	0.088
TIN	0.5491	0.072	0.1266	0.228	0.3367	0.235
Bray-P	0.0537	0.306	0.6052	0.061	0.3979	0.213
K	0.3391	0.126	0.0073	0.460	0.1193	0.352

Note: ηp², partial eta squared. NO3, NH4s, TIN, Bray-P, and K were analysed on log1p-transformed scales. Significant effects ($p < 0.05$) are shown in bold.

The results for nitrogen-rate × crop-rotation response for soil NO3 are presented in Figure 2. Under CCC, profile-mean NO3 increased from 1.52 at zero N to 8.95 at N rate 202 and 12.48 at N rate 269. The response under Cs was substantially weaker than under CCC, while Sc showed little monotonic response across nitrogen rates. This pattern accompanied significant N-rate ($F = 8.36$, $p = 0.0033$), rotation ($F = 6.48$, $p = 0.0087$), and interaction effects ($F = 5.49$, $p = 0.0056$). Points are the profile-mean NO3 concentrations and error bars are standard errors between replicate plots.

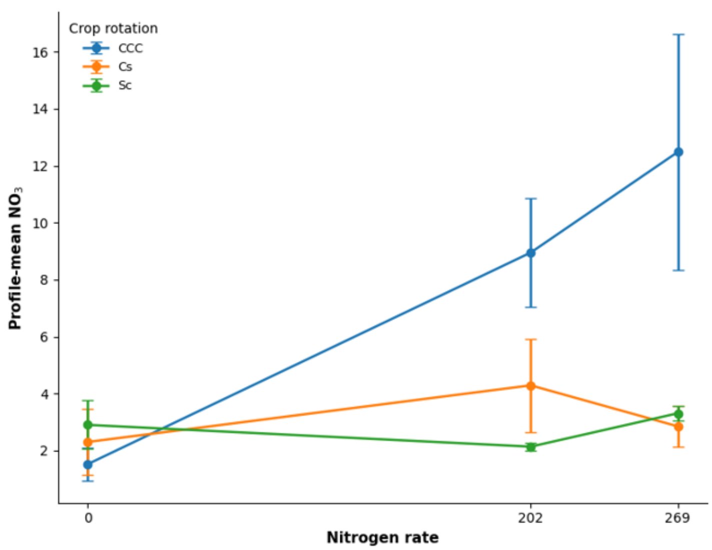

Figure 2. Interactive effects of nitrogen application rate and crop rotation on soil nitrate status.

3.4 Associations Between Physicochemical Characteristics and Nutrient Status

Unique relationships were found between soil physicochemical properties and soil nutrient status. The Spearman correlations for the five physicochemical characteristics on the five nutrient variables are shown in Figure 3, after false-discovery-rate correction. Fourteen of the 25 physicochemical–nutrient associations remained significant after FDR correction. SOM showed the strongest positive relationships, particularly with NH4s (ρ = 0.797), TIN (ρ = 0.781), K (ρ = 0.677), and NO3 (ρ = 0.537), with an additional positive association with Bray-P (ρ = 0.374). WAS was negatively associated with Bray-P (ρ = −0.556) and K (ρ = −0.433). Soil pH was negatively correlated with NO3 (ρ = −0.428) and TIN (ρ = −0.283). After FDR correction, CEC was positively related to NH4s, TIN, Bray-P and K, while BD was only positively related to Bray-P. Cell values are Spearman correlation coefficient (ρ) values; asterisks denote significant correlations (adjusted p < 0.05) after Benjamini–Hochberg false-discovery-rate correction.

