

Research Article

Quantitative Analysis of Iron Activity in Agricultural Soils Using X-ray Fluorescence Spectrometry: Comparative Study with an Undisturbed Reference Site in Niankhene, Senegal

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Abstract

An essential micronutrient for plant growth and development, iron (Fe) affects a number of physiological processes, including respiration and photosynthesis. This study compares the amounts of iron in agricultural zones and reference zones, describes the geographic distribution of iron, and assesses its accessibility to cultures. The aim is to assess the deficiencies and excess soil disturbance in the Niankhene agricultural site while maintaining a stable site. Soil samples were taken at 0–20 cm and 20–40 cm depths from 47 agricultural stations and three reference points using X-ray fluorescence (XRF) spectroscopy. Significant variation in Fe concentrations was found by the research, with an average of roughly 3310.95 ppm and moderate variation between samples. An analysis conducted in comparison with reference locations revealed a widespread lack of Fe in the research area, with 85.71% of samples displaying depletion and only 14.29% displaying accumulation of Fe. This discrepancy emphasizes the necessity of focused soil management techniques to raise Niankhene's agricultural output. The results highlight how crucial it is to use site-specific soil management strategies in order to overcome Fe deficits and raise crop yields. This research highlights the possibility for establishing targeted fertilization and corrective procedures to maximize Fe availability by utilizing XRF technology for reliable soil nutrient monitoring. The study's findings offer insightful information for enhancing fertilization techniques and improving soil management techniques, which will support sustainable farming methods and increased crop yield in the area.

Keywords

Soil, XRF, Iron (Fe), Agricultural Productivity, Fertilization Strategies

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1. Introduction

A vital micronutrient for plant growth, iron (Fe) affects vital physiological processes like respiration, photosynthesis, and nitrogen fixation [1, 2]. It is essential to comprehend the distribution and availability of iron in agricultural soils in order to maximize crop yield and maintain sustainable agricultural practices [3, 4]. This is especially important in areas like Senegal's Niakhene department, where soil fertility and nutrient management have a direct bearing on agricultural sustainability and productivity. Recent developments in analytical methods have greatly enhanced the analysis of soil nutrients. X-ray fluorescence spectrometry (XRF) is one of these techniques that has become a potent tool for elemental analysis. XRF uses X-rays to precisely identify and quantify elements, including iron, without causing any damage to soil samples. [5, 6]. In this work, soil samples from a reference site and a research site in Niakhene are analyzed using XRF technology. The goals are to determine which sample has an iron accumulation or a carence by characterizing the spatial distribution of iron, comparing the iron activity in the study site and the reference site, and evaluating the availability of iron to crops. [7, 8]. It is hoped that the research's conclusions would provide insightful information on soil management techniques, such as focused fertilization methods and remediation initiatives meant to maximize iron availability and raise agricultural output in Niakhene. This report presents the results of our XRF analysis and soil sample, discusses their implications for sustainable agriculture in the area, and goes into detail about the methods used.

2. Resources and Techniques

2.1. An Explanation of the Research and the Source Website

The research location is in Niakhene, which is in the department of Tivaouane in Thiès. Dakar, the capital of Senegal, is around 184 kilometers away from the study site. The majority of the soil at the farming location is light and sandy. This sort of sandy soil has many benefits. For example, it is very permeable to both air and water, which makes drainage and aeration easier. Since the soil is porous, water can naturally percolate through it. Its high filtering capacity, however, also results in low water and nutrient retention. Furthermore, this soil type is prone to erosion brought on by rainfall or

irrigation because of its low organic matter concentration.

2.2. Method of Sampling at the Study and Reference Sites

Plowed soil at the research location in Niakhene has disturbed the humus layer down to a depth of 15 cm. We used a methodical sampling technique to capture the variety in soil attributes. Within the cultivated region, a total of 47 sampling stations were set up along 7 transects. 94 sub-samples from the agricultural site were obtained by taking soil cores at two depths 0–20 cm and 20–40 cm at each sampling location. The sampling plan in detail is depicted in Figure 1, which also shows the depths and sampling points distributed throughout the farmed area. Three reference points were chosen to approximate undisturbed conditions for the reference site, which is seven kilometers away. Three sampling stations, designated as References 1, 2, and 3, were chosen to reflect undisturbed conditions for the reference site, which is situated seven kilometers away. Samples were taken at Ref. 1 down to a depth of 75 cm, yielding 15 sub-samples. In a similar vein, 53 subsamples were gathered at Reference 3 and 19 subsamples at Reference 2. All soil samples were collected, then they were all brought to the lab in plastic bags. Samples were dried, their roots removed, and then they were crushed and sieved in the laboratory in order to get them ready for further study. In order to enable reliable comparison and analysis of soil features, including iron concentration and distribution, this sampling methodology enabled full coverage of soil characteristics at both the study and reference locations.

