



# **Spatial Variability of the Physicochemical Properties of Cotton-growing Soils at Six Locations in Northern Côte d'Ivoire (Boron, Boundiali, Diawala, Ferkessédougou, Kasséré and Korhogo)**

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## ***Authors' contributions***

*This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.*

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## **Abstract**

Cotton-growing soils in northern Côte d'Ivoire differ in their physical and chemical properties, potentially affecting soil fertility management. This study assessed the spatial variability of selected physicochemical indicators at six locations: Boron, Boundiali, Diawala, Ferkessédougou, Kasséré and Korhogo. Composite soil samples were collected from the 0–20 cm layer under cotton

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cultivation. Laboratory analyses included particle size distribution, soil pH, soil organic carbon, total nitrogen, available phosphorus, exchangeable bases, cation exchange capacity (CEC) and base saturation. Differences among locations were examined using statistical and multivariate analyses. Soil pH ranged from 6.45 at Korhogo to 7.12 at Diawala, indicating slightly acidic to neutral conditions. Mean soil organic carbon ranged from 0.7 to 1.8 g kg<sup>-1</sup>, total nitrogen from 0.07 to 0.16 g kg<sup>-1</sup> and available phosphorus from 9 to 30 mg kg<sup>-1</sup>. CEC ranged from 5.64 to 15.32 cmol<sub>+</sub> kg<sup>-1</sup>, while base saturation ranged from 22.9% to 59.4%. Sandy textures predominated at four locations; Diawala had a sandy loam texture and Kasséré a loam texture. The first two principal components explained 71.84% of the observed variability. Coarse silt, fine sand, pH, total nitrogen and CEC were important differentiating variables, and four relatively homogeneous soil groups were identified. These findings indicate that fertility management should consider the contrasting soil properties of the locations studied, particularly nutrient availability, soil texture and exchange capacity.

**Keywords:** Cotton-growing soils; physicochemical properties; spatial variability; soil fertility; soil organic carbon; total nitrogen; cation exchange capacity.

## 1. Introduction

Cotton is a cash crop that contributes to the socioeconomic development of households in cotton-growing regions. It promotes farm diversification, reduces income poverty in villages, improves rural housing, facilitates rural mobility, creates new jobs and improves literacy and health outcomes (Aïwa, 2015 ; Tillie *et al.*, 2018). In Côte d'Ivoire, cotton accounts for 5 to 10% of national exports and generates an annual revenue of approximately 120 billion CFA francs (Berti *et al.*, 2006). Its production contributes 1.7% of the gross domestic product (GDP), and its share of exports has reached 7% (Koffi, 2013). In the northern part of the country, cotton has become the main cash crop (Tillie *et al.*, 2018). Despite substantial fertiliser inputs, the average yield in the cotton sector remains below 1,100 kg·ha<sup>-1</sup> (Food and Agriculture Organization of the United Nations [FAO], 2020). Research on cotton soils indicates that tillage practices and organic inputs can influence the availability of soil macronutrients (Ravali *et al.*, 2024). Surface-soil fertility surveys also use soil reaction, soil organic carbon and available macronutrients to identify nutrient constraints (Patil *et al.*, 2026).

Drawing lessons from the weaknesses of the sector, the government replaced fertiliser subsidies with direct support to the producer price per kilogram of seed cotton from the 2014/2015 cropping season onwards. During the same period, seed cotton production reached a record of 50,000 metric tons, marking a new turning point in the attractiveness of cotton for Ivorian farmers. However, the sector faces strong land pressure, reflected in a gradual and steady decline in cotton area, with an estimated loss of nearly 90,000 ha over four cropping seasons. Current farming practices, which are detrimental to the soil, also reduce the area cultivated per agricultural worker. These practices contribute to soil compaction (Coulouma *et al.*, 2006), erosion (Le Bissonnais *et al.*, 2007) and the decline of soil chemical indicators (Diomandé, Akotto, *et al.*, 2021). Yet the soil provides the physical medium for plant growth and mineral nutrition. These processes have led to a decline in soil fertility in the cotton-growing areas of Côte d'Ivoire, reflected in a gradual decrease in yields. Thus, from 2015 to 2018, seed cotton production averaged 350,280 t on an average area of 357,061 ha, corresponding to a yield of 981 kg·ha<sup>-1</sup> (Fonds Interprofessionnel pour la Recherche et le Conseil Agricoles [FIRCA], 2018, 2019). Several factors account for this yield decline, one of the main ones being the low levels of nutrients essential for cotton (Diomandé, Soro, *et al.*, 2021). Evidence from cotton-based farming systems in Benin indicates that low soil fertility can persist despite annual mineral fertiliser inputs (Dossouhoui *et al.*, 2025). Multivariate methods have also been used to examine the spatial variability of soil characteristics associated with cotton production (Afzal *et al.*, 2024).

However, the combined variation in soil texture, chemical fertility indicators and exchange-complex properties across the six selected cotton-growing locations in northern Côte d'Ivoire requires a location-specific assessment. Such a comparison is needed to distinguish differences in the soil conditions relevant to fertility management.

In this context, the present study was conducted to characterise cotton-growing soils using physicochemical indicators that may be altered by farming practices. Its main objective was to assess the spatial distribution of these indicators across six locations in the cotton-growing region of Côte d'Ivoire. More specifically, it aimed to provide stakeholders in the cotton sector with a tool for assessing soil suitability for cultivation, in order to guide them towards more environmentally friendly production practices.

## 2. Materials and Methods

### 2.1 Study Area

The study was conducted in the Savanes District, the cotton-growing region of northern Côte d'Ivoire (Fig. 1), more precisely in the Bagoué, Poro and Tchologo regions, at the end of the 2019/2020 cropping season.

Sites were selected on the basis of year-round accessibility and the willingness of cotton farmers to participate in the study. Population density was less than 1 inhabitant per km<sup>2</sup>, and cotton was the predominant crop on more than 80% of plots smaller than 5 ha.

Mean annual rainfall ranges from 1,055 to 1,483 mm (Dékoula *et al.*, 2018a, 2018b), and the mean annual temperature from 29 to 30°C. The vegetation consists of dense to degraded wooded savanna and shrub savanna. The dominant rocks are heterogeneous biotite granites and volcano-sedimentary schists, and elevation ranges from 300 to 700 m. The soils are mainly Ferralsols and Gleysols (Diomandé, 2016).

