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RESEARCH ARTICLE

INFLUENCE OF SOIL PHYSICOCHEMICAL PROPERTIES ON URBAN MARKET GARDENING PERFORMANCE IN SARH (CHAD)

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ABSTRACT

Urban market gardening is making an increasingly significant contribution to food security and the livelihoods of urban populations in sub-Saharan Africa, but its performance remains heavily dependent on soil quality. This study analyses the influence of soil physico-chemical properties on the performance of urban market gardening in the town of Sarh, located in the Sudanese zone of southern Chad. Fifteen vegetable plots representative of the main production areas were sampled. The soils underwent physico-chemical analyses for pH, electrical conductivity, organic carbon, organic matter, total nitrogen and available phosphorus. Vegetable yields were estimated at the smallholder level using the density square method, then extrapolated to the hectare. The results show significant textural heterogeneity in the soils, characterised by a predominance of the sandy fraction (58.53 ± 10.84%), followed by clay (27.20 ± 7.99%) and silt (14.27 ± 5.15%). The soils have a slightly acidic to near-neutral pH (6.42 ± 0.38) and an average electrical conductivity of 185.1 ± 44.1 $\mu S \cdot cm^{-1}$, indicating the absence of saline stress. The average organic carbon (3.22 ± 1.05%) and organic matter (5.54 ± 1.79%) contents are relatively high but spatially variable, as is total nitrogen (0.050 ± 0.018%). Estimated vegetable yields range from 9.5 to 15 $t \cdot ha^{-1}$ depending on the site. Statistical analyses performed using R software reveal a strong and significant positive relationship between yield and organic carbon ($r = 0.867$; $p < 0.001$) and organic matter ($r = 0.864$; $p < 0.001$). Principal component analysis highlights a major organo-mineral fertility gradient contrasting organic matter-rich and more clayey soils, associated with higher yields, with less productive sandy soils. PH appears to be a factor that influences nutrient availability, though it is not the primary determinant of productivity. This study highlights the central role of organic matter management and soil structure in the sustainable improvement of urban market gardening in Sarh.

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INTRODUCTION

Urban agriculture, and more specifically urban market gardening, plays a strategic role in the food systems of African cities facing rapid population growth, unplanned urbanization, and persistent food and nutritional insecurity (Aubry & Kebir, 2022; Drechsel *et al*., 2023). In sub-Saharan Africa, urban market gardening contributes significantly to the supply of fresh vegetables to markets, the dietary diversification of urban households, and the creation of jobs for often vulnerable populations (Karg *et al*., 2020; Orsini *et al*., 2020). However, despite its socio-economic and nutritional importance, the productivity of urban market gardening remains severely constrained by biophysical, technical, and institutional factors, among which soil quality plays a central role (Houessou *et al*., 2021; Lal, 2020). Urban soils are often characterized by high spatial heterogeneity, physical and chemical degradation, and potential contamination linked to human activities (Tóth *et al*., 2022). These constraints directly affect crop growth, input efficiency, and ultimately the agronomic and economic performance of urban market gardening systems. The physicochemical properties of soils, including texture, pH, organic matter content, cation exchange capacity, availability of major nutrients (nitrogen, phosphorus, potassium), and exchangeable bases, are major determinants of vegetable crop yields (Havlin *et al*., 2019; Weil & Brady, 2023). Several studies have shown that nutritional imbalances, low organic matter content, or excessive soil acidity can significantly limit vegetable productivity, particularly in intensive urban market gardening systems (Bationo *et al*., 2021; Tittonell *et al*., 2020).