3. X-ray Fluorescence Analysis of Samples

3.1. Experimental Approach

A silver Ag anode is used as the excitation source and an improved large-geometry detector with various filters is used as a secondary source when soil samples are directly fed into the X-ray fluorescence analyzer. A clear representation of the Niton XLT900s X-ray tube's filter setup can be found in Figure 1.

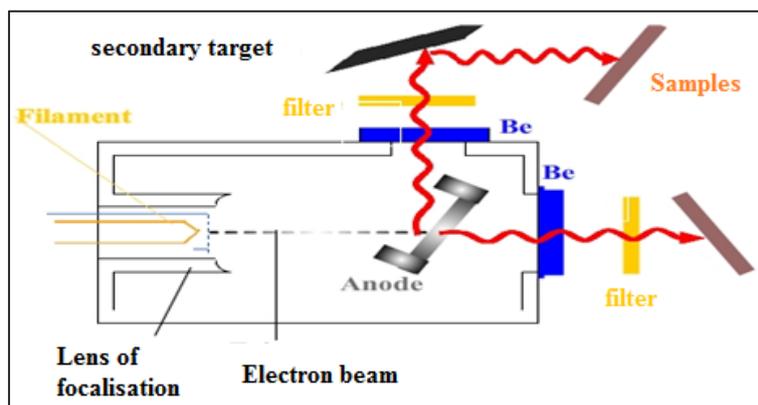


Figure 1. X-ray tube with typical excitation geometry.

The features and operational parameters of the Niton XLT900s spectrometer with various filter types are shown in table 1.

Table 1. Niton XLT900s Spectrometer specification and operating conditions.

| | |
|---------------------------|---|
| Resolution | 178 eV@ Mn K α |
| Window thickness | 12.7 μ m Be |
| Excitation Tube | 50KV, 40 μ A maximum power 2W |
| Beam diameter | 7mm |
| Filters | List of targeted elements |
| Excitation Source Ag | Sb, Sn, Cd, Pd, Ag, Mo, Nb, Zr, Sr, Rh, Bi, As, Se, Au, Pb, W, Zn, Cu, Re, Ta, Hf, Ni, Co, Fe, Mn, Cr, V, Ti, Th, U |
| Sandwich of Al, Ti and Mo | Ba, Sb, Sn, Cd, Pd, Ag |
| Filter of Cu | Cr, V, Ti, Ca, K |
| No Filter | Al, P, Si, Cl, S, Mg |

3.2. The X-ray Fluorescence Principle Spectrometry

The basic idea behind X-ray fluorescence spectrometry (XRF) is to ionize atoms in a sample by applying powerful X-ray radiation. Atoms in the sample absorb energy from X-rays, which leads to the ejection of inner-shell electrons from their orbitals close to the nucleus. An electron with a higher energy level fills the vacancy that is subsequently created in the inner electron shell. The energy difference between the beginning and final states of the electron rearrangement correlates to the characteristic X-ray fluorescence photons that are released during this transition [9, 10].

The emitted X-ray photons are specific to the elements present in the sample, providing a unique spectral fingerprint that reflects the elemental composition. By measuring the intensity of these fluorescence photons across different energy levels, an X-ray emission line spectrum is generated.

This spectrum allows for the identification and quantification of elements in the sample based on their atomic numbers and characteristic X-ray emissions [11]. The atomic number of the elements affects how useful XRF analysis is. When compared to heavier elements, elements with low atomic numbers (low Z) have lower X-ray fluorescence yields, which may limit the sensitivity for detecting these elements [12].

4. Results and Discussions

4.1. Concentrations of Fe in the Agricultural Site

The geographical distribution of iron (Fe) concentrations at depths of 0 to 20 cm in Niakhène has been mapped through elemental analysis of samples using X-ray fluorescence (XRF) technology. This analysis allows for a detailed understanding of Fe content across the agricultural site. The

results of Fe concentrations (in ppm) noted Fe (1) from various samples at the Niakhène agricultural site are as follows in the [table 2](#).