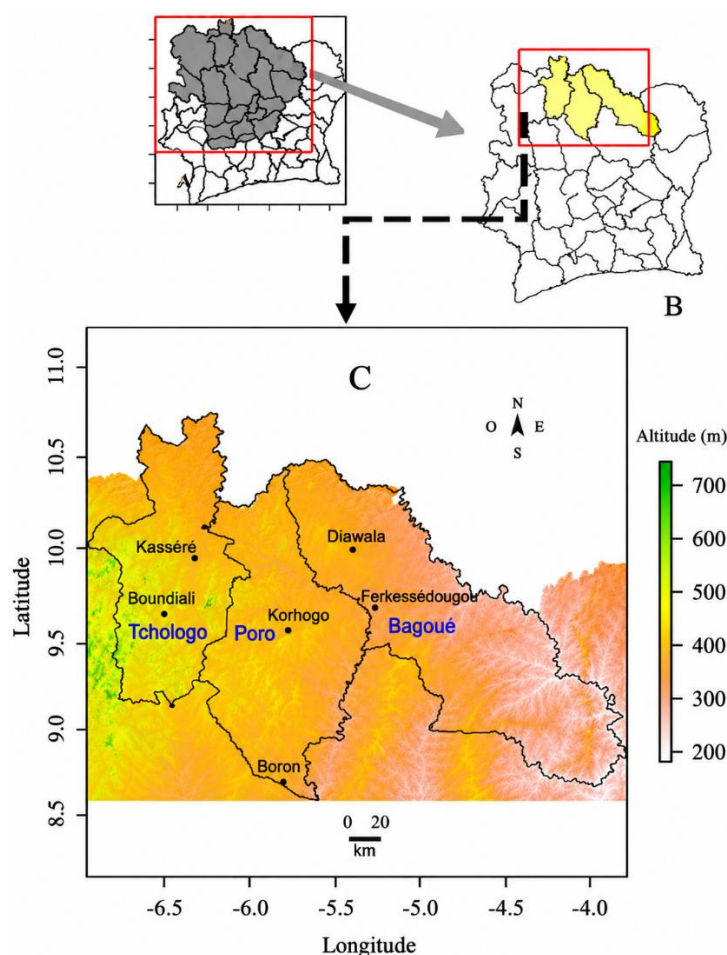


**Fig. 1. Location of the study area in Côte d'Ivoire (A : Côte d'Ivoire ; B : cotton-growing region ; C : Savanes District ; blue : regions)**

## 2.2 Soil Sampling

Soil samples were collected at six locations : Boron (8.41° N, 5.58° W), Boundiali (9.53° N, 6.48° W), Diawala (10.11° N, 5.48° W), Ferkessédougou (9.58° N, 5.20° W), Kasséré (8.83° N, 6.22° W) and Korhogo (9.46° N, 5.63° W). On each plot, random composite sampling was carried out in the 0–20 cm layer under cotton, with four samples collected from each plot. This approach aimed to assess the effect of the crop on the physical and chemical fertility of the soil.

## 2.3 Laboratory Analyses of Composite Soil Samples

Samples were air-dried, sieved through a 2-mm mesh and analysed for particle size distribution, pH, total nitrogen, available phosphorus ( $P_2O_5$ ) and exchangeable potassium, calcium, magnesium and sodium. Particle size distribution was determined by the Robinson pipette method (Pauwels *et al.*, 1992). Soil pH (pH  $H_2O$ ) was measured with a pH meter in a soil : distilled water suspension at a ratio of 1 : 2.5. Soil organic carbon (SOC) was determined by the Walkley and Black method, total nitrogen (Nt) by the Kjeldahl method and available phosphorus by the Olsen method. Exchangeable bases ( $Ca^{2+}$ ,  $K^+$ ,  $Mg^{2+}$  and  $Na^+$ ) were extracted with ammonium acetate buffered at pH 7 and determined by atomic absorption spectrophotometry. The cation exchange capacity (CEC) was determined by the Kjeldahl method on the  $NH_4^+$  ions displaced by a 10% NaCl solution, after removal of the excess ammonium acetate with alcohol.

Soil reaction (pH  $H_2O$ ) and the saturation deficit of the exchange complex with respect to alkaline earth cations ( $Ca^{2+}$  and  $Mg^{2+}$ ) and alkali cations ( $Na^+$  and  $K^+$ ) were interpreted by comparing the measured values with critical thresholds (Tables 1 and 2).

**Table 1. Soil acidity classes**

| Range | pH < 4.5    | 4.5 < pH < 5.0 | 5.0 < pH < 6.5  | 6.5 < pH < 7.5 | 7.5 < pH < 8.5 |
|-------|-------------|----------------|-----------------|----------------|----------------|
| Class | Very acidic | Acidic         | Slightly acidic | Neutral        | Basic          |

Source : Arrouays *et al.* (2012)

**Table 2. Critical interpretation thresholds for nutrient contents and CEC**

| Element                                                          | Critical interpretation values |              |              |         |           |
|------------------------------------------------------------------|--------------------------------|--------------|--------------|---------|-----------|
|                                                                  | Very low                       | Low          | Normal       | High    | Very high |
| Nt ( $\text{g}\cdot\text{kg}^{-1}$ )                             | < 0.5                          | 0.5 to 1.0   | 1.0 to 1.5   | > 2.5   |           |
| P <sub>2</sub> O <sub>5</sub> ( $\text{mg}\cdot\text{kg}^{-1}$ ) | < 15                           | 15 to 25     | 25 to 50     | > 100   |           |
| SOC ( $\text{g}\cdot\text{kg}^{-1}$ )                            | < 0.5                          | 0.5 to 1.0   | 1.0 to 1.5   | > 2.5   |           |
| K ( $\text{cmol}_+\cdot\text{kg}^{-1}$ )                         | < 0.10                         | 0.10 to 0.15 | 0.15 to 0.40 | > 15    |           |
| Ca ( $\text{cmol}_+\cdot\text{kg}^{-1}$ )                        | < 1.0                          | 1.0 to 2.5   | 2.5 to 3.5   | > 7.0   |           |
| Mg ( $\text{cmol}_+\cdot\text{kg}^{-1}$ )                        | < 0.5                          | 0.5 to 1.0   | 1.0 to 1.5   | > 3.0   |           |
| CEC ( $\text{cmol}_+\cdot\text{kg}^{-1}$ )                       | < 2                            | 2 to 3       | 3 to 8       | 8 to 15 | > 15      |

## 2.4 Statistical Analysis

The dataset comprised geographic coordinates (longitude and latitude), physical parameters (clay, coarse and fine silt, coarse and fine sand) and chemical parameters (pH, SOC, Nt, C/N ratio, available P, CEC,  $\text{Ca}/(\text{Mg} + \text{K})$  ratio, sum of exchangeable bases and base saturation). Differences between locations in the topsoil layer (0–20 cm) were analysed with R software version 4.2.3 (R Core Team, 2023) through the RStudio interface (RStudio Team, 2023). Pearson's parametric test was applied to compare particle size distribution, pH, organic matter, available phosphorus, CEC and exchangeable bases between soil groups. The normality of each variable was checked beforehand with the Shapiro–Wilk test.

