International Journal for Research in Agricultural and Food Science

Published by: **Green Publication Services**
ISSN (Online): **2208-2719**
Volume 12 Issue 02 June 2026

ASSESSMENT OF SOIL PROPERTIES AND THEIR INFLUENCE ON CROP YIELD

Dr C R Meera[1]

[1]St Mary's College, Thrissur, Kerala, India.

Corresponding Author: Dr C R Meera, meera.cr@smctsr.ac.in

ABSTRACT

Soil quality is a key determinant of crop productivity because soil physical and chemical characteristics regulate nutrient availability, water retention, root development, and plant growth. The present study was aimed at understanding the variability in the soil physicochemical properties and their correlation with pigeonpea yield under rain-fed situations. Descriptive statistics, correlation analysis, principal component analysis and regression modelling were used to assess soil characteristics and crop performance in 23 soil phases. Soil texture, water-retention levels, nutrient availability, cation exchange capacity, organic carbon and micronutrients differed significantly across the soils. Mean pigeonpea seed yield increased from 1300.91 ± 51.01 kg ha^{-1} in 2018–19 to 1421.00 ± 47.69 kg ha^{-1} in 2019–20. The first soil property, iron, had the strongest positive association with seed yield ($r = 0.653$, $p < 0.001$), while sulfur was negatively associated with yield ($r = -0.474$, $p = 0.022$). Soil status analysis revealed positive relationships between yield and the bulk of CEC, FC, AWC, clay, calcium, magnesium, manganese, potassium, nitrogen and organic carbon, and negative relationships with bulk of sand and bulk density. Eight components accounting for 86.59% of the total soil variability were found using principal component analysis. The results indicate that the interplay of soil fertility, water holding capacity, soil texture and micronutrient status can play a crucial role in crop productivity under rainfed conditions.

Keywords: Soil physicochemical properties; crop yield; pigeonpea; soil fertility; cation exchange capacity; micronutrients; principal component analysis

Article Type: **Research**
Doi**: 10.53555/gafs.v12i2.2581**
Received: **09/05/2026,** Revised: **10/06/2026**, Accepted: **17/06/2026**, Published: **24/06/2026**

1. Introduction

Soil quality is a prerequisite for agricultural production as it affects the availability of nutrients, water, root development, soil microbial activity and crop resistance to environmental stresses. There can therefore be significant differences in growth and yield within agroecological regions due to differences in soil physicochemical properties. The soil properties, including soil texture, pH, electrical conductivity, organic carbon, bulk density, CEC, water-holding and macro/micronutrient availability, all create the soil environment in which crops grow. The soil biophysical properties affect biological processes strongly; particularly, the productivity of crops is not a function of a single property, but a product of soil physical, chemical and biological properties (Chen et al., 2020).

A primary goal of sustainable crop production is, therefore, to improve soil quality. Soil management practices that are agronomic and help to optimize plant growth, such as promoting soil aggregation, nutrient cycling and organic matter, can help improve the productive capacity of the agricultural soil and help to maintain greater stability in yields. Sustainable soil-management strategies have been proven to enhance soil quality and crop productivity in diverse agroecosystems, especially those with nutrient limitations and low organic matter (Dubey et al., 2020). Likewise, crop yield and nutrient content of harvested products vary greatly between farms and soils, which may indicate that fertility of soils is tightly linked to agricultural production (Fischer et al., 2020). The relationship between these is especially important in rainfed situations where crop production is closely linked to the water-holding capacity of the soil and its nutrient supply potential in response to fluctuating rainfall.

Soil physical properties are important factors affecting the availability of water and nutrients to plants. Texture, Bulk density, Field capacity, Permanent Wilting point and Available water capacity are all factors that influence infiltration, aeration, root penetration, and moisture-holding capacity. Appropriate soil and water conservation practices can thus enhance both the physicochemical properties and crop productivity, especially in moisture-stressed and land-degraded regions (Jiru & Wegari, 2022). Crop-residue management also boosts water-use efficiency and can lead to higher yield by increasing soil moisture conservation and nutrient recycling (Lu, 2020). But better soil indicators are not necessarily correlated with better crop yields. For instance, the carbon sink in soils upon adoption of regenerative farming has not been correlated with the scaling of productivity, as other soil and management variables interact (Jordon et al., 2022).

The role of soil organic matter and organic carbon in soil aggregation, nutrient retention, biological activity and water-holding capacity make these widely recognized as important indicators of soil quality. However, the relationship between soil organic matter and yield is complex and may depend on the soil type, climate, nutrient level, and crop management. For large-scale assessments it has been shown that not all agricultural conditions correlate with higher soil organic matter and crop yield increases (Vonk et al., 2020). This makes it very clear that it is important to evaluate the soil properties as a whole and not rely on any single indicator. Therefore, the quality of the soil and the yield of the crop should be considered as part of a wider sustainable agricultural system in which all its physical, chemical and biological functions are integrated (Papatheodorou & Monokrousos, 2022).

Changes in soil properties and yield responses over time can be achieved through management practices like conservation agriculture, crop rotation, residue incorporation and soil amendments. In the Indo-Gangetic Plains of India, soil-management approaches under intensive agriculture practices have been linked to soil-quality, microbial diversity, and crop-productivity changes, highlighting the significance of soil-management strategies in intensive agriculture (Singh et al., 2020). Similarly, large-scale field trials have shown significant variability in crop yield response to biochar soil amendments, indicating that the success of biochar soil amendment relies heavily on the initial soil conditions, crop species and varieties, climate, and management practices (Vijay et al., 2021). These results confirm the criticality of the soil properties most closely related to crop productivity under certain field conditions.