Urban soils are often characterized by high spatial heterogeneity, physical and chemical degradation, and potential contamination linked to human activities (Tóth *et al*., 2022). These constraints directly affect crop growth, input efficiency, and ultimately the agronomic and economic performance of urban market gardening systems. The physicochemical properties of soils, including texture, pH, organic matter content, cation exchange capacity, availability of major nutrients (nitrogen, phosphorus, potassium), and exchangeable bases, are major determinants of vegetable crop yields (Havlin *et al*., 2019; Weil & Brady, 2023). Several studies have shown that nutritional imbalances, low organic matter content, or excessive soil acidity can significantly limit vegetable productivity, particularly in intensive urban market gardening systems (Bationo *et al*., 2021; Tittonell *et al*., 2020). Furthermore, most existing research on urban market gardening in sub-Saharan Africa focuses either on socio-economic and organizational aspects or on cultivation practices, with limited attention paid to detailed analysis of soil–plant–yield relationships in urban market gardening systems (Kahane *et al*., 2020; Poulsen *et al*., 2021). This gap limits the ability to formulate agronomic recommendations based on solid scientific foundations and adapted to local realities. In this context, analyzing the influence of soil physicochemical properties on urban market gardening performance appears to be an essential lever for sustainably improving the productivity and resilience of these production systems. A better understanding of the soil constraints specific to urban market gardening sites would not only optimize soil fertility management, but also contribute to the ecological intensification of urban market gardening, reconciling agronomic performance, environmental sustainability, and food security (Lal, 2020; Vanlauwe *et al*., 2022). This article aims to analyze the influence of soil physicochemical properties on urban market gardening performance in the city of Sarh (southern Chad) in order to identify the main edaphic factors that limit or promote market garden productivity. The expected results should contribute to improving soil management practices, developing more rational fertilization strategies, and supporting local urban agriculture development policies.

MATERIALS AND METHODS

The study was conducted in the city of Sarh, located in the Sudanian zone of southern Chad, characterized by a humid tropical climate with a marked rainy season and a strong urban and peri-urban market gardening dynamic. The market gardening sites studied were selected in a reasoned manner to represent the diversity of soil and hydrological conditions and farming practices observed in the city's main urban market gardening areas. Three vegetable production areas (Kamati, Tombalbaye, and Jardin) were selected on the basis of their agronomic importance, accessibility, and intensity of exploitation. Within each area, plots were chosen to cover the spatial variability of soils (texture, local topography, proximity to water sources) and management practices (organic inputs, mineral fertilization, crop intensity). A total of 15 market garden plots were sampled, ensuring sufficient representativeness of urban market garden soils in Sarh, in accordance with methodological recommendations for soil studies applied to tropical agricultural systems. On each selected plot, soil samples were taken from the surface horizon (0–20 cm), corresponding to the main rooting zone of vegetable crops and the layer most influenced by cultivation practices. A composite sample was taken per plot from five sub-samples taken in a zigzag pattern to reduce the effect of intra-plot heterogeneity. The composite samples were dried in the open air, sieved to 2 mm for physicochemical analysis, and then stored under appropriate conditions until laboratory analysis. The physico-chemical analyses of the soils were carried out at the Soil-Water-Plant Analysis Laboratory of the Chadian Agronomic Institute for Development (ITRAD) in N'Djamena. These analyses focused on the main physical and chemical properties of soils that determine fertility and vegetable productivity. The methods used are internationally recognized reference methods, ensuring the comparability of results with scientific literature:

- **Particle size (sand, silt, clay):** determined by the sedimentation method (pipette or hydrometer method), after chemical and mechanical dispersion.
- **Soil pH:** measured in a soil-water suspension (ratio 1:2.5) using an electronic pH meter.