## 3. Results and Discussion

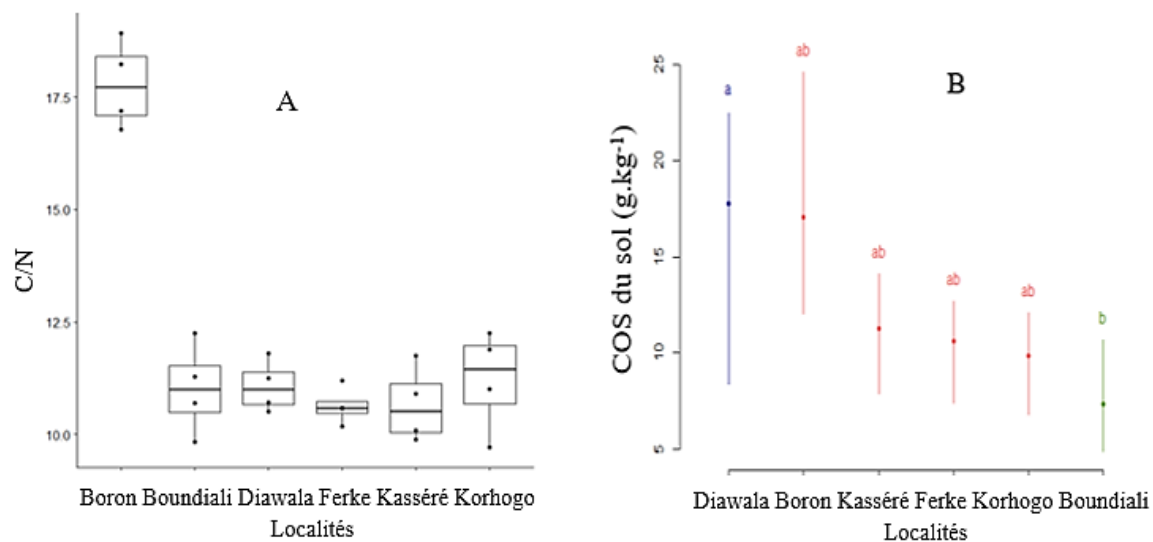
### 3.1 Variability of Soil Analytical Characteristics in the Cotton-Growing Area of Northern Côte d'Ivoire

#### 3.1.1 Soil Reaction (pH H<sub>2</sub>O)

Soils at the six locations ranged from slightly acidic to neutral, with mean pH values of  $6.45 \pm 0.27$  at Korhogo and  $7.12 \pm 0.34$  at Diawala. pH differed significantly between cotton-growing locations ( $p = 0.036$ ), owing to the neutral pH at Diawala and the slightly acidic pH at Korhogo (Table 3).

#### 3.1.2 Organic Matter Components

Soil organic carbon content ( $0.7 \pm 0.27 \text{ g}\cdot\text{kg}^{-1} < \text{SOC} < 1.8 \pm 0.34 \text{ g}\cdot\text{kg}^{-1}$ ) varied among the six locations. SOC was highest at Diawala ( $1.8 \pm 0.34 \text{ g}\cdot\text{kg}^{-1}$ ) and lowest at Boundiali ( $0.7 \pm 0.27 \text{ g}\cdot\text{kg}^{-1}$ ). Total nitrogen ranged from  $0.07 \pm 0.25 \text{ g}\cdot\text{kg}^{-1}$  at Boundiali to  $0.16 \pm 0.59 \text{ g}\cdot\text{kg}^{-1}$  at Diawala and was classified as very low at all sites (Table 2). Available phosphorus ranged from  $9 \pm 0.043 \text{ mg}\cdot\text{kg}^{-1}$  at Diawala to  $30 \pm 0.260 \text{ mg}\cdot\text{kg}^{-1}$  at Kasséré, spanning very-low, low and normal classes (Table 2). SOC mineralisation was high (rapid), with a mean C/N ratio close to 12. The C/N ratio differed significantly between locations ( $p = 3.14 \times 10^{-10}$ ; Fig. 2A) because of the higher value at Boron ( $\text{C}/\text{N} = 17$ ) compared with the other sites ( $\text{C}/\text{N} = 10.00\text{--}11.25$ ). P<sub>2</sub>O<sub>5</sub> contents were highest at Kasséré ( $30 \pm 0.260 \text{ mg}\cdot\text{kg}^{-1}$ ) and Boundiali ( $29 \pm 0.040 \text{ mg}\cdot\text{kg}^{-1}$ ), with an overall difference among sites ( $F(5, 15) = 4.21$ ;  $p = 0.014$ ). Figs. 2 and 3 show the variation in the C/N ratio and the multiple comparisons of SOC and P<sub>2</sub>O<sub>5</sub> contents, and Table 3 summarizes the mean values of soil reaction and organic matter components.

**Fig. 2. Variation in the C/N ratio (A) and multiple comparison of soil organic carbon (SOC) contents (B)**

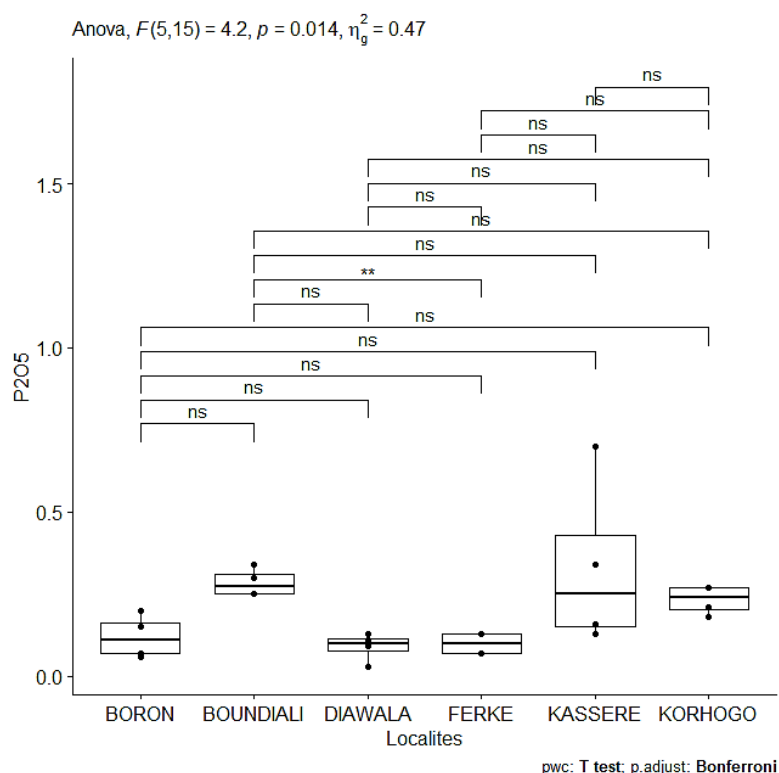


Fig. 3. Available phosphorus in cotton-growing soils (multiple comparisons with Bonferroni adjustment)