Although many efforts have been made to research soil fertility and crop management, there is still uncertainty in what combinations of soil properties are best to predict the variability in yields within heterogeneous agricultural landscapes. The texture, water retention, nutrient level and exchange properties of the soil can play an important role in crop performance, especially in rainfed production systems. A comprehensive soil characterization study in relation to crop production may thus provide useful information in determining soil constraints, prioritizing nutrient and water-management interventions and aiding in site-specific agricultural decision-making.

For this reason, the present study was conducted to evaluate the soil physicochemical properties and study their relationship to the yield of crops as a function of different soil phases under a rain-fed situation.

Objectives

1. To assess the variability of the key physical, chemical and nutrient-based soil properties within the soil phases selected.
2. To measure crop growth and yield differences and to establish the interrelationships of specific soil properties with seed yield.
3. To use multivariate analysis and regression to determine the most important soil-property combinations and the most important predictors of crop yield variability.

2. Materials and Methods

2.1 Study Design and Data Source

The study design used in this research was a quantitative secondary data analysis to evaluate soil properties and their relationship with crop production. The publicly available dataset titled “Support for improved program integration under rainfed areas” (deposited in Mendeley Data in 2021) was used for the analysis (N. L., 2021). The dataset consists of soil physicochemical properties, pigeonpea (Cajanus cajan L.) growth parameters, crop yield parameters and some field management data under rainfed agricultural practices of Karnataka, India.

2.2 Study Area and Sampling Framework

The original dataset was created from the micro-watershed of Kalmandari in the Northern Dry Zone of Karnataka, India. The study area is a semi-arid rain-fed agriculture area with predominantly Vertisols and Alfisols. The soil observations were grouped into 23 soil phases that were relatively homogeneous in terms of soil texture, slope, erosion, gravelliness, and other characteristics. These soil phases were considered as analytical units for connecting the soil properties to the soil-growth and yield measurements of the plants.

2.3 Soil and Crop Variables

Soil properties included physical and chemical properties like sand, silt, clay, field capacity, permanent wilting point, available water capacity, bulk density, pH, electrical conductivity, organic carbon, calcium carbonate, calcium, magnesium, sodium, cation exchange capacity, and exchangeable sodium percentage. The soil fertility indicators were available nitrogen, phosphorus (P_2O_5), potassium (K_2O), sulfur, zinc, iron, copper, manganese and boron. In the dataset the crop tested was Pigeonpea. Crop characteristics were plant height, number of branches, leaf area index, number of pods per plant, seed yield and stover yield. The dependent variable used was seed yield (kg ha-1), and soil properties were treated as explanatory variables.

2.4 Data Integration and Preparation

Soil and crop datasets were merged by Soil Phase as a common identifier for the 2018–2019 and 2019–2020 cropping seasons. Data were first checked for missing values, duplicates, inconsistent identifiers, inappropriate data types, and extreme values before analysis. Where necessary, continuous variables were standardized for multivariate analysis (and were measured on different scales). A special focus was placed on the temporal structure of the data; thus, the soil properties before sowing were given priority in analyzing their association with the crop yield.

2.5 Statistical Analysis

Soil properties and crop-yield characteristics were summarized using descriptive statistics such as mean, standard deviation, minimum, maximum and coefficient of variation. Pearson's correlation coefficient was calculated for the relationships between individual soil variables and pigeonpea seed yield, when normality and linearity were assumed; otherwise, Spearman's rank correlation was assumed. Since many soil-phase variables were interrelated in the data set, PCA was employed to reduce dimensionality and to determine the major groups of soil properties that explained soil variability.

2.6 Assessment of Soil Influence on Crop Yield

Selected principal components or few statistically and agronomically significant soil variables were entered into regression analysis with seed yield as the dependent variable and the combined effect of soil characteristics and crop yield was determined. The coefficient of determination (R^2) adjusted R^2, regression coefficients and the significance values associated with them were used as the evaluation criterion of the model performance. The adequacy of the model was also checked for multicollinearity, residual normality, linearity and homoscedasticity. A p-value of < 0.05 was considered to be statistically significant. Since the data were observational, the results were chiefly interpreted in terms of association between soil properties and yield of the crops and not their causal effects.

2.7 Ethical Considerations

There was no direct contact with human subjects or experimental animals, and the study employed an openly accessible secondary agricultural data source. For this reason, additional ethical approval was not necessary for the present analysis. The dataset "Support for improved program integration under rainfed areas" was used under the open access conditions of the dataset and was cited as such.

3. Results

3.1 Soil Physicochemical Properties

There was significant variation among the 23 soil phases for both physical and chemical properties. As shown in Table 1, sand content ranged from 18.62% to 55.20%, while clay content ranged from 24.80% to 55.13%. The mean and available water capacity for the period 2018-19 were 41.16% and 27.93%, respectively. Soil pH ranged from moderately acidic (6.08) to alkaline (8.60) with relatively high CV (32.00%), while EC exhibited relatively low CV (7.00%). The organic carbon content was 0.55%, on average, and mean cation exchange capacity was 32.21 cmol(p^+) kg^{-1}. The differences in productivity among the soil phases and seasons are shown in Figure 1.