Table 2. Iron concentrations in ppm from various sample at the Niankhene site.

| Samples | Fe (1) in ppm | Samples | Fe (1) in ppm |
|---------|---------------|---------|---------------|
| S1 | 4103.12±65.77 | S106 | 3634.22±61.94 |
| S8 | 4055.26±60.79 | S108 | 2916.82±55.23 |
| S10 | 2082.75±43.85 | S114 | 2662.71±49.14 |
| S22 | 2923.53±55.89 | S116 | 3553.62±61.10 |
| S24 | 2955.12±55.64 | S134 | 3753.05±62.26 |
| S28 | 3434.14±59.63 | S136 | 2824.2±50.63 |
| S30 | 3135.82±57.22 | S138 | 3469.63±56.10 |
| S50 | 2969.65±55.89 | S140 | 3259.88±58.33 |
| S52 | 3442.19±59.95 | S142 | 3353.26±59.05 |
| S54 | 3451.85±56.12 | S144 | 3213.34±52.65 |
| S60 | 4048.3±66.33 | S146 | 4286.42±66.94 |
| S78 | 3548.04±63.41 | S148 | 3290.46±57.86 |
| S82 | 2571.05±48.49 | S162 | 4072.93±65.09 |
| S84 | 3203.1±56.62 | S164 | 3522.96±59.63 |
| S86 | 3516.06±60.42 | S168 | 2798.97±55.99 |

| Samples | Fe (1) in ppm | Samples | Fe (1) in ppm |
|---------|----------------|---------|---------------|
| S88 | 2875.53±57.955 | S170 | 3162.14±57.70 |
| S90 | 2771.8±53.93 | S178 | 3710.4±63.41 |

The bar chart above displays the Fe concentration (in ppm) for each sample, including error bars representing the standard deviation. This analysis shows ([Figure 1](#)) that the Fe concentration varies significantly across the samples, with the highest concentration in sample S146 and the lowest in sample S10. The standard deviations indicate the variability of measurements around the mean values for each sample. The average Fe concentration across all samples is approximately 3310.95 ppm. The standard deviation is 494.80 ppm, indicating a moderate spread of Fe concentrations around the mean. The Fe concentrations range from a minimum of 2082.75 ppm (sample S10) to a maximum of 4286.42 ppm (sample S146). This wide range suggests significant variability in Fe content across different samples. Samples with the highest Fe concentrations are S146 (4286.42 ppm) and S1 (4103.12 ppm) and the samples with the lowest Fe concentrations are S10 (2082.75 ppm) and S82 (2571.05 ppm). Samples such as S1, S8, S60, and S162 have relatively high Fe concentrations and exhibit consistent standard deviations, indicating reliable measurement consistency. On the other hand, samples like S10 and S82, with lower Fe concentrations, also have lower standard deviations, suggesting less variability in these measurements.