Table 3. Soil reaction (pH H<sub>2</sub>O) and organic matter components at the six cotton-growing sites

| Location            | pH H <sub>2</sub> O | SOC (g·kg <sup>-1</sup> ) | Nt (g·kg <sup>-1</sup> ) | C/N          | P <sub>2</sub> O <sub>5</sub> (mg·kg <sup>-1</sup> ) |
|---------------------|---------------------|---------------------------|--------------------------|--------------|------------------------------------------------------|
|                     | Mean ± SD           | Mean ± SD                 | Mean ± SD                | Mean         | Mean ± SD                                            |
| Boron               | 6.60 ± 0.34         | 1.7 ± 5.68                | 0.10 ± 0.27              | 17.00        | 12 ± 0.070                                           |
| Boundiali           | 6.55 ± 0.27         | 0.7 ± 0.27                | 0.07 ± 0.25              | 10.00        | 29 ± 0.040                                           |
| Diawala             | 7.12 ± 0.34         | 1.8 ± 0.34                | 0.16 ± 0.59              | 11.25        | 9 ± 0.043                                            |
| Ferkessédougou      | 6.85 ± 0.48         | 1.1 ± 0.48                | 0.10 ± 0.22              | 11.00        | 10 ± 0.035                                           |
| Kasséré             | 6.75 ± 0.10         | 1.1 ± 2.58                | 0.11 ± 0.173             | 10.00        | 30 ± 0.260                                           |
| Korhogo             | 6.45 ± 0.27         | 1.0 ± 2.24                | 0.09 ± 0.171             | 11.11        | 23 ± 0.045                                           |
| <b>Overall mean</b> | <b>6.71</b>         | <b>1.23</b>               | <b>0.11</b>              | <b>11.73</b> | <b>20</b>                                            |

SD : standard deviation. Means followed by the same lowercase letter are not significantly different at the 5% probability level ; ns : not significant ; \*\*: significant at  $p < 0.001$

### 3.1.3 Exchange Complex

Table 4 summarizes the distribution of the exchange complex in the sampled soils. The mean Ca/(Mg + K) ratio ranged from 1.45 at Boundiali to 3.44 at Korhogo, exceeding 2 at five of the six locations. It did not differ significantly between sites, the observed variations being due to chance ( $p = 0.089$ ). The mean Ca/Mg ratio ranged from 1.65 to 4.30 and remained within the stated optimal range (optimal range :  $1.5 < \text{Ca/Mg} < 5$ ). It differed significantly between locations ( $p = 0.0219$ ), owing to higher values at Korhogo (Fig. 4A). CEC ranged from 5.64 to 15.32  $\text{cmol}_+ \cdot \text{kg}^{-1}$ , encompassing the normal, high and very high classes and differed significantly between sites ( $p = 0.0013$ ), owing to the higher CEC at Kasséré (Fig. 4B). Base saturation ( $22.9\% \leq \text{S/T} \leq 59.4\%$ ) was generally low and differed significantly between sites ( $p = 0.00098$ ), owing to the higher value at Boron (Fig. 4C). Overall, the soils analyzed ranged from strongly desaturated (Hyperdystric) to moderately desaturated (Dystric) Ferralsols.

### 3.1.4 Particle Size Distribution

Table 5 summarizes the particle size distribution of the sampled soils. Clay, silt and sand contents differed significantly between locations. Clay content was highest in the cotton-growing soils of Kasséré and Diawala, while Kasséré had the lowest sand content. Silt content was highest at Kasséré ( $364.83 \text{ g} \cdot \text{kg}^{-1}$ ), with an overall difference among locations ( $p = 0.0477$ ). Clay content was below  $150 \text{ g} \cdot \text{kg}^{-1}$  at Boron, Boundiali, Ferkessédougou and Korhogo, resulting in an overall coarse, sandy texture. This texture is associated with a particulate structure of high porosity, making these highly permeable soils prone to a sharp reduction in the water reserve available to crops.

