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Iron Heterogeneity in Soil and its Relation to its Uptake by Water Leaf (*Talinum Triangulaire L.*)

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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

This study investigated the relationship between iron (Fe) heterogeneity in soil and Fe uptake by water leaf (*Talinum triangulaire*). A greenhouse pot experiment was conducted with water leaf grown under three treatments; control (0mg/kg Fe added), homogeneous (1000mg/kg Fe added), and heterogeneous (simulated realistic heterogeneity) for six weeks after initial establishment in the nursery for four weeks). At harvest, plant samples were cut, washed, dried, milled into powder and analyzed for iron concentrations using the Atomic Absorption Spectrometer (AAS) Thermos Fisher Scientific Model 3000 ICE after acid digest by Nitric acid (HNO_3). The mean root Fe concentrations of the control, homogeneous and heterogeneous treatments were 1263 ±154mg/kg, 1504 ±178mg/kg and 1393mg/kg ±140mg/kg respectively. The mean shoot Fe concentrations of the control, homogeneous and heterogeneous treatments were 904 ±174u mg/kg, 1401±117 mg/kg and 1045 ±95 mg/kg respectively. There was no statistically significant difference ($p > 0.005$) in shoot and root Fe concentration between treatments. However, the homogeneous treatment was 0.19

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times higher than the control and 0.07 times higher than the heterogeneous treatment. Iron level in the roots was 0.35 times high as the control and 0.25 times higher than the heterogeneous treatment. The Concentration factors for the control, homogeneous, and heterogeneous treatments were 0.1118, 0.1498 and 0.1258 respectively. The similarity in concentration factor between treatments showed that it is an accumulator of Fe and has the affinity for Fe irrespective of the varied soil concentrations. These findings indicate that water leaf possesses mechanisms enabling efficient Fe acquisition from variable soil conditions. Overall, the study provides initial evidence that water leaf is resilient to variability in soil Fe distribution, holding implications for its improved cultivation. However, further research on the specific genes and processes governing iron mobilization and uptake in water leaf is recommended.

Keywords: Iron; heterogeneity; uptake; water leaf; treatments.

1. INTRODUCTION

Iron (Fe) is an essential micro nutrient for plant growth and development. It plays a vital role in chloroplast development and photosynthetic electron transport [1]. However, iron availability is often limited in aerobic soils due to the low solubility of Fe (III) oxides and hydroxides at neutral to basic pH conditions [2]. As a result, iron deficiency is one of the most common nutritional disorders, leading to chlorosis and reduced crop yields worldwide [3].

The bioavailability of trace elements to plants is strongly dependent on its distribution and speciation in the soil [3]. Soils often show a heterogeneous pattern of iron distribution, with concentrations varying across short distances [3]. This uneven distribution leads to the development of nutrients deficiency symptoms in some plants, even when total iron content in the soil is adequate [4]. Spatial variability in plant-available nutrient forms poses a major challenge for detecting and correcting iron deficiencies in the field [5].

Water leaf (*Talinum triangulare*) is an annual herbaceous plant commonly grown as a leafy vegetable in tropical and subtropical regions. Previous studies have reported chlorosis in some water leaf plants grown in iron-rich soils, indicating variability in trace metal bioavailability [6]. However, research on iron heterogeneity in soil and its effects on water leaf iron nutrition is lacking.

Nutrient availability in soils is highly heterogeneous, with concentrations varying across short distances even within the same field [1]. This spatial variability is attributed to the uneven distribution of different iron forms and complexes in the soil matrix [2]. Factors such as soil texture, mineralogy, organic matter content, pH, and redox status influence iron speciation and distribution patterns in soils [7].

Common geochemical techniques used to characterize element heterogeneity include selective dissolution methods, synchrotron-based X-ray spectroscopy, and diffusive gradients in thin films (DGT) [8]. These advanced analytical approaches have revealed a complex mosaic of trace metal accumulation zones interspersed with areas of iron depletion in soils [9]. Nanometer-scale analyses further demonstrate the presence of iron-rich microenvironments associated with organic matter and soil minerals [10].