Table 1. Descriptive statistics of selected soil physicochemical properties

Soil property	2018–19 Mean ± SD	Range	CV (%)	Subsequent soil status Mean ± SD	Range
Sand (%)	38.87 ± 9.47	18.62–55.20	24.35	38.87 ± 9.47	18.62–55.20
Clay (%)	37.97 ± 8.49	24.80–55.13	22.35	37.97 ± 8.49	24.80–55.13
Field capacity (%)	41.16 ± 5.00	33.45–49.74	12.14	32.34 ± 3.94	25.21–39.74
AWC (%)	27.93 ± 4.73	21.00–36.14	16.93	19.07 ± 3.92	13.76–26.94
Bulk density	1.30 ± 0.04	1.25–1.36	2.97	1.30 ± 0.05	1.21–1.38
pH	6.75 ± 0.57	6.08–8.60	8.46	6.63 ± 0.44	5.88–7.78
EC (dS m^{-1})	0.32 ± 0.10	0.13–0.50	32.00	0.28 ± 0.09	0.11–0.49
Organic carbon (%)	0.55 ± 0.09	0.32–0.74	16.43	0.50 ± 0.09	0.27–0.69
CEC	32.21 ± 2.35	27.59–34.75	7.30	33.16 ± 2.35	28.54–35.70

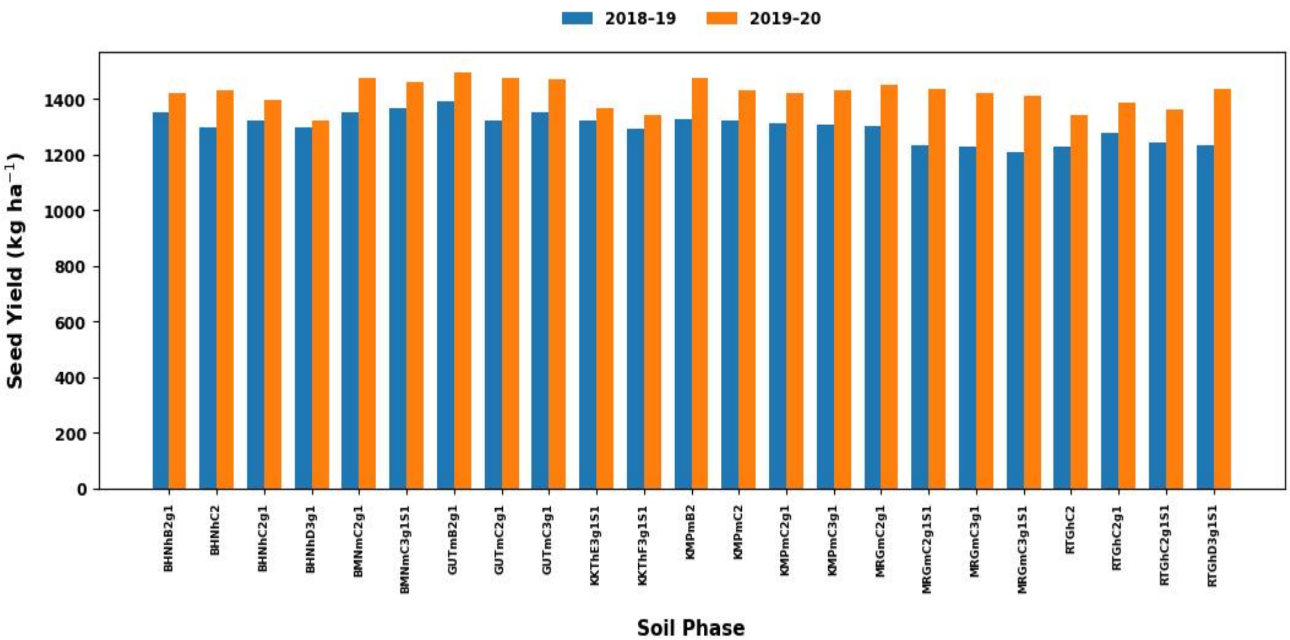

Figure 1. Variation in pigeonpea seed yield across the 23 soil phases during 2018–19 and 2019–20

3.2 Soil Nutrient Status

There was also a great deal of variability in soil nutrient concentrations, as shown in Table 2. During 2018–19, mean available N, P_2O_5, and K_2O were 248.05, 40.60, and 371.25 kg ha^{-1}, respectively. The relative variability (CV) of micronutrients ranged from the highest for Fe (34.06%) to the lowest for Ni (4.37%). The nutrient content differences suggested that soil fertility varied across the study area.

Table 2. Descriptive statistics of major and micronutrient soil properties

Variable	Mean ± SD	Minimum	Maximum	CV (%)
N (kg ha^{-1})	248.05 ± 40.68	144.00	333.00	16.40
P_2O_5 (kg ha^{-1})	40.60 ± 7.28	27.50	51.80	17.94
K_2O (kg ha^{-1})	371.25 ± 45.75	311.98	459.39	12.32
S	8.69 ± 2.08	5.00	11.60	23.99
Zn (ppm)	0.65 ± 0.16	0.38	0.99	24.03

Fe (ppm)	3.22 ± 1.10	1.30	4.80	34.06
Cu (ppm)	0.95 ± 0.19	0.65	1.31	19.73
Mn (ppm)	11.06 ± 2.18	7.59	14.70	19.67
B (ppm)	0.43 ± 0.06	0.30	0.50	12.69

3.3 Crop Growth and Yield

The yield of pigeonpea varied significantly from one phase of soil to the other and one period of cropping to the other. As presented in Table 3, mean seed yield increased from 1300.91 ± 51.01 kg ha^{-1} in 2018–19 to 1421.00 ± 47.69 kg ha^{-1} in 2019–20, representing an increase of approximately 9.23%. This increase was statistically significant when compared with the paired comparison ($t = 11.31$, $p < 0.001$). The two time periods also differed significantly in their stover yield ($p < 0.001$). The differences are apparent in both the seasons and the soil phases and are shown in Figure 1.