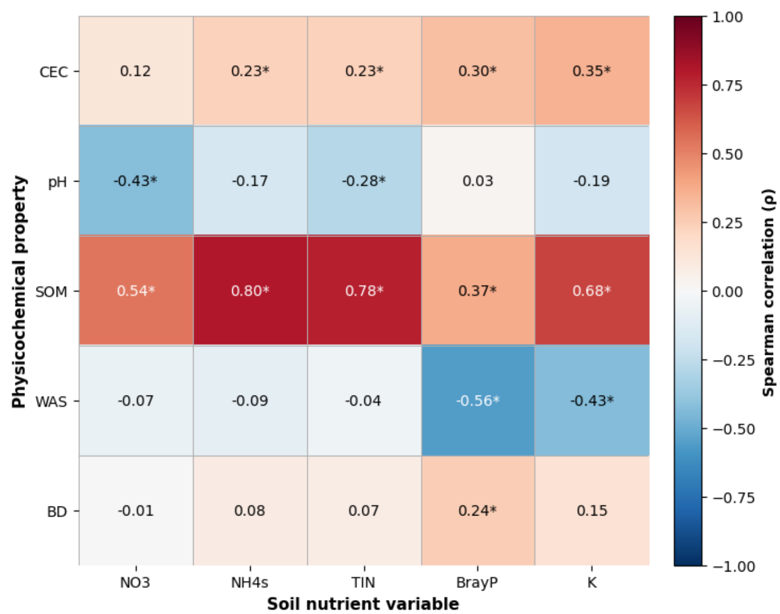

Figure 3. Spearman correlations between soil physicochemical characteristics and nutrient variables.

3.5 Independent Physicochemical Predictors of Soil Nutrients

After accounting for soil depth, nitrogen rate and crop rotation, the independent associations of each physicochemical characteristic and nutrient status were further distinguished by the use of multivariable models. In Table 4, the cluster-robust regression estimates for the 5 nutrient outcomes are provided. Minimal multicollinearity was observed between the different physicochemical predictors (VIF 1.06–1.30). Higher pH independently corresponded to lower NO3 (β = −0.320, p < 0.001). SOM was positively associated with NH4s (β = 0.835, p = 0.0197) and TIN (β = 0.710, p = 0.0227), while pH also showed a weaker negative association with TIN (β = −0.103, p = 0.0325). BD positively predicted Bray-P (β =

0.093, p = 0.0101), and CEC positively predicted K (β = 0.063, p = 0.0057). All six main associations were still in the same direction after sensitivity analysis; five were still significant after excluding the influential observations for the outcome, while the pH–TIN association was diluted (p = 0.141).

Table 4. Multivariable associations between soil physicochemical characteristics and nutrient status

Outcome	Significant predictor	β	SE	95% CI	p-value	Adjusted R^2
NO3	pH	−0.320	0.085	−0.487 to −0.154	<0.001	0.591
NH4s	SOM	0.835	0.358	0.133 to 1.537	0.0197	0.579
TIN	pH	−0.103	0.048	−0.198 to −0.009	0.0325	0.630
TIN	SOM	0.710	0.312	0.099 to 1.321	0.0227	0.630
Bray-P	BD	0.093	0.036	0.022 to 0.164	0.0101	0.661
K	CEC	0.063	0.023	0.018 to 0.108	0.0057	0.822

3.6 Multivariate Structure of Soil Characteristics

Three components were determined by principal component analysis that accounted for 72.11% of the total variance. PC1 accounted for 40.47%, PC2 for 19.46%, and PC3 for an additional 12.18%. The PC1–PC2 biplot accounts for 59.93% of the total multivariate variance and is shown in Figure 4. PC1 had its largest positive loadings for TIN (0.892), SOM (0.856), NH4s (0.820), K (0.807), and NO3 (0.683). PC2 was characterized primarily by positive WAS loading (0.626) and negative Bray-P (−0.621), pH (−0.557), and CEC (−0.524) loadings. The multivariate separation between soil depths was obvious as mean PC1 scores became more negative the farther down the profile, from 2.662 at 0–15 cm, to 0.656 at 15–30 cm, to −1.467 at 30–60 cm, and to −1.851 at 60–90 cm. PC1 accounts for 40.47% of the variance, and PC2 accounts for the next 19.46% of the variance. The points are soil observations, and the vectors are variable loadings for the soil by sampling depth.