The implications of iron heterogeneity for plant nutrition can be significant. Studies show that patchy distribution of plant-available iron limits nutrient acquisition and causes chlorosis in susceptible crops, even when total iron content is high [3]. Site-specific management approaches to mitigate iron deficiency chlorosis focus on in-season correction of localized patches through foliar sprays or soil amendments [11]. Further research is needed to link indicators of iron heterogeneity to plant responses across different soil types and crop species including water leaf (*Talinum triangulare*).

Soil heterogeneity refers to spatial variability in soil properties across landscapes as a result of diverse soil forming factors and processes [12] Modern techniques and technologies have enhanced our ability to measure and map soil heterogeneity [13].

Modern digital soil mapping and proximal soil sensing techniques are used to quantify and map soil spatial variability through statistical measures like semivariograms, autocorrelation, and heterogeneity indices [14,13]. Accounting for heterogeneity allows for site-specific management practices.

Iron is an essential trace metal required for healthy plant growth and development. However,

nutrient availability and uptake by plants is strongly influenced by soil conditions. Iron deficiency is a common nutritional disorder, especially in high pH soils, where iron becomes less soluble and available to plants.

Water-leaf (*Talinum triangulaire*) is an important leafy vegetable cultivated across many tropical regions. Previous studies have shown that water-leaf is susceptible to iron deficiency when grown on alkaline and calcareous soils, leading to reduced growth and yield and consequent availability of human or animal diet.

Soil iron exists in different chemical forms and pools with varying bioavailability to plants. One factor that can influence iron heterogeneity in soils is pH. As pH increases, iron oxides and hydroxides precipitate, reducing soluble and exchangeable iron fractions available for plant uptake.

Additionally, the spatial distribution of soil iron can be highly variable at the microscopic scale relevant to plant roots. This iron heterogeneity in the rhizosphere may create localized deficiency or toxicity affecting water-leaf iron nutrition.

However, there is limited research on the relationship between soil iron heterogeneity and waterleaf iron uptake. Elucidating this relationship would provide important insights into improving the iron nutritional status and productivity of waterleaf on different soil types.

The study contributes to the scientific understanding of the intricate relationship between soil iron distribution and iron uptake by plants, with a specific focus on water leaf (*Talinum triangulare*). The findings will expand existing knowledge in the fields of soil science, plant nutrition, and molecular biology.

Insights from the study can inform agricultural practices aimed at optimizing nutrient management, particularly iron, for water leaf cultivation. This has the potential to enhance crop yield and quality, contributing to food security and sustainable agriculture.

The study may uncover mechanisms that contribute to the resilience and adaptation of water leaf plants to varying soil iron conditions. This knowledge can be utilized in breeding programmes to develop crop varieties with improved nutrient uptake efficiency.

Recommendations arising from the study can guide the development of sustainable agricultural practices that balance the need for increased crop production with environmental sustenance. This is particularly important in the context of global efforts towards sustainable and responsible agriculture.

This study's findings may have implications for agricultural policies related to nutrient management and soil health. Policymakers can use the research outcomes to formulate guidelines and regulations that promote sustainable agricultural practices and ensure the efficient use of resources.

The research contributes to educational resources in the fields of agronomy, soil science, and plant biology. It serves as a valuable reference for students, researchers, and educators interested in understanding the complexities of nutrient uptake by plants in heterogeneous soil environments.

This research aims to explore the heterogeneous distribution of iron (Fe) in soil and its direct connection to iron uptake by the water leaf plant (*Talinum triangulaire*).

Iron deficiency in plants could reduce crop yields. Understanding iron availability and uptake mechanisms is crucial for optimizing plant nutrition and agricultural productivity.

Soils often exhibit heterogenous distribution of iron, with concentrations varying across small special scales. This uneven distribution can lead to localized iron deficiencies, even when the total iron content in the soil is adequate. Elucidating the effects of iron heterogeneity on plant uptake is necessary for accurate detection and correction of iron deficiencies in the field.

Waterleaf is an important leafy vegetable crop, particularly in tropical and subtropical regions. Previous studies have reported chlorosis in waterleaf plants grown in iron-rich soils, suggesting variability in iron bioavailability. However, there is a lack of research specifically investigating the relationship between soil iron heterogeneity and iron uptake in waterleaf.

The study aims to provide practical recommendations for optimizing iron availability in the soil for waterleaf cultivation. This knowledge can contribute to enhancing crop yield and quality, thereby improving food security and sustainable agriculture.