Table 3. Pigeonpea growth and yield characteristics

Variable	**2018–19 Mean ± SD**	**2019–20 Mean ± SD**	**Range, 2018–19**	**Range, 2019–20**
Plant height at harvest (cm)	122.52 ± 6.93	124.57 ± 6.98	110–134	111–136
Branches at harvest	13.17 ± 1.27	16.17 ± 1.27	11–15	14–18
LAI at harvest	1.07 ± 0.30	1.17 ± 0.30	0.64–1.85	0.74–1.95
Pods plant^{-1}	54.48 ± 5.03	59.74 ± 5.96	45–64	49–73
Seed yield (kg ha^{-1})	1300.91 ± 51.01	1421.00 ± 47.69	1207–1394	1325–1496
Stover yield (kg ha^{-1})	3806.70 ± 74.27	3914.09 ± 151.16	3657–3902	3621–4236

3.4 Relationship Between Soil Properties and Yield

The correlation analysis showed that the selected soil properties were significantly correlated with pigeonpea seed yield as shown in Table 4. Soil Fe was strongly positively associated with yield ($r = 0.653$, $p < 0.001$) while soil S was significantly negatively associated with yield ($r = -0.474$, $p = 0.022$) under the initial conditions of the 2018–19 soil. The general correlation pattern is given in Figure 2 and the positive correlation between Fe and seed yield in Figure 3.

For the subsequent soil-status observations, CEC exhibited the strongest positive correlation with yield ($r = 0.743$, $p < 0.001$), followed by field capacity ($r = 0.697$, $p < 0.001$), Mn ($r = 0.685$, $p < 0.001$), AWC ($r = 0.652$, $p < 0.001$), clay ($r = 0.646$, $p = 0.001$), and Ca ($r = 0.638$, $p = 0.001$). Yield (kg) was negatively associated with sand content ($r = -0.662$, $p < 0.001$).

Table 4. Correlation of selected soil properties with pigeonpea seed yield

Soil property	2018–19 r	p-value	Subsequent soil status r	p-value
Sand	−0.222	0.309	−0.662	<0.001
Clay	0.151	0.492	0.646	0.001
Field capacity	0.159	0.469	0.697	<0.001
AWC	0.160	0.465	0.652	<0.001
Bulk density	−0.168	0.444	−0.545	0.007
Organic carbon	0.034	0.877	0.423	0.045
CEC	0.284	0.189	0.743	<0.001
N	0.039	0.861	0.424	0.044
K_2O	−0.085	0.699	0.539	0.008
S	**−0.474**	**0.022**	−0.221	0.312
Fe	**0.653**	**<0.001**	0.394	0.063
Mn	0.069	0.754	0.685	<0.001

Ca	0.024	0.912	0.638	0.001
Mg	0.011	0.961	0.583	0.004

Bold values indicate statistically significant correlations at $p < 0.05$.

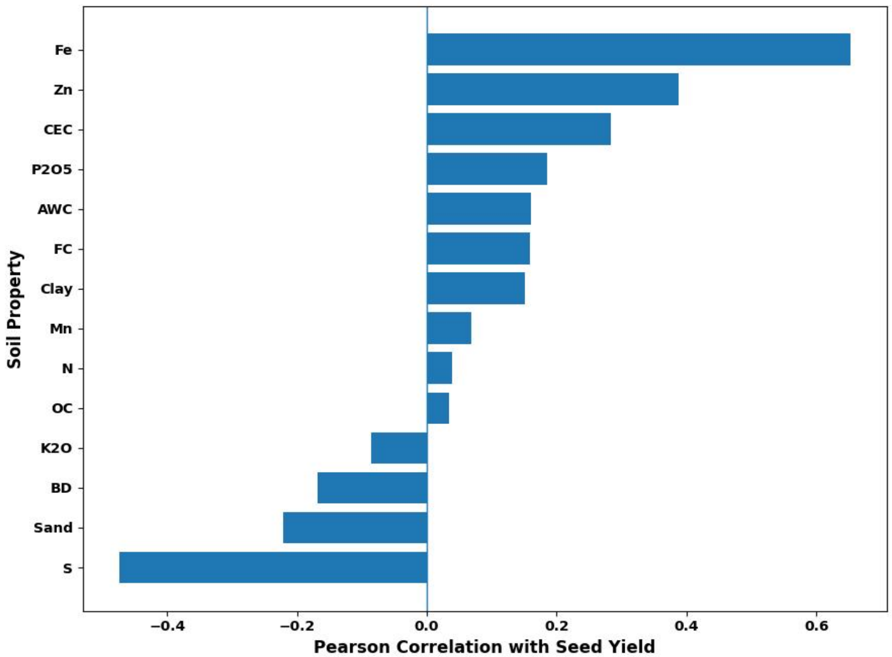

Figure 2. Pearson correlation coefficients between selected initial soil properties and pigeonpea seed yield during 2018–19