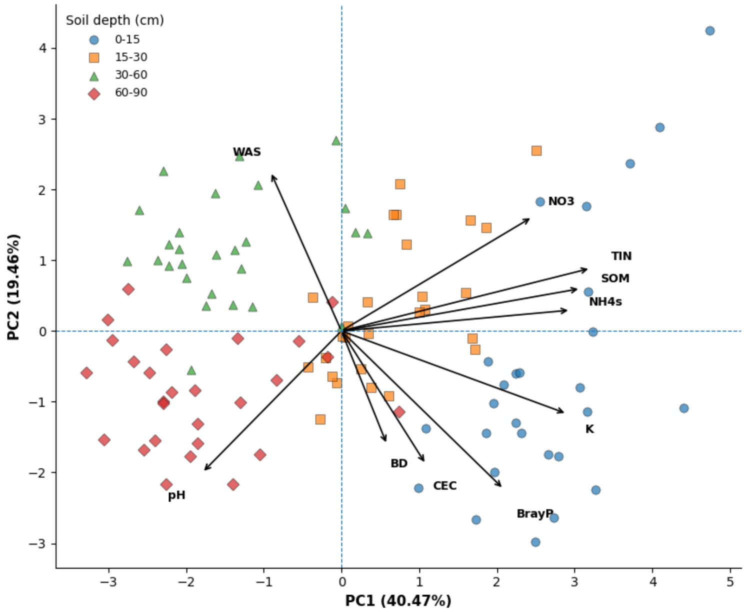

Figure 4. Principal component analysis of soil physicochemical characteristics and nutrient status across soil depths.

4. Discussion

The results show an obvious vertical zonation of soil physicochemical properties and nutrient contents. The concentration of soil organic matter (SOM) decreased regularly as the depth increased, and the concentration of nitrate nitrogen (NO3), ammonium nitrogen (NH4s), total inorganic nitrogen (TIN), Bray-extractable phosphorus (Bray-P) and potassium (K) was found mainly in the surface layer. The soil pH increased with depth, while the water-stable aggregates (WAS) showed a non-linear trend, with the highest at the 30-60 cm depth. The principal component analysis confirmed this surface depth gradient, with positive scores on PC1 being associated with the surface observations, and high loadings for TIN, SOM, NH4s, K, and NO3. These patterns suggested that the nutrient status was well differentiated in the soil and closely related to the changes in the physicochemical conditions. Management effects were not uniform with respect to soil characteristics. Nitrogen rate significantly affected NO3, and this response varied according to crop rotation. The very strong interaction between nitrogen rate and rotation for NO3 was most notable, as a higher rate of nitrogen application led to a large increase for CCC but a notably smaller increase for Cs and Sc. This pattern showed that soil nitrate status was not just a function of the amount of nitrogen added to the soil, but rather of the cropping sequence in which the nitrogen was applied. The association and regression analyses also revealed different physicochemical associations with nutrient status. The correlations of SOM were the highest in the positive direction with NH4s and TIN and also significantly positive with Bray-P and K, whereas WAS was negatively correlated with Bray-P and K, and pH was negatively correlated with NO3 and TIN. Soil organic matter was also a positive predictor of NH4s and TIN; pH independently predicted lower NO3; BD positively predicted Bray-P, and CEC positively predicted K after simultaneous adjustment for soil depth, nitrogen rate, and crop rotation. The pH–TIN relationship was not as stable as most of these relationships, as it was weakened following influential observations from the data set.