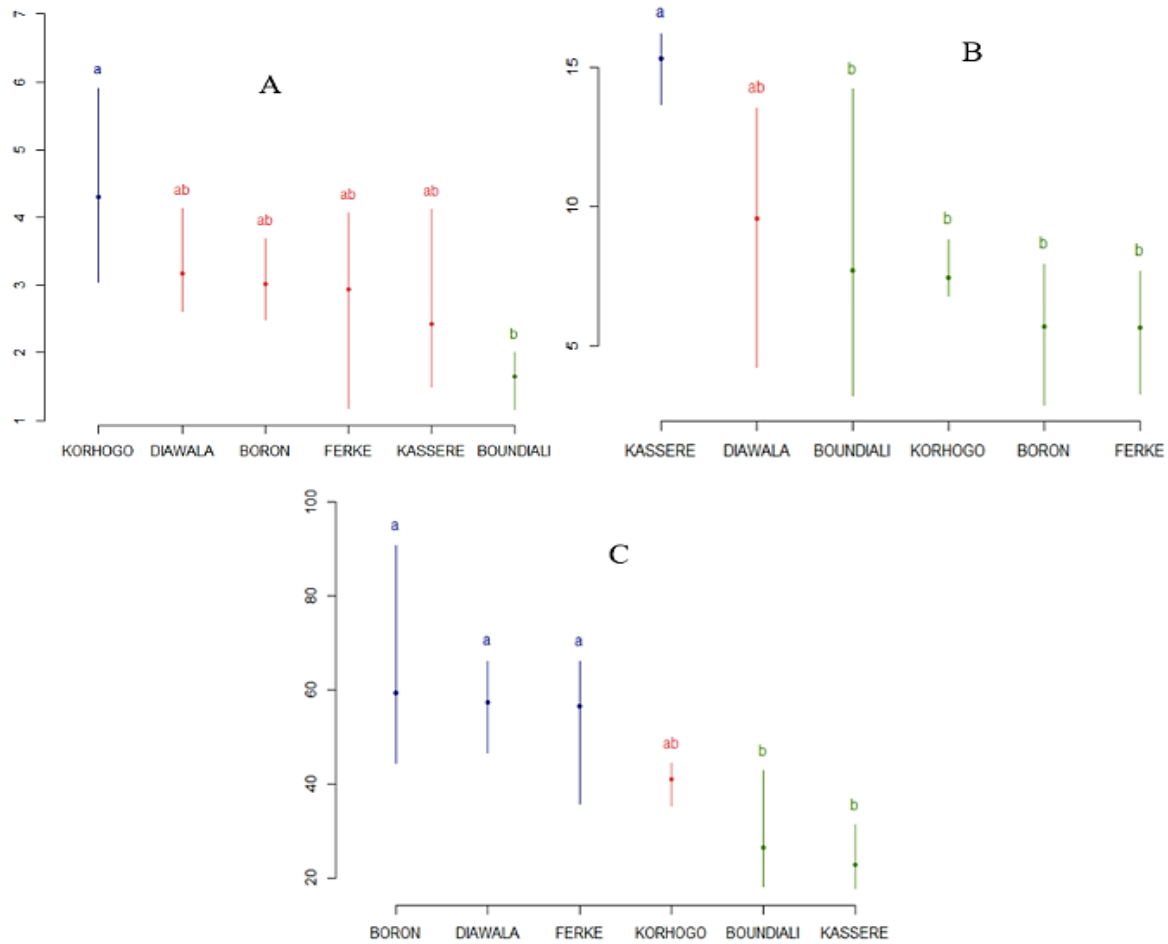


Fig. 4. Multiple comparisons of the Ca/Mg ratio (A), cation exchange capacity (CEC) (B) and base saturation (C)

Table 4. Spatial distribution of the exchange complex in soils under cotton

| Location       | Ca/ (Mg + K) |        | Ca/Mg       |        | CEC (cmol <sub>e</sub> ·kg <sup>-1</sup> ) |        | Base saturation S/T (%) |        |
|----------------|--------------|--------|-------------|--------|--------------------------------------------|--------|-------------------------|--------|
|                | Mean ± SD    | Median | Mean ± SD   | Median | Mean ± SD                                  | Median | Mean ± SD               | Median |
| Boron          | 2.28 ± 0.48  | 2.38   | 3.01 ± 0.50 | 2.93   | 5.68 ± 2.41                                | 5.96   | 59.4 ± 21.8             | 51.3   |
| Boundiali      | 1.45 ± 0.34  | 1.44   | 1.65 ± 0.40 | 1.72   | 7.71 ± 4.68                                | 6.72   | 26.4 ± 11.5             | 22.3   |
| Diawala        | 2.42 ± 1.06  | 2.49   | 3.18 ± 0.66 | 2.99   | 9.56 ± 3.90                                | 10.20  | 57.3 ± 9.22             | 58.3   |
| Ferkessédougou | 2.34 ± 0.98  | 2.64   | 2.93 ± 1.23 | 3.24   | 5.64 ± 1.82                                | 5.80   | 56.4 ± 13.9             | 62.0   |
| Kasséré        | 2.17 ± 1.00  | 1.83   | 2.43 ± 1.19 | 2.06   | 15.32 ± 1.19                               | 15.70  | 22.9 ± 5.92             | 21.2   |
| Korhogo        | 3.44 ± 0.89  | 3.30   | 4.30 ± 1.22 | 4.13   | 7.44 ± 0.92                                | 7.08   | 41.0 ± 4.19             | 42.1   |

SD : standard deviation

Table 5. Particle size distribution of the sampled soils (g·kg<sup>-1</sup>)

| Location       | Clay     | Silt     | Sand     | Texture    |
|----------------|----------|----------|----------|------------|
| Boron          | 131.25ab | 208.25b  | 660.50ab | Sandy      |
| Boundiali      | 144.25ab | 279.50b  | 576.25ab | Sandy      |
| Diawala        | 167.50a  | 268.50ab | 564.00ab | Sandy loam |
| Ferkessédougou | 120.00ab | 301.25b  | 578.75ab | Sandy      |
| Kasséré        | 183.75a  | 364.83a  | 451.43b  | Loam       |
| Korhogo        | 93.25b   | 133.50b  | 773.25a  | Sandy      |
| p-value        | 0.0039** | 0.0477*  | 0.0285*  |            |

Means followed by the same letter within a column are not significantly different at  $p < 0.05$ ; \*: significant at  $p < 0.01$ ; : significant at  $p < 0.05$

### 3.2 Hierarchical Ascending Classification (HAC) of Explanatory Variables (0–20 cm)

Fig. 5 presents the results of the hierarchical ascending classification (HAC). It reveals a contrast between two statistical classes (C1 and C2) : on the one hand, the spatial components (longitude and latitude) associated with soil reaction (pH, organic matter, base saturation), and on the other hand, the variables describing the soil capacity factor, i.e. its fixation capacity (CEC, clay, fine silt and coarse silt).