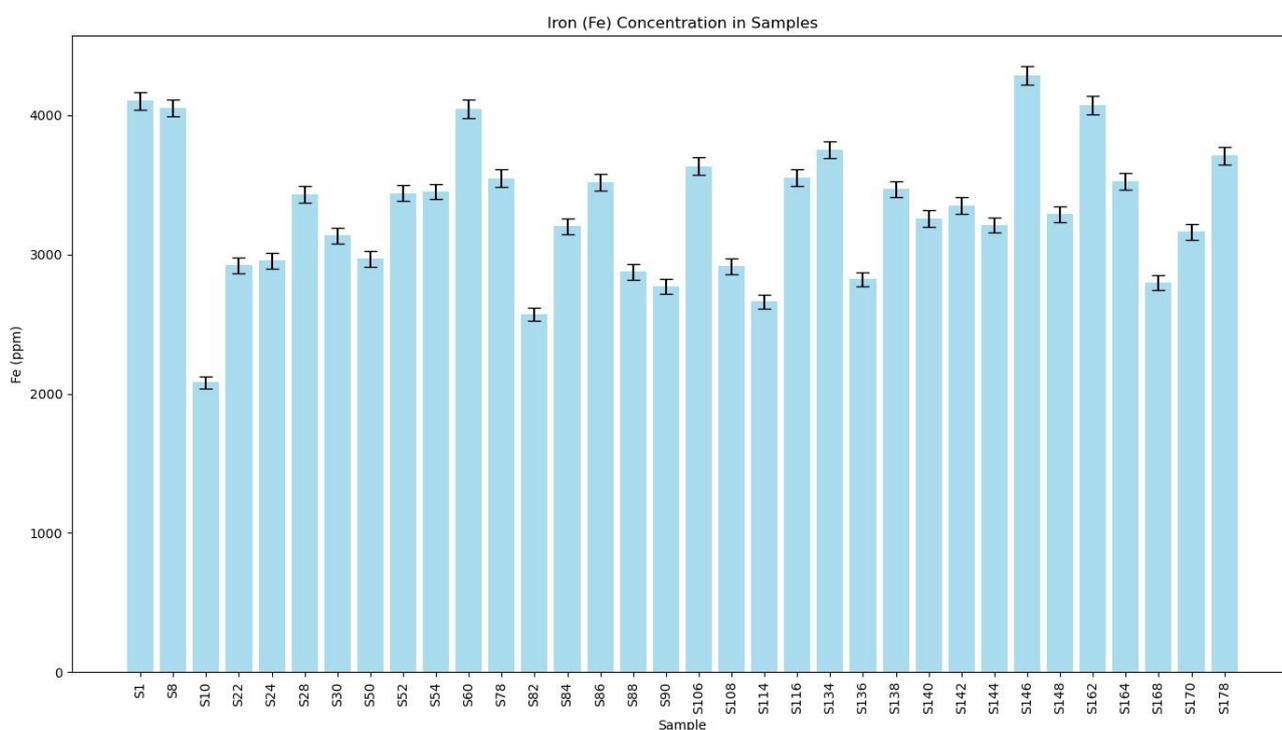


Figure 2. Distribution of iron concentration in the study site.

4.2. Concentration in the Reference Site

To compare the iron (Fe) noted Fe (2) concentrations from the Niakhène agricultural site with reference sites, we would typically refer to background Fe concentrations in similar environments or specific reference sites that have been studied and documented. These reference sites can provide a baseline or control values for Fe concentration against which the Niakhène samples can be compared. Assuming we have typical values of Fe concentrations for reference sites in similar agricultural or natural environments, here's a synthesized presentation of these values. (In actual practice, specific reference sites and their Fe concentrations should be provided based on existing studies or environmental reports. The Descriptive Statistics for Reference Site show the mean of Fe

(ppm) was 4280.9.

4.3. Presentation of Different Phenomena

To determine whether there is accumulation or deficiency, we introduce the parameter $Cor = Fe(2) - Fe(1)$ to identify the points that show accumulation, deficiency, or those that do not present any problems. The Cor parameter helps us to evaluate the changes in iron (Fe) concentrations between two sets of measurements, Fe (1) and Fe (2). By calculating $Cor = Fe(2) - Fe(1)$ for each sample, we can classify the points into three categories: If $Cor > 0$, there a deficiency is of iron, If $Cor < 0$, there is an accumulation of iron, If $Cor = 0$, there is no significant change in iron concentration. The different phenomena are presented in the following table.

Table 3. Different phenomena observed in the study.

| Samples | Fe (1) | Fe (2) | Cor = Fe(2) - Fe(1) | Observations |
|---------|---------|---------|---------------------|--------------|
| S1 | 4303.12 | 4280.90 | -22.20 | Accumulation |
| S8 | 4455.26 | 4280.90 | -174.34 | Accumulation |
| S10 | 2082.75 | 4280.90 | 2198.17 | Deficiency |
| S22 | 2923.53 | 4280.90 | 1357.39 | Deficiency |
| S24 | 2955.12 | 4280.90 | 1325.8 | Deficiency |
| S28 | 3434.14 | 4280.90 | 846.78 | Deficiency |
| S30 | 3135.82 | 4280.90 | 1145.1 | Deficiency |
| S50 | 2969.65 | 4280.90 | 1311.27 | Deficiency |
| S52 | 3442.19 | 4280.90 | 838.73 | Deficiency |
| S54 | 3451.85 | 4280.90 | 829.07 | Deficiency |
| S60 | 4348.3 | 4280.90 | -68.38 | Accumulation |
| S78 | 3548.04 | 4280.90 | 732.88 | Deficiency |
| S82 | 2571.05 | 4280.90 | 1709.87 | Deficiency |
| S84 | 3203.1 | 4280.90 | 1077.82 | Deficiency |
| S86 | 3516.06 | 4280.90 | 764.86 | Deficiency |
| S88 | 2875.53 | 4280.90 | 1405.39 | Deficiency |
| S90 | 2771.8 | 4280.90 | 1509.12 | Deficiency |
| S114 | 2662.71 | 4280.90 | 1618.21 | Deficiency |
| S116 | 3553.62 | 4280.90 | 727.3 | Deficiency |
| S134 | 3753.05 | 4280.90 | 527.87 | Deficiency |
| S136 | 2824.2 | 4280.90 | 1456.72 | Deficiency |
| S138 | 3469.63 | 4280.90 | 811.29 | Deficiency |
| S140 | 3259.88 | 4280.90 | 1021.04 | Deficiency |
| S142 | 3353.26 | 4280.90 | 927.66 | Deficiency |