The findings may uncover resilience mechanisms that enable water leaf plants to acquire iron consistently despite heterogeneous distribution in the soil. This understanding can inform breeding programs to develop crop varieties with improved nutrient uptake efficiency, leading to better adaptation to diverse soil conditions.

Overall, the study addresses a significant knowledge gap by exploring the nexus between iron heterogeneity in soil and its bioavailability to an economically important vegetable crop. The findings hold the potential to inform agricultural practices, breeding programs, and policy initiatives aimed at enhancing crop productivity, food security and environmental sustainability.

2. METHODS

2.1 Experimental Design

Heterogeneity model was simulated (using excel computer models with a combination of the Robust ANOVA- a visual basic Programme developed based on a FORTRAN programme and previous work (Ramsey et al., 1994), which will generate the levels of heterogeneity like those that have been found in field sites and previous field studies. "The scale of heterogeneity used, the plant species selected, and the mean Fe concentrations chosen were based upon conclusions of the first pot trials in earlier studies" [15].

"The sample size was determined using power analysis to estimate the minimum number of replicates required to detect a statistically significant difference between means of different treatments based on the assumption that data will be normal in their distribution. Data from the establishment was used for power analysis having been confirmed normally distributed using the Kolmogorov Smirnov test. It is impossible to simulate the exact *in situ* heterogeneity (real life situation). The actual spatial heterogeneity of nutrients can only be estimated by sampling at the field site, and it is practically impossible to recreate the exact *in situ* heterogeneity in pot trials. In view of this potential complexity, the model of heterogeneity was designed to simulate as closely as practicably possible the *in-situ* heterogeneity of trace elements measured at this scale in field sites in an earlier study with a range of intermediate HF (HF ranged from 1 to 3.22 (3.22 at the 20 m scale)" [15]. The proposed simulation of heterogeneity factors (HF) were 1.00, 1.25, 2.00 and 3.19 while an overall mean concentration of approximately 1000 mg/kg in all treatments was maintained (List 1 and 2). The simulation was based on the log-normal distribution observed in those field sites, with increasing values of geometric standard deviation (GSD) and hence the values of HF. The central cell (C3) of all treatments was maintained at 1000 mg/kg Fe. This is to ensure that the heterogeneity treatment did not deferentially affect the early establishment of the seedling.

2.2 Initial Establishment of *T. triangulaire* in the Nursery

T. triangulaire species was grown in a nursery for initial establishment in the un spiked soil after 7 days of nursery to ensure proper growth and establishment before the actual transplant into the trace metal spiked growth medium.

List 1a. Homogeneous---GSD 0.0; robust mean=1000; HF=1.00

Cells	1	2	3	4	5
A	1000	1000	1000	1000	1000
B	1000	1000	1000	1000	1000
C	1000	1000	1000	1000	1000
D	1000	1000	1000	1000	1000
E	1000	1000	1000	1000	1000

List 1b. Heterogeneous--GSD 0.1 Robust mean =1029; HF=1.2

Cells	1	2	3	4	5
A	900	700	900	1100	900
B	1100	1100	1400	1400	1400
C	1100	700	1000	900	900
D	1100	900	1100	1800	900
E	900	1100	900	1100	700

After the initial growth and the development of the first true leaves, plants of approximately equal size were selected and transplanted into the centre of the separate circular 1- litre pots (15 cm deep and 12 cm wide) pots for each species containing unspoked growth medium (washed silver sand, John Innes compost II, 7 parts sand to 3-part compost). Fifteen seedlings of the plant species were transplanted into pots (making a total of 60 seedlings) of unspiked growth medium first for two weeks and was watered daily using a fine rose watering can. This was maintained under 16 hours of natural light at 30 ± 5 ^{o} C in the greenhouse. Two weeks after the first transplanting ten seedlings of *T. triangulaire* were transplanted into 15 pots containing growth medium spiked with Fe at concentrations of 1000spiked with homogeneous and other concentrations as shown List 1b for the realistic heterogeneity treatment.

A total of 30 pots will be maintained (1000 mg/kg (homogenous) mg/kg added treatment (control and heterogeneous treatments) for 6 weeks under a photoperiod of 16-hour natural sunlight at 30 ± 5˚C in the greenhouse. These were maintained in 3.5-litre square pots (dimensions 17 cm x 24 cm) in a simple randomized block design both in 1000 mg/kg Fe added and 0 mg/kg added Fe as control and heterogeneous treatment. Pots were rotated clockwise by 90^{o} weekly to reduce the effect of uneven environmental conditions within the greenhouse.