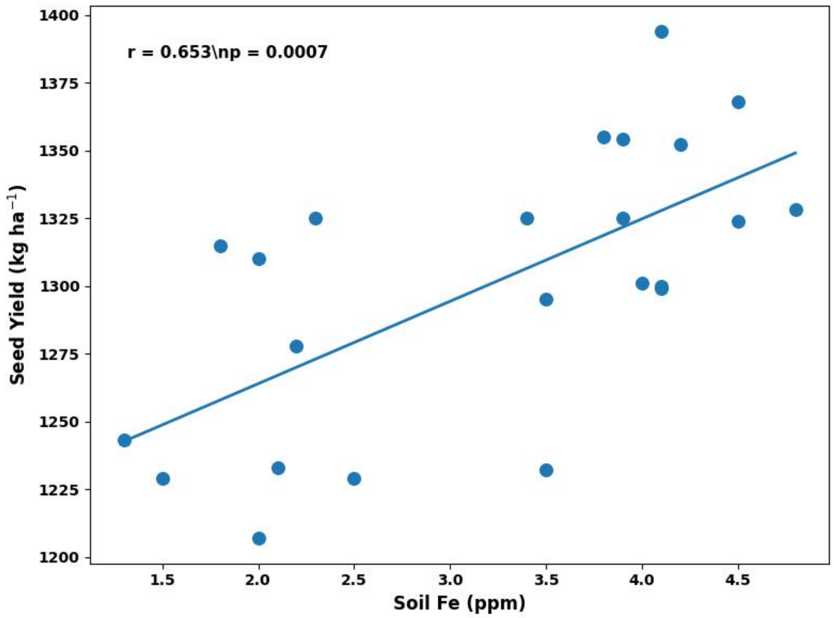

Figure 3. Relationship between initial soil Fe concentration and pigeonpea seed yield during 2018–19

3.5 Principal Component and Regression Analyses

The principal component analysis gave eight components with eigenvalues > 1, and the total variance of soil characteristics accounted for about 86.59%, as shown in Table 5. PC1 explained 37.24% of the variance and was mainly related to CEC, field capacity, Ca, clay, Mg and Mn, while it had a negative relationship with bulk density and sand. Fe, Zn and B were the major elements found in PC3. The contribution of the successive components to the variance is shown in Figure 4.

Table 5. Summary of principal component analysis

Component	Eigenvalue	Variance explained (%)	Cumulative variance (%)	Major contributing variables
PC1	9.733	37.24	37.24	CEC, FC, Ca, clay, Mg, Mn, BD, sand
PC2	3.486	13.34	50.58	Na, ESP, silt, OC, N
PC3	2.157	8.25	58.83	Fe, Zn, B

PC4	1.957	7.49	66.32	Cu, Na, ESP, P_2O_5
PC5	1.616	6.18	72.50	EC, silt, AWC
PC6	1.566	5.99	78.49	Mixed soil attributes
PC7	1.105	4.23	82.72	Mixed soil attributes
PC8	1.011	3.87	86.59	Mixed soil attributes

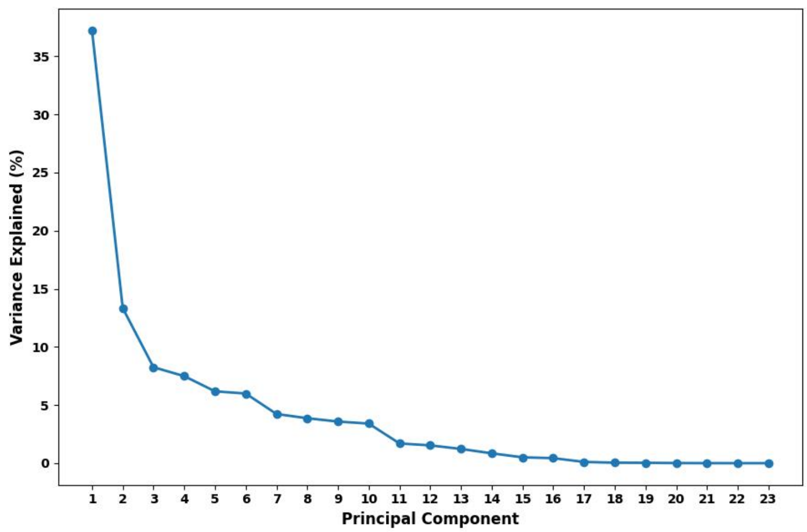

Figure 4. Percentage of total variance in soil properties explained by successive principal components

PCA regression accounted for 49.3% of the variance in seed yield, but the overall model of these eight components was not significant ($R^2 = 49.3\%$, adjusted $R^2 = 20.3\%$, $p = 0.184$). Its Fe and Zn content was the main characteristic of PC3, which was individually significant ($\beta = 17.01$, $p = 0.022$). The seed yield variation ($R^2 = 0.623$, adjusted $R^2 = 0.586$; $p < 0.001$) was better explained by a more parsimonious exploratory model that included Fe and S. Fe exerted a significant positive effect ($B = 29.43$, $p < 0.001$), whereas S showed a significant negative coefficient ($B = -10.89$, $p = 0.004$). It is seen in Figure 5 that there is a good agreement between the observed and predicted yield values for this model.