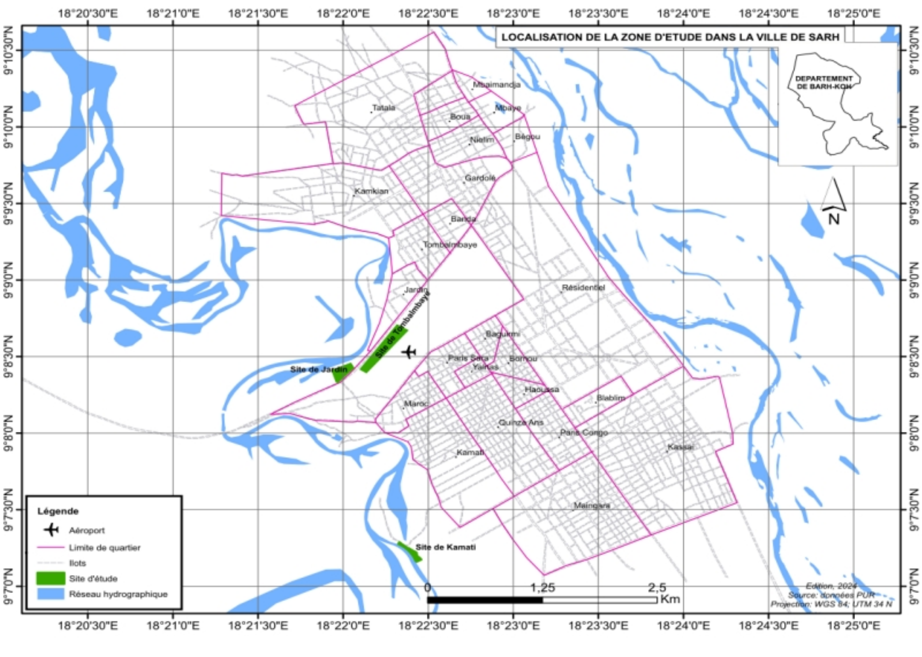

Figure 1: Map showing the location of the three production sites in the city

- **Electrical conductivity (EC):** measured in the aqueous soil extract, expressed in $\mu S \cdot cm^{-1}$, in order to assess the salinity level.
- **Organic carbon (OC):** determined using the Walkley and Black method.
- **Organic matter (OM):** estimated from organic carbon by applying a standard conversion factor.
- **Total nitrogen (TN):** measured using the Kjeldahl method.
- **Assimilable phosphorus (P):** extracted using a method adapted to tropical soils and quantified by colorimetry.

These parameters were chosen because of their central role in vegetable crop nutrition and their ability to explain yield variations observed in tropical urban environments. Vegetable yields were estimated directly in rural areas using the density square method, commonly used to assess agricultural production under real growing conditions. On each plot, squares of known area (6 m^2) were delimited randomly or systematically, taking into account planting density and the apparent homogeneity of the vegetation cover. The produce harvested within each square was weighed using precision scales, then extrapolated to the hectare to obtain the yield expressed in tons per hectare ($t \cdot ha^{-1}$). This method limits the bias associated with producers' declarative estimates and provides more reliable and comparable yield data between sites. The collected data were entered, processed, and analyzed using R software (latest version), a statistical environment widely used in agricultural research. The statistical analyses were conducted according to the following steps:

- Descriptive statistics: calculation of means, standard deviations, coefficients of variation (CV), minimum and maximum values to characterize the variability of soil properties and vegetable yields.
- Normality tests: the normality of the variables was assessed using the Shapiro–Wilk test, which determined the choice of subsequent statistical analyses.
- Correlation analyses: the relationships between the physicochemical properties of soils and vegetable yields were examined using:
- Pearson's correlation when normality conditions were satisfied,
- Spearman's correlation when they were not.
- Principal component analysis (PCA): PCA was performed to identify major soil fertility gradients and visualize the structure of vegetable plots based on soil properties and yield levels. This multivariate approach allows information to be synthesized and associations between variables to be highlighted.

All statistical results were interpreted at a significance level of 5% ($p < 0.05$), in accordance with standards in agricultural science.

RESULTS AND DISCUSSION

Descriptive statistics of the main physicochemical properties of the vegetable garden soils studied: Table 1 presents descriptive statistics for the main granulometric (sand, silt, clay) and physicochemical properties of the vegetable garden soils studied (pH, electrical conductivity, organic carbon, organic matter, total nitrogen, and assimilable phosphorus), calculated from 15 soil samples. None of the variables analyzed had any missing values, ensuring the robustness of the statistical estimates. The texture parameters indicate a clear dominance of the sand fraction, with an average content of 58.53 ± 10.84%, compared to 27.20 ± 7.99% for clay and 14.27 ± 5.15% for silt. The moderate to high coefficients of variation (18.52–36.08%) reflect significant textural heterogeneity between vegetable plots. Chemically, the soils have a slightly acidic to near-neutral pH (mean = 6.42 ± 0.38), with low variability (CV = 5.90%), suggesting conditions that are generally favorable for nutrient availability. The average electrical conductivity (185.1 ± 44.1 μS/cm) remains well below critical salinity thresholds, indicating the absence of saline constraints for vegetable crops. The organic carbon (3.22 ± 1.05%) and organic matter (5.54 ± 1.79%) contents are relatively high but marked by significant variability (CV ≈ 32%), reflecting heterogeneous organic fertilization practices between sites. Total nitrogen, with an average of 0.05 ± 0.018%, also shows high dispersion (CV = 35.46%), suggesting uneven nitrogen enrichment levels, which may be limiting for some plots. In contrast, assimilable phosphorus levels appear relatively high (45.35 ± 7.41 mg/kg) and more homogeneous (CV = 16.34%), which may reflect regular application of phosphate fertilizers or accumulation linked to intensive farming practices.