Randomized blocks were between treatments because of the available space/m^{2} of greenhouse benches.

2.3 Greenhouse Pot Trial

This was done as described by Solomon-Wisdom et al*.,* 2015. Fifteen (15) rigid square pots (14 X14 cm and 17 cm deep) were thoroughly washed using detergent and labelled with the name of the plant species and the treatments (i.e control, homogeneous and heterogeneous) .

A customized cell divider made from a 1 mm clear polyethylene terephthalate glycol (PTEG) sheet was inserted into the pots to produce a 5 by 5, 2-dimensional grid with each cell measuring 25 mm square and 170 mm deep. This was used to create the designed heterogeneity models. The relatively thin PETG helped to maintain the heterogeneity design by reducing the collapse of each column after its removal. Labeled paper liners were inserted into each cell while filling cells with growth media. It provided a filling template, to help to maintain the structural integrity of the divider and minimize spillage from adjacent cells.

The gap between the paper liners and the outer edge of the pot was packed with an inert Sinclair Perlite (grain size 2.0-5.0 mm) because of the non-vertical sides of pots. Cells were filled according to the particular designed model of heterogeneity. Filling of the pots was done in two stages to ensure that equal volume of growth medium goes into the cells and that the growth medium is evenly distributed throughout the pot. The gently compacted growth medium was measured with a 100 ml customized container into each cell according to the design. The growth medium will be tapped down before an additional 50 ml was added and tapped down again.

Completed pots were placed on drip trays and arranged on benches in the randomized block design with blocks of 3 rows and 3 columns.

The growth medium was moistened from below by capillary action before transplanting seedlings already established in an unspiked growth media for two weeks. Tap water was applied using a fine rose watering can. This ensured that the heterogeneity is disturbed to a minimal extent. The percentage moisture content of the growth media was taken. The pH of the growth media was also taken. Ten replicates of each treatment were maintained in the greenhouse for six weeks under simulated sunlight using light-emitting diodes (LED) lights (under a photoperiod of 12 hours) at 30 ±5 C.

2.4 Harvesting

Plant stems were cut 0.01 mm above the soil surface and soil was removed from the root using a sieve. Soils were removed from harvested plant materials by repeated washing using tap water and dried at 60^{o}C for 48 hours. This was milled (using an herbage mill) for acid digestion using nitric and perchloric acids and analyzed for Fe using the AAS.

2.5 Chemical Analysis

“Shoots and roots were carefully washed to remove soil particles that could introduce

potential bias in measurements of metal concentration. Harvested roots and shoots were dried at 60ºC for 48 hours in a fan oven, weighed for Dried Weight, and analyzed for Fe concentration using an Atomic Absorption Spectrometer (AAS) after acid digestion using nitric acid" [16]. The growth media were analyzed for their actual Fe concentration.

2.6 Data Analysis

Data were analyzed using statistical software Minitab 18 and SPSS 25 for Windows. Statistical tools such as analysis of variance (ANOVA), RANOVA (robust analysis of variance), Tukey post-hoc test. and the mixed model ANOVA (treatment used as fixed factor and block as a random factor) were used to test for significance of measured variables whilst Kolmogorov-Smirnov test was used to test for normal distribution of data. Other relevant statistical tools and software packages was used to analyze and model data from this study.

2.7 Sample Preparation

All the reagents used were of analytical grade. Distilled water was used for distillation and preparation of reagents and standards. All glassware and plastic containers used were washed with liquid soap and rinsed with water before soaking in 10% nitric acid for 24 hours, cleaned thoroughly with distilled water and dried to ensure that there was no contamination.

2.8 Preparation of Samples for Analysis

The samples were selected to be debris and dirt free. Grains and pebbles were manually removed from the roots. Then the roots were properly washed under running tap water to remove soil particles and then rinsed with distilled water. Samples were dried in an oven at a temperature of 40^0C. The dried roots and shoots were milled into powdered form and then sieved using 0.500mm mesh size sieve and stored in polythene bags, until ready for acid digestion.