The relationships observed between soil characteristics and nutrient status are consistent with other evidence that physicochemical properties have a strong influence on soil functional capacity and nutrient availability (Li et al., 2020). The value of integrated nutrient-management practices could change soil fertility and its physicochemical properties at the same time, indicating the importance of considering nutrient availability in the broader soil context (Paramesh et al., 2023). Prolonged soil physicochemical changes have also been shown to be stable under various nutrient-management strategies in long-term management experiments (Sandhu et al., 2020). The surface enrichment of SOM and nutrients also aligns with the understanding that agricultural practices and inputs affect nutrient and macro- and micronutrient accumulation and distribution in soils (Dhaliwal et al., 2019). Within the managed soil profile, vertical differences in the composition of organic matter have also been found, which is reflected in the pronounced SOM stratification in this case (Sharma et al., 2017). The different nutrient patterns that were found in the present analysis (Xu et al., 2023) also support the observed fertility differences between surface and subsurface soil, as well as different cultivation patterns.

SOM has tight linkages with NH4s, TIN and other nutrients, which help explain its well-documented capacity to maintain soil fertility by retaining, transforming and cycling nutrients (Gerke, 2022). The negative independent correlation between pH and NO3 also emphasizes the importance of soil reaction to nutrient distribution. Long-term fertilization has been linked to depth-dependent soil acidity and other soil chemical properties, indicating that soil nutrient management can create nutrient-stratified soil chemical conditions (Souza et al., 2023). The response to nitrogen rate is another illustration of the dependence of management on determining the fate of fertilizer. The NUE and fertilizer retention are highly dependent on cropping and management systems, and this means that compared to the same N input, different N outputs may be achieved (Quan et al., 2021). The differences in the physicochemical properties and fertility status of the various soils under different long-term land-use conditions further demonstrate that the behavior of nutrients is not independent of the soil environment in which management operations are carried out (Olorunfemi et al., 2018). The importance of SOM in the relationships described here is further illustrated by the close association between SOM, soil properties and nutrient inputs, as described elsewhere (Voltr et al., 2021).

The results affirm the idea of a holistic perspective on nutrient management, which considers the application of fertilizers, crop rotation, depth of soil and its physicochemical condition simultaneously. The highly vertical stratification suggests surface measurements may not be a good indicator of distribution over the rooting profile. SOM was shown to be particularly informative since it was consistently associated with a few nutrient indicators and was an independent predictor of NH4s and TIN. Other nutrient-specific information was given by CEC, pH and BD. The interaction of nitrogen rate with crop rotation for NO3 also indicates that the cropping sequence must be taken into account when making nitrogen recommendations, and that the rate of nitrogen should not be made as a stand-alone crop management decision. Thus, in addition to making suitable fertilizer adjustments, favourable soil physicochemical conditions and adequate nutrient inputs can be maintained for a better sustainable nutrient management basis.

There are some restrictions to be taken into account. Observations reported were from one long-term experimental site and may not be readily extrapolated to predict effect magnitudes for different soils and climatic regions. There were also influential observations in some nutrient models, but for most of the main relationships, sensitivity analysis was conducted, and the results did not change. The relationship between these could be explored in other soil types, cropping systems and environments in future studies. There is the potential to further elucidate whether physicochemical–nutrient relationships identified are consistent throughout growing seasons and longer management periods by repeating the temporal sampling and by incorporating complementary biological indicators.

5. Conclusion

The physicochemical properties of the soil were strongly correlated with soil nutrient distribution under different management conditions in the soil profile. High concentrations of nutrients and SOM were restricted to the topsoil horizons, and the pH rose as depth increased, indicating strong vertical stratification. Crop rotation had an impact on a number of soil properties and nutrient indicators, while N rate had a significant effect on NO3 and interacted with crop rotation, indicating that fertilizer response was dependent on cropping context. Sensitivity analyses showed that the direction of all primary associations was retained after influential observations were excluded, while five of the six significant relationships remained statistically significant. The findings were confirmed by PCA, which separated surface and deeper soils according to a nutrient–organic matter gradient. The findings suggest that a comprehensive nutrient management system should be based on soil depth, crop rotation, fertilizer rate, and the physicochemical properties of the soil and not only on nutrient levels. This can help to better understand the distribution of soil fertility and guide more specific nutrient-management decisions.

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