Analysis of correlations between the physicochemical properties of soils and fertility indicators: Pearson's correlation matrix highlights a strong structuring of edaphic properties around a core of organic–nitrogen–clay fertility. Organic matter, total nitrogen, electrical conductivity, and clay content show high positive correlations (r = 0.73 to 0.93), reflecting a co-variation in chemical fertility and retention capacity indicators. Conversely, the sandy fraction is strongly and negatively correlated with these parameters (r = −0.63 to −0.89), confirming the less fertile and less buffered nature of sandy soils. pH shows a negative correlation with available phosphorus (r = −0.68), suggesting that P availability is controlled by soil reaction. These results indicate that the performance of urban market gardening in Sarh is closely dependent on the level of organic matter, soil nitrogen, and fine texture, justifying integrated fertility management strategies based on organic amendments.

Structuring of the physicochemical properties of soils using principal component analysis (PCA): Principal component analysis (PCA) applied to the physicochemical variables of market garden soils reveals a marked structuring of plots along the first two factor axes, which together explain 87.8% of the total variance, with 63.7% for axis 1 (PC1) and 24.1% for axis 2 (PC2). This high proportion of explained variance attests to the strong discriminating power of the soil variables considered. The main axis (PC1) is mainly structured by an organo-mineral fertility gradient, strongly positively correlated with organic matter (OM), organic carbon, total nitrogen (Nt), clay (A), and electrical conductivity (EC). Conversely, the sandy fraction (S) is projected negatively on this axis, reflecting a clear contrast between fine-textured, nutrient-rich and chemically active soils, and coarse-textured, poorer soils with low mineral retention capacity. The distribution of sites on the factorial plane clearly reflects this contrast. Plots located on the positive side of PC1 (particularly sites T1 to T5) are associated with more clayey-loamy soils, richer in organic matter and nitrogen, and therefore potentially more favorable for intensive vegetable production. Conversely, sites projected on the negative side of PC1 (mainly sites J and K) correspond

Table 1. Descriptive statistics of the physicochemical properties of market garden soils in Sarh (southern Chad)

Variable	Unit	n	Mean ± SD	CV (%)	Min	Max
Sand (S)	%	15	58.53 ± 10,84	18.52	45.00	72.00
Silt (L)	%	15	14.27 ± 5,15	36.08	9.00	28.00
Clay (A)	%	15	27.20 ± 7,99	29.39	17.00	39.00
pH (H_2O)	%	15	6.42 ± 0,38	5.90	5.84	6.85
Electrical conductivity (EC)	µS cm^{-1}	15	185.1 ± 44,1	23.84	103.0	244.0
Organic carbon (OC)	%	15	3.22 ± 1,05	32.49	2.05	5.18
Organic matter (OM)	%	15	5.54 ± 1,79	32.28	3.50	8.90
Total nitrogen (TN)	%	15	0.050 ± 0,018	35.46	0.02	0.07
Assimilable phosphorus (P)	mg kg^{-1}	15	45.35 ± 7,41	16.34	35.11	57.46

Note. Values are expressed as mean ± standard deviation. CV = coefficient of variation. pH measured in water. EC = electrical conductivity of soil.

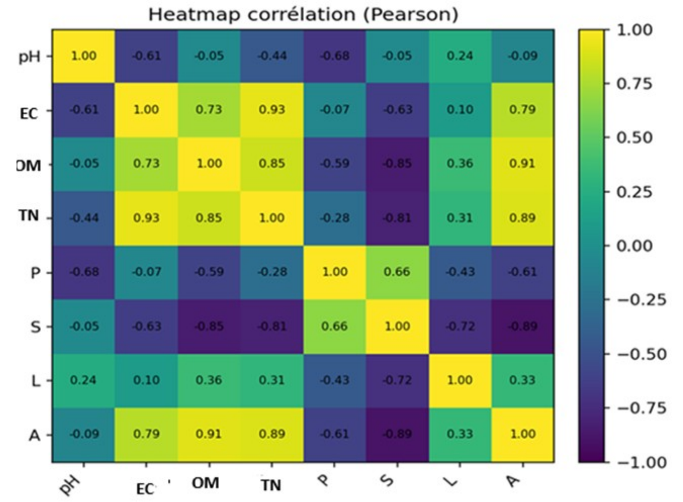

Figure 2. Correlations between the physicochemical properties of soils and fertility indicators