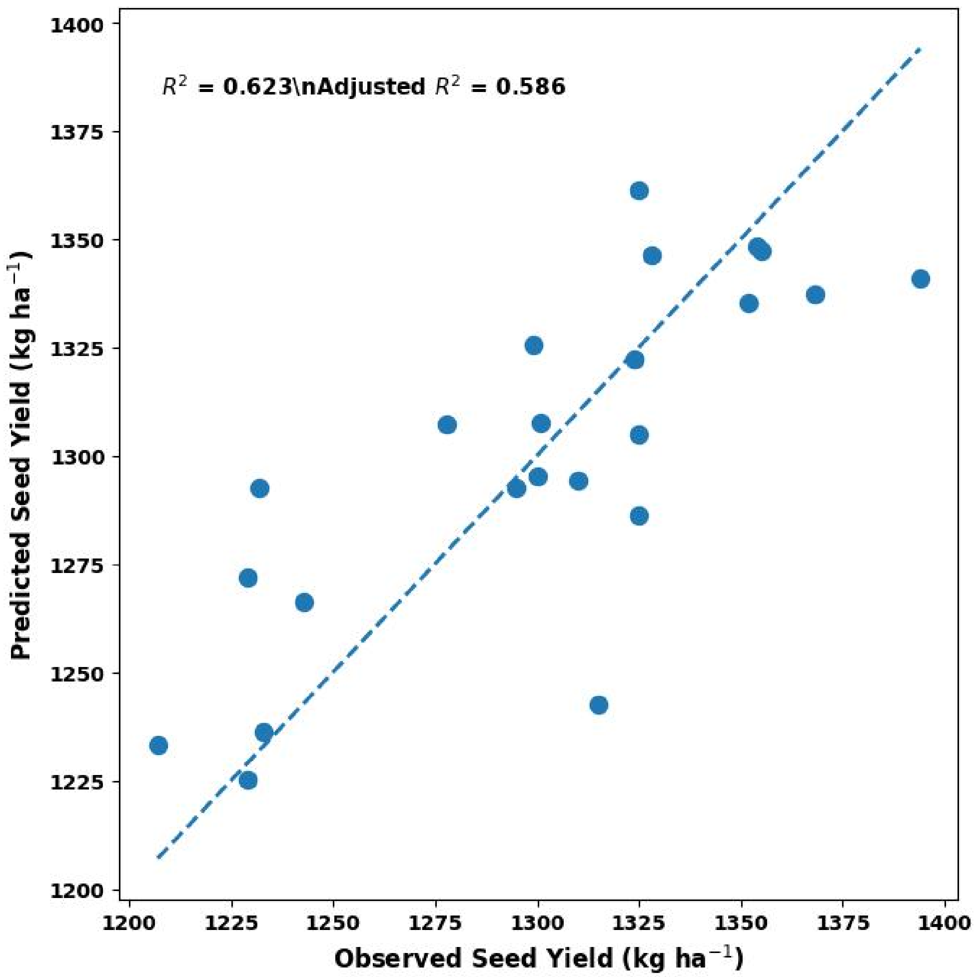

Figure 5. Observed and predicted pigeonpea seed yield obtained from the Fe–S regression model

3.6 Summary of Results

In general, the soil phases showed very high physical, chemical, and nutritional heterogeneity, and pigeonpea productivity. There was a notable difference in seed yield between the two cropping periods (1301 kg ha^{-1} vs. 1421 kg ha^{-1}). Fe was most highly associated with a positive yield, while S was significantly and negatively associated. The overall soil status studies showed that the levels of CEC, field capacity, clay content, available water capacity, Ca, Mg, Mn, K_2O, N and organic carbon were positively correlated with yield, whereas sand content and bulk density were negatively correlated. PCA also showed that the soil texture, water retention, exchange characteristics and micronutrient status were responsible for a significant amount of the soil variability. The parsimonious Fe–S regression model was found to account for about 62% of the variation in pigeonpea seed yield, which suggested that the selected soil fertility parameters were significant factors to explain the differences in yields among the soil phases studied.

4. Discussion

In the present study, significant differences were found in soil salinity, soil texture and soil productivity in the different soil phases which were evaluated, thus confirming that the yield performance is closely related to the soil environment. Variations in seed yield of pigeonpea were associated with the differences in texture, field capacity, available water capacity, cation exchange capacity, nutrient availability and micronutrient status. This is in line with the general evidence that after evaluating soil fertility and hydro-physical conditions, productivity of crops is related to management-induced changes in soil quality as a whole and not solely to one of the soil properties (Allam et al., 2022).

Iron had the highest positive relationship to seed yield, while sulfur had a significant negative relationship among the initial soil properties. The positive effect of micronutrient availability is agronomically feasible as it enables the photosynthetic process, enzymatic reactions and plant metabolic processes to occur. The impacts of soil amendments on nutrient availability have been observed to significantly affect crop productivity in similar studies, though soil type and fertility levels have varied in response to amendments (Dong et al., 2022). Crop-yield responses to soil amendment are also strongly dependent on the soil context; for instance, biochar use in tropical sandy soil had a very context-sensitive effect on crop production over repeated crops (Frimpong et al., 2021). This negative correlation between sulfur and yield seen here should be interpreted with caution because it could be due to the interaction with other fertility attributes rather than the direct negative effect of sulfur.

The general soil status analysis showed high positive relationships of yield with CEC, field capacity, available water capacity, clay content, calcium, magnesium, manganese, potassium, nitrogen, and organic carbon. The results showed the significance of nutrient retention and soil moisture storage for rainfed production under the production conditions. Increasing production in semi-arid systems due to soil physical condition and nutrient dynamic improvement through tillage, residue management, and fertilization also been reported (Houshyar & Esmailpour, 2020). Long-term use of straw and biochar has also been found to affect the fertility of soils and crop yields by altering the nutrient cycle, soil structure and moisture availability (Hu et al., 2021). The intensity of these responses, however, may be related to initial soil properties and climatic conditions, so that some soil indicators were more strongly correlated with yield than others.