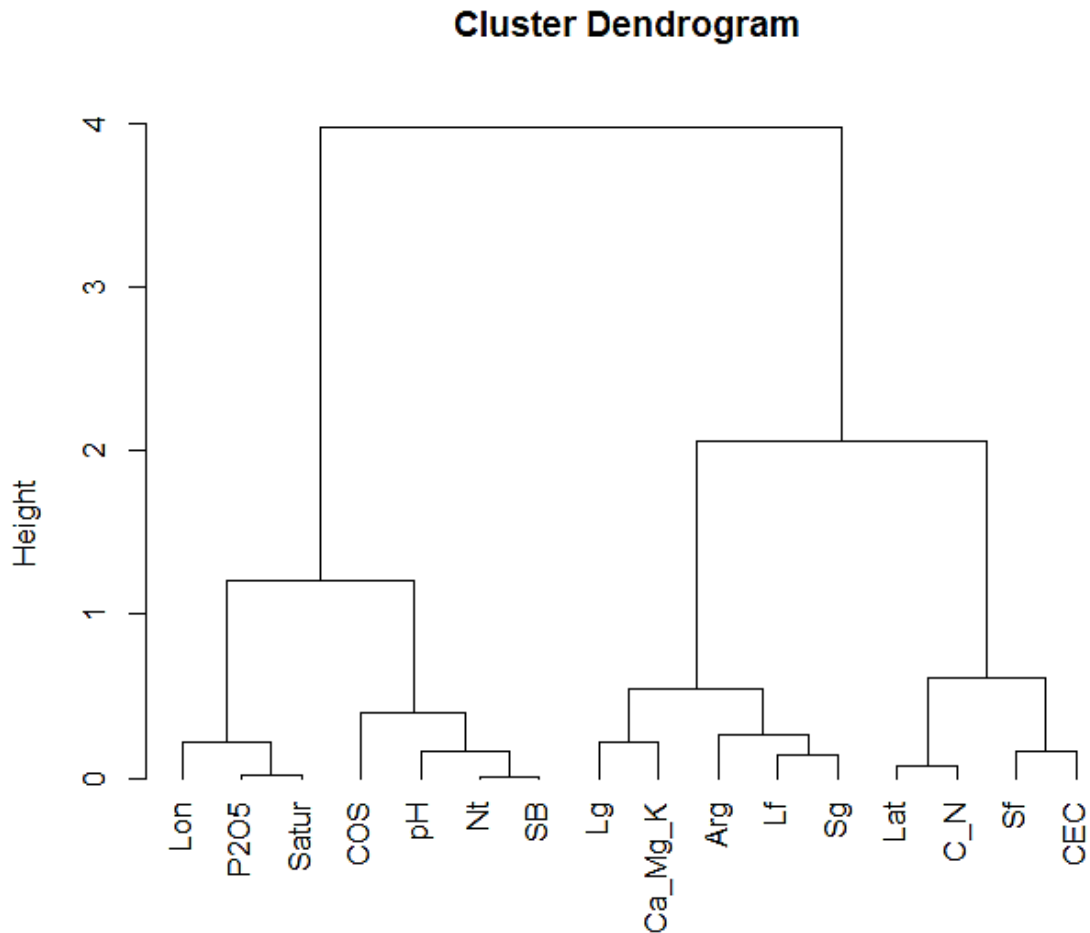


**Fig. 5. Dendrogram from the hierarchical ascending classification of the 16 variables measured in the 0–20 cm layer of cotton-growing soils**

The first statistical class was subdivided into two subclasses (C11 and C12) :

- **C11 comprises two groups** : one formed by the spatial component longitude (Lon), and the other by base saturation (Satur) and available phosphorus ( $P_2O_5$ ). C11 reflects the components related to phosphorus-fixing capacity.
- **C12 comprises three groups** : SOC, pH  $H_2O$ , and a group formed by total nitrogen (Nt) and the sum of exchangeable bases (SB). SOC and Nt are components of soil organic matter (SOM), while SB represents nutrient supply. Overall, in C12, pH emerges as the predictor that positively influences the success of soil restoration through the mobilisation of SOM and nutrients in drained soils under cotton.

The second statistical class also comprised two subclasses (C21 and C22) :

- C21 includes coarse silt (Lg) and the chemical balance ratio  $Ca/(Mg + K)$  in Group 1, clay (Arg) alone in Group 2, and fine silt (Lf) and coarse sand (Sg) in Group 3. C21 highlights the binding capacity of silicates and the role of the specific surface area of clays.
- C22 groups latitude and the SOM mineralisation rate in Group 1, and fine sand (Sf) and CEC in Group 2. C22 appears to indicate the factors that govern decisions on soil amendment and the cation exchange capacity of the soil.

Overall, these sets of variables can be used to define homogeneous soil groups.

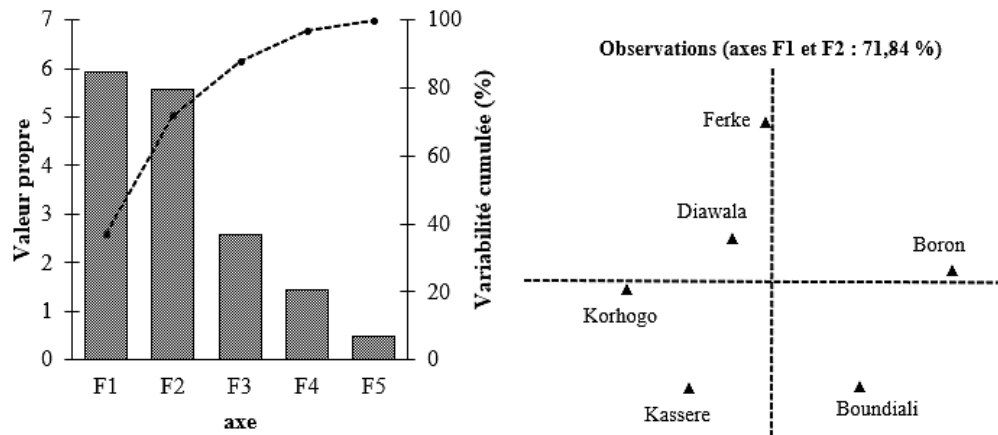


Fig. 6. Eigenvalues, percentage of inertia and projection of the locations on the factorial plane

### 3.3 Soil Typology and Structure of the 16 Variables across the Six Locations

The nature of the data called for a principal component analysis (PCA). The plane formed by the first two axes explained 71.84% of the total variance (Fig. 6), and Fig. 7 shows the variables that most influence this distribution :

- Base saturation and longitude, which are correlated with each other, are inversely correlated with soil  $P_2O_5$  content. Diawala showed average characteristics (points close to the origin), whereas Boundiali showed above-average characteristics. The Boundiali soils form a homogeneous group reflecting phosphorus-fixing capacity, corresponding to subclass C11.
- pH was positively related to total nitrogen and the sum of bases, both characteristic of the Ferkessédougou soil, which forms a homogeneous group corresponding to subclass C12.
- Particle size reveals a contrast between the fine fraction (coarse silt, fine silt and clay) and the coarse fraction (coarse sand). The three fine components are correlated with one another and inversely correlated with the percentage of coarse sand. Two sites form a homogeneous group on this basis : Kasséré, which had the lowest total sand content among the locations ( $451.43 \text{ g}\cdot\text{kg}^{-1}$ ), and Boron, characterised by its high coarse silt content. This third soil group corresponds to subclass C21.
- Latitude, SOM mineralisation rate, fine sand content and CEC characterise the fourth soil group. Judging by its angle with the axes, fine sand (Sf) has the greatest influence on this distribution. Sf is characteristic of the Korhogo soils, for which decisions on soil amendment and cation exchange capacity must be taken into account in cotton cultivation (subclass C22).