| Samples | Fe (1) | Fe (2) | Cor = Fe(2) - Fe(1) | Observations |
|---------|--------------|---------|---------------------|--------------|
| S144 | 3213.34 | 4280.90 | 1067.58 | Deficiency |
| S146 | 4286.42 | 4280.90 | -5.5 | Accumulation |
| S148 | 3290.46 | 4280.90 | 990.46 | Deficiency |
| S162 | 4372.93 | 4280.90 | -92.01 | Accumulation |
| S164 | 3522.96 | 4280.90 | 757.96 | Deficiency |
| S168 | 2798.97 | 4280.90 | 1481.95 | Deficiency |
| S170 | 3162.14 | 4280.90 | 1118.78 | Deficiency |
| S178 | 3710.4±63.41 | 4280.90 | 570.52 | Deficiency |

4.4. Analysis and Interpretation of Results

The table presents data on iron (Fe) levels at two different times for various samples. The difference between these levels, labeled as Cor, indicates whether there has been an accumulation or deficiency of iron over time. Here's a detailed analysis and discussion based on the provided data. The majority of the samples (85.71%) exhibit iron deficiency, while a minority (14.29%) show accumulation. This indicates a general trend of decreasing iron levels over the observed period. This observation aligns with studies that highlight iron deficiency as a common issue in various soils due to factors like high pH, calcareous conditions, and poor soil management practices [13]. The Cor values among the deficiency samples are substantial, indicating significant iron loss. The highest recorded deficiency is 2198.15 (Sample S10), suggesting severe depletion. Such severe deficiencies can lead to reduced plant growth, chlorosis, and overall poor crop yields [14]. The accumulation values are relatively minor compared to the deficiencies, with the highest accumulation being -5.52

(Sample S146). This suggests that iron accumulation, when it occurs, is minimal and less impactful [15]. The consistent deficiency across various samples indicates a systemic issue rather than isolated incidents. This can be due to uniform soil conditions, climatic factors, or widespread agricultural practices that limit iron availability. The bar chart clearly shows Figure 3 that the number of samples with iron deficiency (30) is significantly higher than those with accumulation (5). This highlights a prevalent issue of iron deficiency across the samples [16]. Climatic factors, such as temperature and rainfall patterns, also influence soil iron dynamics and can contribute to iron deficiencies. Iron deficiency in soil can have several adverse effects on crop health and yield: Iron is crucial for chlorophyll synthesis and enzyme function. Deficiency can lead to stunted growth and reduced biomass [17]. A common symptom of iron deficiency is chlorosis, characterized by yellowing of leaves due to impaired chlorophyll production. Prolonged iron deficiency can result in significant yield losses, impacting agricultural productivity and profitability.

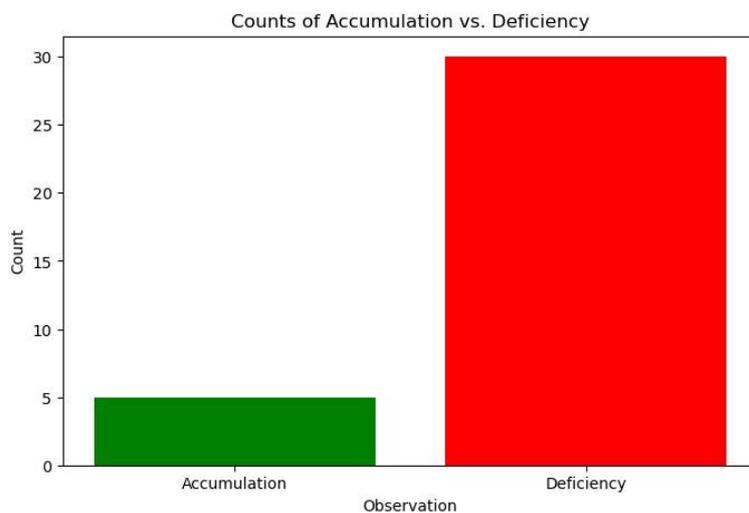


Figure 3. Counts of accumulation vs deficiency.

The histogram displays the distribution of Cor values, illustrating the range and frequency of iron accumulation and deficiency: The majority of Cor values fall on the positive side, indicating deficiency; A small number of samples have negative Cor values, indicating accumulation; The distribution of deficiency values is wide, ranging from 500 to over 2000, showing Figure 4 varying degrees of iron deficiency severity. The box plot compares the Cor values for accumulation and deficiency: Accumulation: The values are close to zero, with minimal variation.