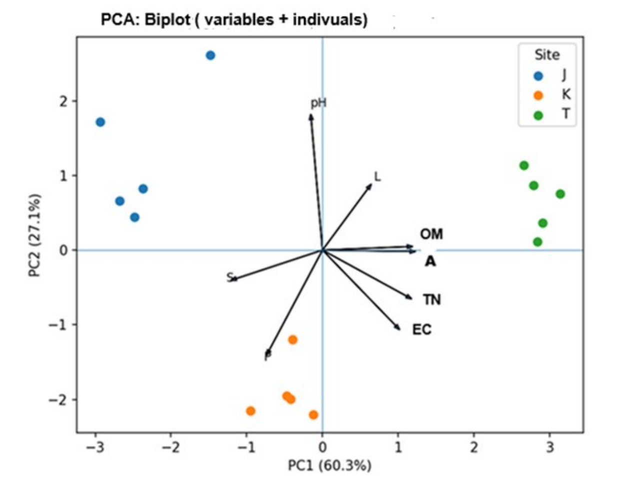

Figure 3. Structuring of soil physicochemical properties using principal component analysis (PCA)

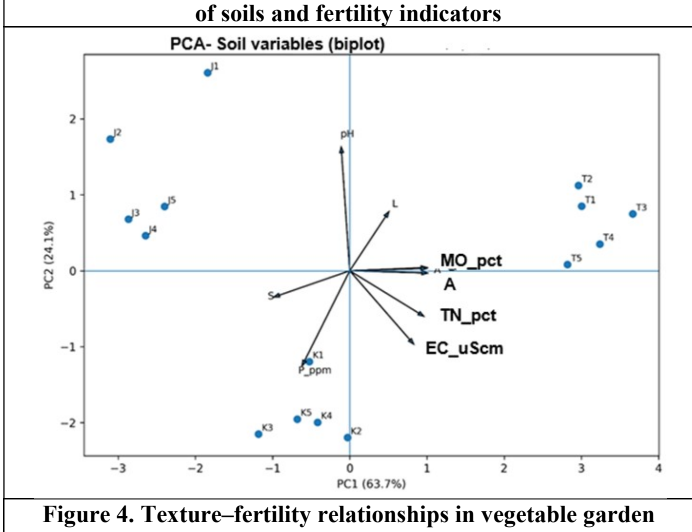

Figure 4. Texture–fertility relationships in vegetable garden soils (PCA)

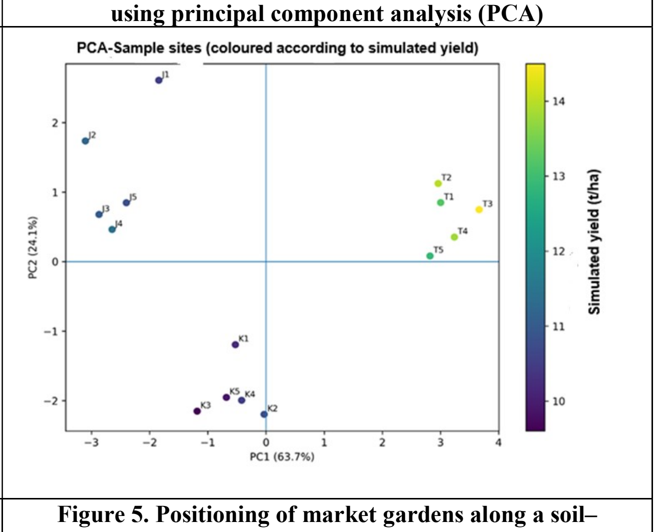

Figure 5. Positioning of market gardens along a soil–productivity gradient revealed by PCA

to predominantly sandy soils, characterized by lower fertility and greater vulnerability to nutrient losses, requiring more intensive and targeted fertility management strategies. The secondary axis (PC2) is mainly influenced by pH, which partially opposes variables related to available phosphorus (P). This structure suggests that pH plays a role in modulating nutrient availability rather than overall fertility levels, particularly with regard to phosphorus solubilization and fixation processes. Thus, soils with contrasting pH levels may have comparable nutrient stocks but different absorption efficiencies for vegetable crops. Overall, this PCA highlights that the potential performance of urban market gardening is closely linked to the combination of texture, organic matter, and nitrogen, while pH is a secondary but structuring factor that determines the effective accessibility of nutrients. These results confirm the central role of organic matter management and soil structure improvement in the sustainable optimization of vegetable productivity in Sarh.