The soil physical quality was further supported by the negative correlation between sand content, bulk density and yield. A greater proportion of sand in the soil will generally reduce its water and nutrient holding capacity, as well as its ability to allow roots to penetrate it, to allow air to flow in and out of it, and to allow water to flow in and out of it. Increased proportions of sand will generally decrease water and nutrient holding capacity as well as the ability to penetrate with roots, aerate, and transport water and nutrients. The same restrictions have been noted in sandy soils where nutrient retention and amendment effects on soil functionality were shown to greatly influence crop responses (Knoblauch et al., 2021). Organic amendments have also been linked to improved hydro-physical properties, which have led to improved crop growth and productivity—for soils with limited water availability (Sharma et al., 2021). However, not every kind of soil amendment leads to a proportional change of soil properties and crop yield, as this can be seen in field trials where maize crop growth was better despite moderate changes in the measured soil properties (Medyńska-Juraszek et al., 2021).

The mean seed yield also showed an increase between the two cropping periods, suggesting that the productivity of the crops was not constant from one season to another. The variation here may be due to a variety of soil, rainfall, nutrient supply and management factors. The long-term conservation agriculture experiments conducted in India have also revealed that an increase in soil carbon, soil aggregation, and soil quality can lead to better crop performance in the long-term future (Mondal et al., 2021). In addition, integrated nutrient management has been documented to boost crop productivity, soil biological activity and soil carbon stocks (Padbhushan et al., 2021). Similar results have been found in maize–chickpea cropping systems with conservation agriculture and balanced nutrient management in improving maize productivity and some soil properties (Pooniya et al., 2021).

In addition, the multivariate analysis showed that soil properties were interacting groups. The first principal component was mainly influenced by CEC, field capacity, calcium, clay, magnesium, and manganese, and the third component was influenced primarily by iron, zinc, and boron. This structure validates the idea that soil fertility and physical property gradients are interrelated and affect crop yield. The role of multivariate soil controls on pigeonpea productivity has also been reported previously, where combinations of soil nutrients, water-retention and exchange properties accounted for significant variation in yield (Rajesh et al., 2023). Likewise, a study on the effect of conservation agriculture on the soil quality in North-West India showed that the improvement of the soil in this context is a multidimensional phenomenon arising from changes in physical, chemical and biological properties together (Roy et al., 2022).

The soil variables explained a significant portion of seed yield variation in the parsimonious Fe–S regression model, indicating that a limited number of soil variables can sometimes be helpful in providing predictive information. However, this information should not be taken to mean that productivity is dependent entirely on these two nutrients. Crop response is influenced by other soil-management interactions, such as for INM under rain-fed (Sharma et al., 2020) and for residue-based soil amendments to enhance soil functionality and crop performance under difficult conditions (Singh et al., 2021). The overall conclusion of the findings is the importance of managing soil physical, nutrient and water-holding capacity to increase crop productivity under rainfed agriculture.

5. Conclusion

It has been proved from the present study that soil properties such as physicochemical properties have a significant influence on the productivity of crops under rain-fed conditions. There were marked differences between soil phases evaluated for texture, water-holding capacity, nutrient availability, cation exchange capacity, organic carbon and micronutrient status. The difference in yield of pigeon pea was also found to be very high between the cropping periods, which shows that both soil as well as seasonal factors had an influence on the productivity.

The first soil characteristics were most strongly correlated with seed yield, with iron having a positive correlation and sulfur having a negative correlation. The broader soil-status analysis also emphasized the critical role of the cation exchange capacity, field capacity, available water capacity, clay content, and content of calcium, magnesium, manganese, potassium, nitrogen and organic carbon for higher yields. Conversely, productivity was negatively correlated with the amount of sand and bulk density. Soil properties were revealed to be related as a group instead of being independent in relation to each other, especially regarding gradients in water retention, exchange capacity and micronutrients by principal component analysis.

The results overall indicate that sustainable yield improvement should be achieved by integrated management of soil fertility, nutrient balance and hydro-physical properties. Therefore, site-specific soil assessment and specific management actions can potentially be used to enhance crop production, especially in heterogeneous rainfed agricultural reliefs.

References

1. Allam, M., Radicetti, E., Quintarelli, V., Petroselli, V., Marinari, S., & Mancinelli, R. (2022). Influence of organic and mineral fertilizers on soil organic carbon and crop productivity under different tillage systems: A meta-analysis. *Agriculture*, *12*(4), 464.
2. Chen, M., Xu, J., Li, Z., Zhao, B., & Zhang, J. (2020). Soil physicochemical properties and bacterial community composition jointly affect crop yield. *Agronomy Journal*, *112*(5), 4358-4372.
3. Dong, L., Wang, J., Shen, M., Zhang, H., Wang, L., Li, C., & Lu, C. (2022). Biochar combined with nitrogen fertilizer affects soil properties and wheat yield in medium-low-yield farmland. *Soil Use and Management*, *38*(1), 584-595.
4. Dubey, R. K., Dubey, P. K., Chaurasia, R., Singh, H. B., & Abhilash, P. C. (2020). Sustainable agronomic practices for enhancing the soil quality and yield of Cicer arietinum L. under diverse agroecosystems. *Journal of environmental management*, *262*, 110284.
5. Fischer, S., Hilger, T., Piepho, H. P., Jordan, I., Karungi, J., Towett, E., ... & Cadisch, G. (2020). Soil and farm management effects on yield and nutrient concentrations of food crops in East Africa. *Science of the Total Environment*, *716*, 137078.
6. Frimpong, K. A., Phares, C. A., Boateng, I., Abban-Baidoo, E., & Apuri, L. (2021). One-time application of biochar influenced crop yield across three cropping cycles on tropical sandy loam soil in Ghana. *Heliyon*, *7*(2).
7. Houshyar, E., & Esmailpour, M. (2020). The impacts of tillage, fertilizer and residue managements on the soil properties and wheat production in a semi-arid region of Iran. *Journal of the Saudi Society of Agricultural Sciences*, *19*(3), 225-232.
8. Hu, Y., Sun, B., Wu, S., Feng, H., Gao, M., Zhang, B., & Liu, Y. (2021). After-effects of straw and straw-derived biochar application on crop growth, yield, and soil properties in wheat (Triticum aestivum L.)-maize (Zea mays L.) rotations: A four-year field experiment. *Science of the Total Environment*, *780*, 146560.
9. Jiru, E. B., & Wegari, H. T. (2022). Soil and water conservation practice effects on soil physicochemical properties and crop yield in Ethiopia: review and synthesis. *Ecological Processes*, *11*(1), 21.