This indicates that when accumulation occurs, it is relatively minor. Deficiency: The values show Figure 5 a much broader range and higher median, indicating significant and varying levels of iron deficiency across the samples. The presence of outliers further emphasizes the severity in some cases.

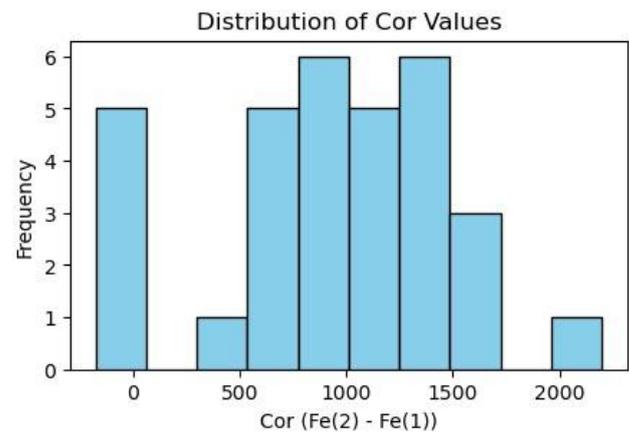


Figure 4. Distribution of Cor values.

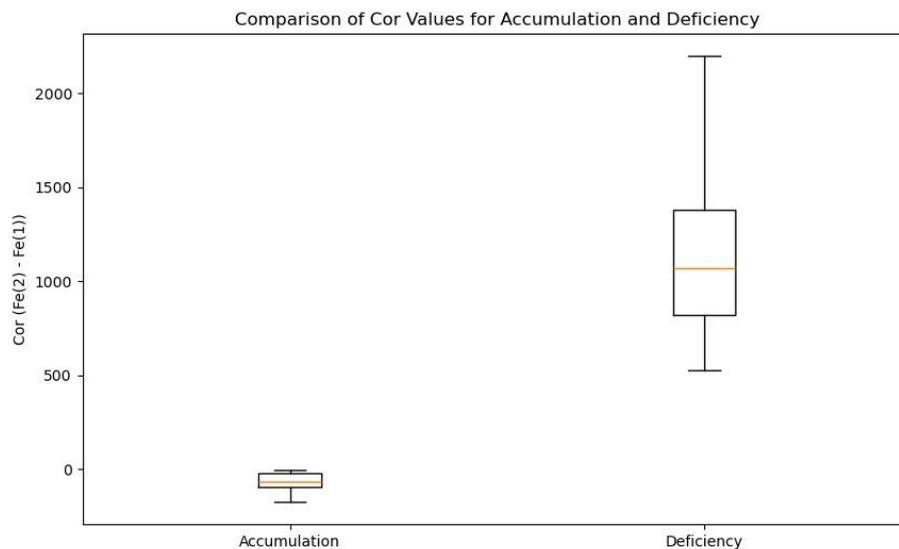


Figure 5. Comparison of cor values for accumulation and deficiency.

4.5. Potentials Causes and Implications

Environmental Factors: Widespread iron deficiency could result from environmental conditions such as alkaline soils, waterlogging, or poor soil aeration, which reduce iron availability to plants.

Agricultural Practices: Farming practices, including improper fertilization, over-irrigation, or the use of iron-chelating pesticides, might impact soil iron levels. Practices that do not replenish soil nutrients effectively can lead to cumulative deficiencies.

Plant Variety: Different plants have varying abilities to absorb and retain iron. The variations in deficiency severity among the samples could be due to different plant species or cultivars with distinct iron uptake capabilities.

5. Physics-Based Solutions for Iron Deficiency and Accumulation

5.1. Soil Water Movement and Irrigation Management

Proper irrigation management is crucial for preventing both iron accumulation (due to waterlogging) and deficiency (due to inadequate moisture). The following formulas from fluid dynamics and soil physics can help optimize irrigation practices. Darcy's Law for Water Flow in Soil:

$$Q = -K.A.\frac{dh}{dz} \tag{1}$$

Q: Water flow rate (m³/s); K: Hydraulic conductivity of the soil (m/s); A: Cross-sectional area through which water flows (m²); $\frac{dh}{dz}$: Hydraulic gradient (change in head per unit distance).

Darcy's Law is a cornerstone of hydrogeology and soil physics, providing a quantitative description of the flow of fluids through porous media. Named after Henry Darcy, the

law is fundamental for understanding and predicting water movement in soils, which is critical for agricultural practices, groundwater management, and environmental engineering. Darcy's Law is a foundational principle for understanding and managing water flow in soils. Its application is crucial for effective agricultural practices, groundwater management, and environmental engineering.