Texture–fertility relationships in vegetable garden soils (PCA) at the sites studied: Principal component analysis (PCA) applied to the physicochemical and textural variables of market garden soils reveals a clear structuring of the samples along the first two factor axes, which together explain 87.8% of the total variance, with 63.7% for axis 1 (PC1) and 24.1% for axis 2 (PC2). This high proportion of explained variance highlights the relevance of PCA for summarizing edaphic information and discriminating between the types of soils studied. The main axis (PC1) is dominated by an organo-mineral fertility gradient, strongly positively correlated with organic matter and organic carbon content, total nitrogen, electrical conductivity, and clay fraction. In contrast, the sandy fraction is projected negatively on this axis, reflecting a marked contrast between fine-textured soils, which are rich in nutrients and chemically more active, and coarse-textured soils, which are poorer and have a low capacity to retain nutrients and water. The projection of the sites on the factorial plane clearly reflects this contrast. Plots located on the positive side of PC1 (particularly the T sites) are associated with more clayey-loamy soils, enriched in organic matter and nitrogen, suggesting high agronomic potential for market gardening. Conversely, sites positioned on the negative side of PC1 (mainly groups J and K) correspond to sandy soils with low nutrient content, indicating significant edaphic constraints that are likely to limit productivity without appropriate corrective inputs. The secondary axis (PC2) is mainly structured by pH, which projects positively and almost orthogonally to the organo-mineral fertility variables. This configuration indicates that pH acts as a factor independent of the overall nutrient stock, influencing their biological availability more than their total quantity. Variables related to assimilable phosphorus have a more pronounced contribution on the negative part of PC2, suggesting contrasts in phosphorus fixation and mobilization mechanisms depending on soil chemical conditions. Overall, this biplot highlights that the variability of vegetable garden soils is mainly controlled by texture and organic matter management, while pH plays a secondary but structuring role in the expression of chemical properties. These results confirm that strategies for sustainably improving vegetable garden performance must prioritize organic enrichment and soil structure improvement, while taking pH control into account to optimize nutrient availability.

Positioning of market gardening sites along a soil–productivity gradient revealed by PCA: The projection of the sampled sites on the factorial plane of principal component analysis (PCA), colored according to market gardening yield (Figure 5), highlights a clear structuring of the plots along a productivity gradient, mainly driven by axis 1 (PC1), which explains 63.7% of the total variance, while axis 2 (PC2) explains 24.1%. Sites located on the positive side of PC1 (notably T1 to T5) are associated with the highest simulated yields (≈ 12.5–15 t/ha). According to the joint projection of variables (see biplot), this area of the factorial plan corresponds to soils characterized by higher levels of organic matter, total nitrogen, clay, and electrical conductivity, reflecting better nutrient retention capacity and more favorable chemical fertility. These soils thus appear to be the most conducive to intensive and efficient vegetable production. Conversely, sites projected on the negative side of PC1 (mainly groups J and K) show lower simulated yields (≈ 9.5–11 t/ha). They are associated with predominantly sandy soils, which are less rich in nutrients and have a lower capacity to store water and nutrients. This soil configuration likely explains the lower productivity observed, due to increased losses through leaching and more limited nutrient availability for crops. The secondary axis (PC2) introduces an additional differentiation between certain sites with comparable yield levels but contrasting chemical conditions, particularly in relation to pH. This suggests that, at equivalent overall fertility, pH acts as a factor modulating the effective availability of nutrients, influencing yield expression without being the main determinant of productivity. Overall, this analysis clearly highlights a positive relationship between soil organic-mineral fertility and simulated vegetable yield, confirming that urban vegetable farming performance is primarily determined by fine texture and organic matter content, while pH plays a secondary but not insignificant role. These results underscore the importance of targeted management strategies focused on improving soil organic matter and structure in order to reduce productivity differences between plots.