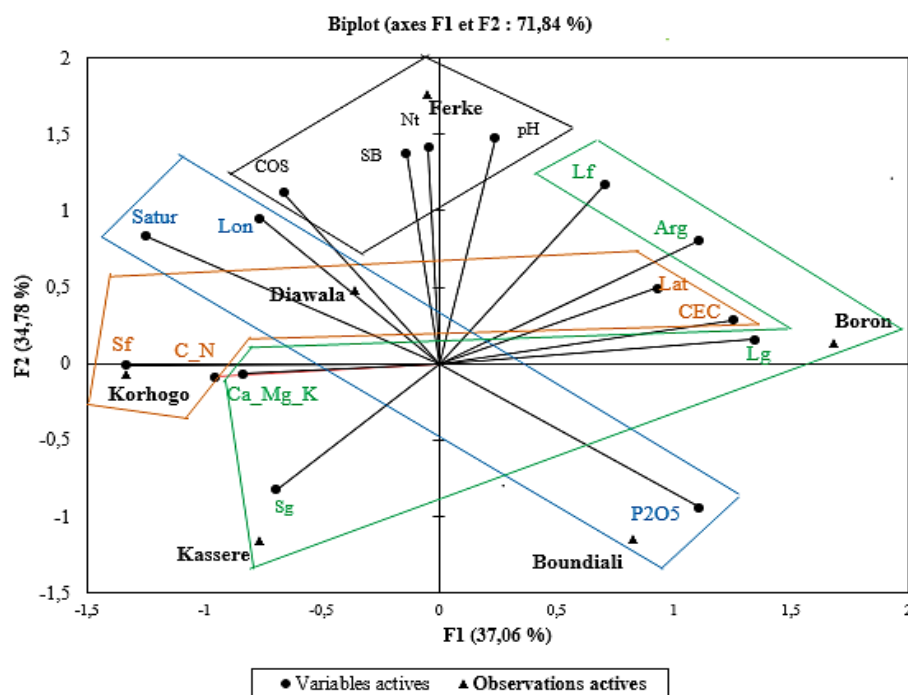


Fig. 7. Homogeneous soil groups of the locations on the factorial planes

According to Table 6, Lg (coarse silt), Sf (fine sand), pH, Nt and CEC each had a reported p-value below 0.05 on at least one of the first two principal axes. Irrespective of the homogeneous soil groups identified, coarse silt, fine sand, soil reaction, total nitrogen and CEC are the variables identified as influential (Table 6).

**Table 6. Coordinates of the influential variables on the first two principal axes**

| Variable | Axis 1 |                  |         | Axis 2 |                  |         |
|----------|--------|------------------|---------|--------|------------------|---------|
|          | Coord. | Cos <sup>2</sup> | p-value | Coord. | cos <sup>2</sup> | p-value |
| Lg       | 0.883  | 0.78             | 0.018   | 0.103  | 0.011            | –       |
| Sf       | –0.877 | 0.77             | 0.022   | –0.008 | 0.000            | –       |
| pH       | 0.157  | 0.025            | –       | 0.969  | 0.938            | 0.004   |
| Nt       | –0.030 | 0.001            | –       | 0.930  | 0.865            | 0.023   |
| CEC      | 0.825  | 0.68             | 0.038   | 0.188  | 0.035            | –       |

*For each variable, values in bold indicate the axis with the largest squared cosine*

The correlogram of the five influential variables (Fig. 8) showed a strong positive linear relationship ( $|r| > 0.7$ ) between pH and Nt. Nt showed moderate positive linear relationships with Lf ( $r = 0.51$ ) and CEC ( $r = 0.50$ ). Similarly, Lf showed moderate positive linear relationships with Lg ( $r = 0.56$ ) and CEC ( $r = 0.46$ ). A positive linear relationship ( $|r| > 0.5$ ) was also observed with CEC.

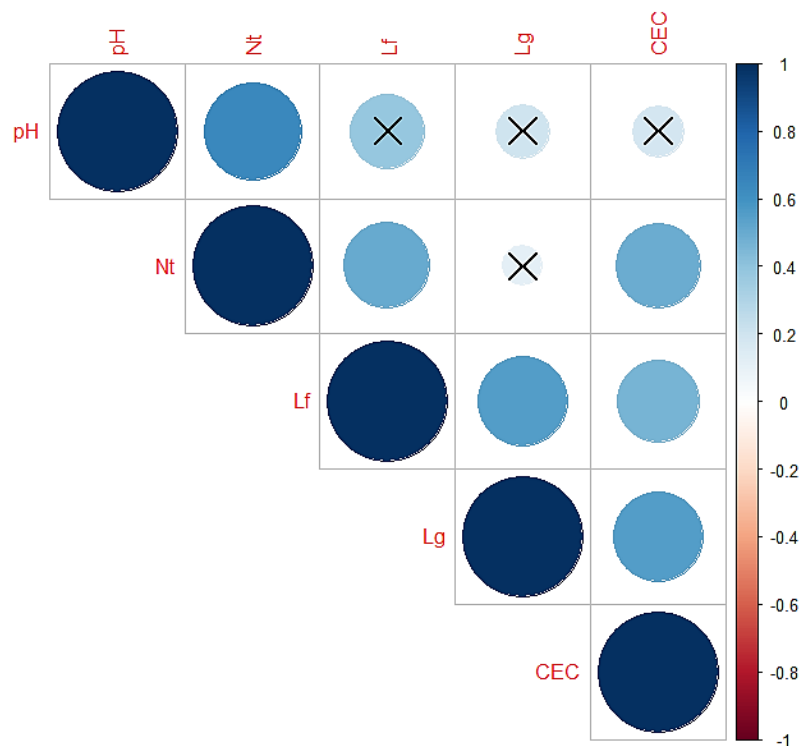


**Fig. 8. Correlogram of the influential soil variables with Pearson significance levels**

*Blue : positive correlation ; red : negative correlation ; colour intensity indicates the level of significance and circle size is proportional to the correlation ; (x) : not significant at  $p < 0.05$*

This study measured a set of physicochemical indicators selected on the basis of previous research (Ama *et al.*, 2022 ; Ballot *et al.*, 2016 ; Kouadio *et al.*, 2018). In addition to in situ observations, laboratory soil analyses (texture, pH, organic matter content and major nutrients N, P and K) are regularly commissioned to enable farmers to assess the impact of their practices and manage their soils more precisely. Soil organic carbon levels ranged from 0.7 to 1.8 g·kg<sup>-1</sup> across the six locations, which can be attributed to the regular application of organic amendments (manure). Manure applications increase surface SOC content, lower the C/N ratio and promote rapid mineralisation of the applied organic matter and of other plant residues (Hien *et al.*, 2003). However, in predominantly sandy soils, this rapid mineralisation does not always make nutrients available at critical stages of crop development. Regardless of soil type, a minimum organic matter content of 5% is recommended, which was not the case in these cotton-growing soils. Approximately 25 kg·m<sup>-2</sup> of compost, applied in several split applications, would therefore be needed to approach this level.