10. Jordon, M. W., Willis, K. J., Bürkner, P. C., Haddaway, N. R., Smith, P., & Petrokofsky, G. (2022). Temperate Regenerative Agriculture practices increase soil carbon but not crop yield—a meta-analysis. *Environmental Research Letters*, *17*(9), 093001.
11. Knoblauch, C., Priyadarshani, S. R., Haefele, S. M., Schröder, N., & Pfeiffer, E. M. (2021). Impact of biochar on nutrient supply, crop yield and microbial respiration on sandy soils of northern Germany. *European Journal of Soil Science*, *72*(4), 1885-1901.
12. Lu, X. (2020). A meta-analysis of the effects of crop residue return on crop yields and water use efficiency. *PLoS One*, *15*(4), e0231740.
13. Medyńska-Juraszek, A., Latawiec, A., Królczyk, J., Bogacz, A., Kawałko, D., Bednik, M., & Dudek, M. (2021). Biochar improves maize growth but has a limited effect on soil properties: Evidence from a three-year field experiment. *Sustainability*, *13*(7), 3617.
14. Mondal, S., Mishra, J. S., Poonia, S. P., Kumar, R., Dubey, R., Kumar, S., ... & McDonald, A. (2021). Can yield, soil C and aggregation be improved under long-term conservation agriculture in the eastern I ndo-G angetic plain of I ndia?. *European Journal of Soil Science*, *72*(4), 1742-1761.
15. N. L., Rajesh (2021). *Support for improved program integration under rainfed areas* (Version 4) [Data set]. Mendeley Data. https://doi.org/10.17632/ng5v92xht3.4
16. Padbhushan, R., Sharma, S., Kumar, U., Rana, D. S., Kohli, A., Kaviraj, M., ... & Gupta, V. V. (2021). Meta-analysis approach to measure the effect of integrated nutrient management on crop performance, microbial activity, and carbon stocks in Indian soils. *Frontiers in Environmental Science*, *9*, 724702
17. Papatheodorou, E. M., & Monokrousos, N. (2022). Crop yield and soil quality are partners in a sustainable agricultural system. *Agronomy*, *12*(1), 140.
18. Pooniya, V., Zhiipao, R. R., Biswakarma, N., Jat, S. L., Kumar, D., Parihar, C. M., ... & Nath, A. (2021). Long-term conservation agriculture and best nutrient management improves productivity and profitability coupled with soil properties of a maize–chickpea rotation. *Scientific Reports*, *11*(1), 10386.
19. Rajesh, N. L., Sathishkumar, U., Wali, V. B., Basavaraj, K., Rudramurthy, H. V., & Desai, B. K. (2023). Variability in soil properties influencing pigeonpea (Cajanus cajana L.) yield: a multivariate statistical analysis. *F1000Research*, *10*, 944.

20. Roy, D., Datta, A., Jat, H. S., Choudhary, M., Sharma, P. C., Singh, P. K., & Jat, M. L. (2022). Impact of long term conservation agriculture on soil quality under cereal based systems of North West India. *Geoderma*, *405*, 115391.
21. Sharma, P., Abrol, V., Sharma, V., Chaddha, S., Rao, C. S., Ganie, A. Q., ... & Mansoor, S. (2021). Effectiveness of biochar and compost on improving soil hydro-physical properties, crop yield and monetary returns in inceptisol subtropics. *Saudi Journal of Biological Sciences*, *28*(12), 7539-7549.
22. Sharma, V., Singh, M. J., & Khokhar, A. K. (2020). Productivity, nutrient uptake and soil properties as influenced by integrated nutrient management in maize-wheat cropping system under rainfed conditions of sub-montane Punjab. *Agricultural Research Journal*, *57*(6), 839-847.
23. Singh, G., Mavi, M. S., Choudhary, O. P., Gupta, N., & Singh, Y. (2021). Rice straw biochar application to soil irrigated with saline water in a cotton-wheat system improves crop performance and soil functionality in north-west India. *Journal of Environmental Management*, *295*, 113277.
24. Singh, S. R., Yadav, P., Singh, D., Tripathi, M. K., Bahadur, L., Singh, S. P., ... & Kumar, S. (2020). Cropping systems influence microbial diversity, soil quality and crop yields in Indo-Gangetic plains of India. *European Journal of Agronomy*, *121*, 126152.
25. Vijay, V., Shreedhar, S., Adlak, K., Payyanad, S., Sreedharan, V., Gopi, G., ... & Aravind, P. V. (2021). Review of large-scale biochar field-trials for soil amendment and the observed influences on crop yield variations. *Frontiers in Energy Research*, *9*, 710766.
26. Vonk, W. J., van Ittersum, M. K., Reidsma, P., Zavattaro, L., Bechini, L., Guzmán, G., ... & Hijbeek, R. (2020). European survey shows poor association between soil organic matter and crop yields. *Nutrient Cycling in Agroecosystems*, *118*(3), 325-334.