DISCUSSION

The results of this study highlight a marked dominance of sandy soil in the market gardens of Sarh, accompanied by significant textural variability between plots (CV between 18 and 36%). This textural heterogeneity reflects contrasting pedogenetic processes and land use conditions, frequently observed in urban and peri-urban market gardening areas in sub-Saharan Africa (Bationo *et al*., 2018; Hounkpatin *et al*., 2020). The predominance of sand is generally associated with low water and nutrient retention capacity, making these soils particularly susceptible to losses through leaching under tropical rainfall regimes or intensive irrigation (Lal, 2020).

However, the significant presence of clay (≈ 27%) in certain plots suggests the existence of soils with differentiated agronomic potential, capable of better storing nutrients when organic management is adequate. Similar observations have been reported in urban market gardening systems in Ouagadougou, Yaoundé, and Abidjan, where textural variability strongly influences crop response to fertilizer inputs (Kouakou *et al*., 2019; Temgoua *et al*., 2021). The relatively high carbon and organic matter contents, although highly variable, reflect the impact of anthropogenic organic inputs (manure, compost, plant residues), which are widely used in African urban market gardening (Drechsel & Keraita, 2014). Nevertheless, the wide variation in total nitrogen content suggests uneven fertility management, which is likely to generate contrasting crop responses. This partial dissociation between organic matter and nitrogen was also observed by Diacono and Montemurro (2010), who emphasize that the quality of organic amendments and their degree of mineralization strongly influence the actual availability of nitrogen for crops. Correlation analysis reveals a consistent structure of soil properties centered around a core of "organic–nitrogen–clay fertility," as opposed to the sandy fraction. This pattern is characteristic of cultivated tropical soils, where fine texture and organic matter play a decisive role in nutrient stabilization and cation exchange capacity (Six *et al*., 2002; Bünemann *et al*., 2018). The negative correlation observed between pH and available phosphorus suggests phosphorus fixation mechanisms modulated by soil reaction, a phenomenon widely documented in mineral-dominant tropical soils (Hinsinger, 2001).

These results confirm that, in the context of Sarh, chemical fertility cannot be dissociated from the physical characteristics of the soil, and that any strategy for intensifying vegetable production must be based on integrated management of functional texture and organic matter. PCA clearly highlights a main gradient of organic-mineral fertility explaining nearly two-thirds of the total variance, contrasting poor sandy soils with more clayey-loamy soils rich in organic matter and nitrogen. This structure is consistent with the work of Barthès *et al*. (2017), which shows that yield variability in tropical vegetable farming systems is mainly controlled by the combination of texture and organic matter rather than by a single isolated nutrient. The secondary but structuring role of pH, highlighted on axis 2, emphasizes that the effective availability of nutrients can vary independently of total stocks, particularly for phosphorus. This observation is consistent with the conclusions of Johnston *et al*. (2014), according to which the agronomic efficiency of fertilizers depends heavily on soil chemical conditions, even at comparable fertility levels. Thus, the differences in yield observed between sites do not only reflect differences in cultivation practices, but also structural soil constraints, reinforcing the need for differentiated approaches to fertility management. The integration of high-quality organic amendments, combined with careful pH management and the limitation of nutrient losses, appears to be an essential condition for the sustainability of urban market gardening in Sarh.

CONCLUSION

This study highlights the decisive role of soil physicochemical properties in the performance of urban market gardening in Sarh, in the Sudanian zone of southern Chad. The results show that the variability in vegetable yields is mainly explained by a gradient of organic-mineral fertility, structured by the content of organic matter, organic carbon, total nitrogen, and the clay fraction of the soils. Conversely, sandy soil appears to be a major limiting factor due to its low water and nutrient retention capacity. Multivariate analyses confirm that vegetable productivity is more influenced by the combination of texture and organic matter than by isolated chemical parameters. Although generally favorable, pH plays a secondary role in modulating nutrient availability, particularly phosphorus, without being the main determinant of yield. These results highlight the importance of an integrated approach to soil fertility, in which organic matter management is the key lever for sustainable productivity improvement. In practical terms, this study suggests that increasing and stabilizing organic inputs, combined with judicious mineral fertilization tailored to soil texture characteristics, are essential for reducing yield variations between plots and increasing the sustainability of urban market gardening systems. More broadly, these results provide robust scientific evidence for the development of strategies for the ecological intensification of urban market gardening in Sudanese Africa and in comparable agroecological contexts, reconciling agronomic performance, sustainable soil management, and food security.

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