Total nitrogen was classified as very low at all six locations (0.07–0.16 g·kg<sup>-1</sup>). Nitrogen stimulates plant growth and is the main yield-determining nutrient, as it is a component of proteins, chlorophyll and enzymes essential for photosynthesis and respiration. Nitrogen deficiency results in markedly reduced growth, smaller leaves and rapid yellowing of the oldest leaves. Phosphorus (P<sub>2</sub>O<sub>5</sub>), which plays an important role in root growth, flowering, and fruit set and ripening, varied from very low (9–12 mg·kg<sup>-1</sup>) to

low ( $23 \text{ mg}\cdot\text{kg}^{-1}$ ) and normal ( $29\text{--}30 \text{ mg}\cdot\text{kg}^{-1}$ ) across the six locations (Tables 2 and 3). Site-specific phosphorus inputs should therefore be considered, as they also promote iron and zinc uptake (Plassard *et al.*, 2015). Phosphorus limitations at some locations should be considered alongside the fact that, in these slightly acidic to neutral soils, phosphorus, potassium, calcium, magnesium, sulfur and molybdenum are more readily absorbed by plants, whereas iron, manganese, boron, copper and zinc are less readily absorbed. Furthermore, most plants grow best at a soil pH between 6 and 7, the range in which most nutrients are available. This may explain the nitrogen deficiency in the sampled soils.

The very low total nitrogen contents ( $0.07\text{--}0.16 \text{ g}\cdot\text{kg}^{-1}$ ) is linked both to the nature of the soils and to temperature-dependent pedoclimatic conditions that govern the decomposition of soil organic matter (SOM). Indeed, most soils showed a high (rapid) SOM mineralisation rate (C/N ratio close to 11). A household survey also revealed that ploughing is practiced in cotton cultivation. These observations are consistent with the findings of Peukert *et al.* (2016), who reported that ploughing reduces organic carbon and nitrogen levels by breaking up soil aggregates, thereby increasing aeration and organic matter mineralisation.

The mean  $\text{Ca}/(\text{Mg} + \text{K})$  ratio was above 2 at five locations but was 1.45 at Boundiali (Table 4). The maximum mean value was recorded at Korhogo (3.44). The mean  $\text{Ca}/\text{Mg}$  ratio ranged from 1.65 at Boundiali to 4.30 at Korhogo (Table 4). Cotton stalks can be difficult for soil microorganisms to decompose because of their high lignin or silica content. This results in slow decomposition and a low degree of mineralisation of organic matter (Hien *et al.*, 2003), particularly in the Boron soils, where the C/N ratio was high ( $\text{C}/\text{N} = 17$ ). Such a high C/N ratio suggests the presence of less reactive organic matter that is difficult to biodegrade.

The results highlighted two sets of parameters forming two distinct statistical classes : those related to soil acidity (pH, base saturation,  $\text{P}_2\text{O}_5$ , SOC, N, SB) and those related to soil fixation capacity (clay, silt, CEC). Based on these two classes, four homogeneous soil groups were identified. Available phosphorus ( $\text{P}_2\text{O}_5$ ) was highest at Kasséré ( $30 \text{ mg}\cdot\text{kg}^{-1}$ ), followed by Boundiali ( $29 \text{ mg}\cdot\text{kg}^{-1}$ ) (Table 3). Kasséré had the lowest total sand content ( $451.43 \text{ g}\cdot\text{kg}^{-1}$ ) and the highest clay ( $183.75 \text{ g}\cdot\text{kg}^{-1}$ ) and silt ( $364.83 \text{ g}\cdot\text{kg}^{-1}$ ) contents (Table 5). In the Poro Region, there was a contrast between the abundance of coarse silt at Boron and of fine sand at Korhogo. In the Bagoué Region, only Ferkessédougou showed an above-average profile, characterised by neutral soils, while Diawala showed an average profile. Ultimately, irrespective of the homogeneous soil groups identified, coarse silt, fine sand, soil reaction, total nitrogen and cation exchange capacity were the variables identified as influential (Table 6), and the agricultural value of these soils will depend on the proportion of coarse particles.

The influence of CEC suggests that exchangeable bases contribute to soil structure by forming “bridges” that bind organic and mineral matter (Collaud *et al.*, 1990), hence their important role in the functioning of the soils studied. Bases also modify soil pH and thus directly influence nutrient availability. CEC depends on texture (clay and fine silt contents) and on soil organic matter content. CEC ranged from  $5.64$  to  $15.32 \text{ cmol}_+ \cdot \text{kg}^{-1}$  across the locations, and soil fertility could be improved by adding organic matter such as compost. An important finding is that the sampled soils were less than 60% saturated with nutrient cations, yet they were not acidic. These results do not agree with those of Collaud *et al.* (1990), who reported that a soil less than 60% saturated with nutrient cations has an acidic pH, with many exchange sites occupied by  $\text{H}^+$  ions. This difference could be explained by current farming practices in the study area, since most farmers use soil amendments to restore fertility in cotton fields. Finally, some of the correlations among the examined variables were positive, although not all pairwise correlations were statistically significant (Fig. 8).

## 5. Conclusion

The pH of the soils studied, ranging from 6.45 to 7.12, indicates a slightly acidic to neutral reaction. Under these conditions, the availability of phosphorus, potassium, calcium and magnesium generally supports plant mineral nutrition, whereas the availability of some micronutrients, notably iron, manganese, boron, copper and zinc, is less favourable. The predominantly sandy texture gives these soils several favourable properties, including rapid warming, good aeration, a generally loose structure and ease of tillage. However, this texture also imposes a major constraint, namely a low capacity to retain water and nutrients. These soils are therefore particularly susceptible to drying out between rainfall events and to nutrient losses through leaching, especially when fertiliser applications are poorly matched to crop needs.

Furthermore, although soil organic carbon varied between  $0.7$  and  $1.8 \text{ g}\cdot\text{kg}^{-1}$ , its rapid mineralisation, favoured by the predominantly sandy texture, can release nutrients at times that do not coincide with crop needs during critical growth stages. This underscores the need to improve sustainably the organic status of these soils in order to enhance their water- and nutrient-holding capacity, improve their fertility and support crop productivity. Regular compost application is an effective way to gradually increase organic matter content. However, the application rate should be determined according to the initial organic matter content, bulk density, the soil depth considered and the composition of the compost. Split applications tailored to soil characteristics and crop requirements will therefore be more effective in improving soil fertility and promoting the sustainable management of soil resources.

## 6. Limitations

The study was restricted to the 0–20 cm soil layer at six selected cotton-growing locations and therefore does not establish conditions in deeper horizons or throughout northern Côte d'Ivoire. Site selection considered accessibility and farmer participation. The available manuscript does not report sufficient sampling detail to assess spatial representativeness fully. The cross-sectional soil measurements also do not demonstrate changes over time or the effects of particular management practices. Fertility-management implications should therefore be evaluated through further site-specific investigation.

## Declaration of AI Use

This manuscript was prepared through the intellectual contributions of the author(s) to the study design, data analysis, interpretation of results, and scholarly content. Grammarly and ChatGPT were used solely to assist with grammatical refinement and reference formatting during manuscript revision. The author(s) accept full responsibility for the accuracy, integrity, and final content of the manuscript.

## Competing Interests

Authors have declared that they have no known competing financial interests or non-financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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