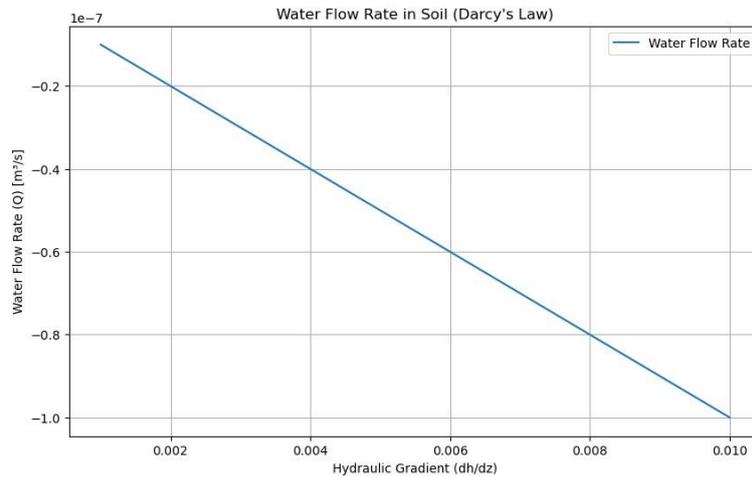


Figure 6. Darcy's Law for Water Flow in Soil.

5.2. Soil pH and Buffering Capacity

Maintaining optimal soil pH is crucial for iron availability. The buffering capacity of soil indicates its ability to resist changes in pH. The formula for buffering capacity (BC) can be given as:

$$BC = \frac{\Delta \text{Acid/Base}}{\Delta \text{pH}} \quad (2)$$

Δ Acid/Base: Amount of acid or base added (mol); Δ pH: Change in pH

Applying this concept helps determine the amount of lime needed to adjust soil pH to optimal levels for iron availability. In soil, buffering capacity acts similarly by absorbing or releasing ions to maintain pH stability. Soils with high buffering capacity are like a large sponge that can absorb more changes in pH without significant swings.

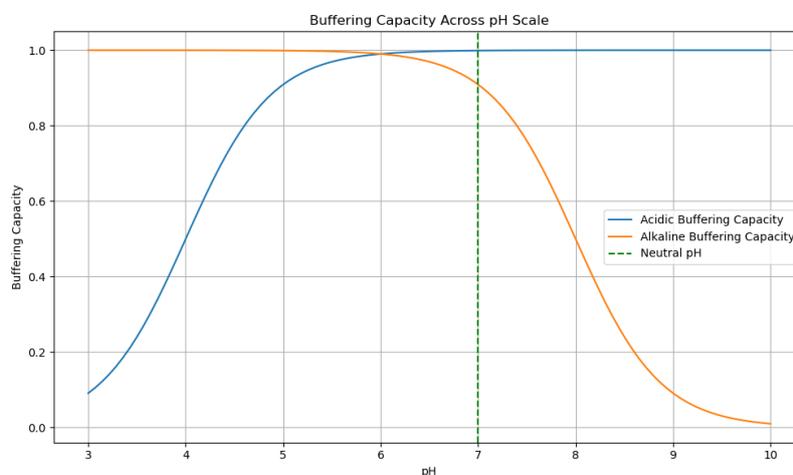


Figure 7. Buffering capacity across pH Scale.

5.3. Nutrient Transport in Soil

The transport of iron and other nutrients in soil can be modeled using Fick's Law of Diffusion, which describes the flux of ions due to concentration gradients. The Fick's first Law whrote by the following formula

$$J = -D \frac{dC}{dx} \tag{3}$$

J: Diffusive flux (mol/m²s); D: Diffusion coefficient (m²s);
 $\frac{dC}{dx}$: Concentration gradient (mol/m³per m)

This formula helps understand how iron moves through soil, aiding in the design of efficient fertilization strategies.

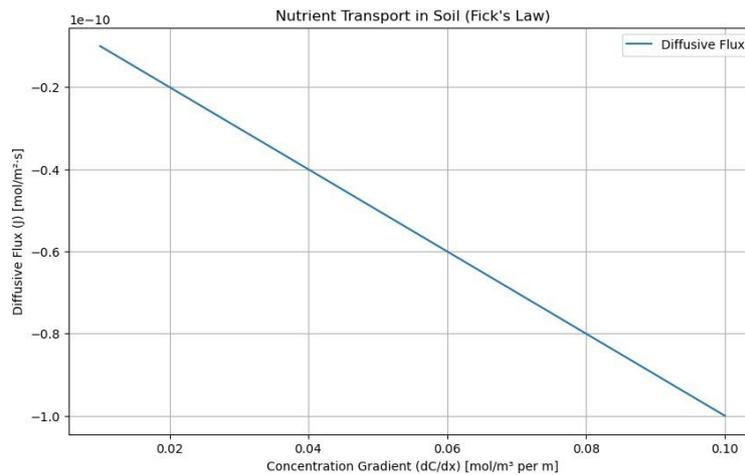


Figure 8. Darcy's Law and Fick's Law.

5.4. Application of Chelated Iron Fertilizers

To calculate the precise amount of chelated iron fertilizer needed, we use the following formula, considering the target iron level, current level, and fertilizer efficiency. The formula for the Fertilizer Requirement was:

$$Fe_{required} = \frac{(Target\ Fe - Current\ Fe) \times soil\ volume}{Fertilizer\ Efficiency} \tag{4}$$

Fe_{required}: Amount of chelated iron fertilizer required (kg);
 Target Fe: Desired iron concentration in soil (mg/kg);
 Current Fe: Current iron concentration in soil (mg/kg);
 Soil Volume: Volume of soil to be treated (m³);
 Fertilizer Efficiency: Efficiency of the applied fertilizer (fraction).

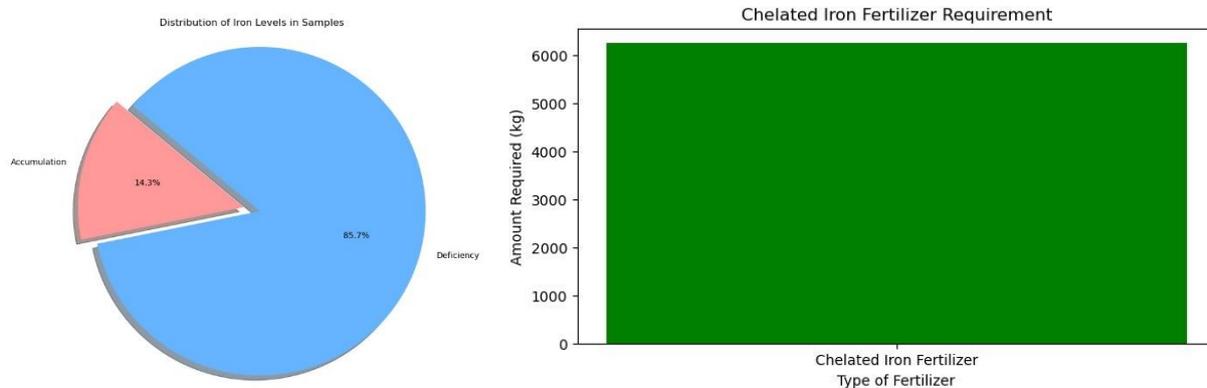


Figure 9. Distribution of iron and chelated iron fertilizer.

6. Conclusion

X-ray fluorescence (XRF) spectrometry was successfully applied in this work to offer a thorough examination of soil iron activity in agricultural samples from Niankhene. The findings show that there is a considerable variance in iron contents among the samples, pointing to both iron buildup and deficient regions. The majority of the soils had an iron deficit, which emphasizes the necessity of specific soil amendments to increase crop output. However, a small number of samples had iron accumulation, indicating the need for routine soil monitoring to avert any potential toxicity problems. The significance of site-specific soil management techniques in maximizing agricultural productivity in Niankhene is highlighted by these results. Achieving balanced soil nutrition can be facilitated by putting plans into practice including applying iron fertilizers to regions that lack it and conducting routine monitoring in places where accumulation has occurred. In addition to offering helpful guidelines for future research, this study helps farmers and agricultural planners in Niankhene increase crop yields and soil fertility. All things considered, XRF spectrometry has shown to be a useful technique for analyzing soil, providing in-depth knowledge about soil iron activity that can guide improved farming methods. Future research ought to think about broadening the focus to incorporate additional vital nutrients and investigating the long-term effects of customized soil management techniques on crop productivity and soil health in the area.

Abbreviations

| | |
|-----|--------------------|
| XRF | X-Ray Fluorescence |
| ppm | Parts Per Million |

Author Contributions

Djicknack Dione: Formal Analysis, Methodology, Software, Writing – original draft, Writing – review & editing

Papa Macoumba Faye: Methodology, Sampling

Oumar Ndiaye: Software, Writing – review & editing

Nogaye Ndiaye: Writing – review & editing

Moussa Hamady Sy: Writing – review & editing

Alassane Traor é: Sampling, Methodology

Ababacar Sadikhe Ndao: Conceptualization, Validation, Writing – review & editing

Conflicts of Interest

The authors declare no conflicts of interest.

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