2.9 Acid Digestion

Plant and soil samples were acid digested as described by AOAC [17] with slight amendments.. 0.2g each of the powdered samples were weighed into a digestion tube and 10ml of 98% nitric acid added. This was then placed in a water bath and allowed to boil for about 72 hours. It was covered with a lid and transferred to digestion block in a fume cupboard for digestion. The temperature was steadily increased (to prevent fuming) until it reached 105^0C. This was left and allowed to undergo digestion for 30 minutes, after the digestion was completed, the resulting pale-yellow solution was allowed to cool and transferred into a 25ml volumetric flask and filled up to 25ml mark with de-ionized water and was filtered into clean sample bottles.

Reagent blank was prepared in similar manner. Standards concentration of the studied metal (iron) was analyzed to calibrate and blank samples were also analyzed. The acid digested samples were analyzed for iron using a Atomic Absorption Spectrometer (AAS, Thermos Fisher Scientific, model 3000 ICE).

2.10 Quality Control

Appropriate equipment was used, safety precautions and protective measures were followed to ensure the reliability of the test results. The chemical reagents used were of analytical grade. Glass wares and plastic containers used were all cleaned properly and in between the research. Samples were labelled and handled cautiously to avoid contamination or mixing. There were reagent blanks to check for contamination, duplicate samples were used to check for analytical precision and certified reference material (IAEA-V-8) was used to ensure instrumental bias (0% bias) and that the analytical values were within the range of certified value.

2.11 Quantification of Plant Uptake

"A plant's capacity to accumulate metals from the soils can be expressed by a concentration factor (CF)" [15]. "It is defined as the concentration of a particular chemical in a biological tissue per concentration of that chemical in the tissue surroundings" [15]. "Several terms have been used in different studies. In certain studies, concentration factor is also known as phytoextraction or bioaccumulation factor" [18,19]. "It is estimated as the ratio of trace metal concentrations in the aerial + below-ground part of plants and soil trace metal concentration (both expressed on a dry weight (DW) basis), and expressed mathematically" [15].

$$\mathrm{CF_{Total}} = \frac{\text{Concentration of trace metals in shoots and roots } \frac{\mathrm{mg}}{\mathrm{kg}}\,\mathrm{DW}}{\text{Concentration of trace metals in soil } \frac{\mathrm{mg}}{\mathrm{kg}}\,\mathrm{DW}}$$

$$\mathrm{CF_{Total}} = \frac{\mathrm{Cshoot\ and\ root}}{\mathrm{Csoil}} \quad (1)$$

Where,

$$\mathrm{C_{Shoots\ and\ Roots}} = \text{Concentration of trace metals in shoots and roots } \left(\frac{\mathrm{mg}}{\mathrm{kg}}\right)\mathrm{DW}$$

$$\mathrm{C_{Shoots\ and\ Roots}} = \text{Concentration of trace metals in soil } \frac{\mathrm{mg}}{\mathrm{kg}}\,\mathrm{DW}$$

$$\mathrm{CF_{Shoot}} = \frac{\text{Concentration of trace metals in shoots and roots } \frac{\mathrm{mg}}{\mathrm{kg}}\,\mathrm{DW}}{\text{Concentration of trace metals in soil } \frac{\mathrm{mg}}{\mathrm{kg}}\,\mathrm{DW}} \quad (2)$$

$$\mathrm{CF_{Root}} = \frac{\text{Concentration of trace metals in shoots and roots } \frac{\mathrm{mg}}{\mathrm{kg}}\,\mathrm{DW}}{\text{Concentration of trace metals in soil } \frac{\mathrm{mg}}{\mathrm{kg}}\,\mathrm{DW}} \quad (3)$$

Anibasa, [15].

3. RESULTS

The mean concentration of Fe in the three-treatments (control, homogenous and heterogenous) for both roots and shoots in *T. triangulaire* are shown in Table 1. The mean root Fe concentration for the control, homogeneous and heterogeneous treatment were 1263 ±154mg/kg, 1504 ±178mg/kg, and 1393 ±140mg/kg respectively (List 2). The mean shoot Fe concentration for the control, homogeneous and heterogeneous treatment were 904 ±174mg/kg, 1401 ±117mg/kg and 1045 ±95mg/kg respectively (Fig. 1). A comparison of the measured mean shoot and root Fe concentration in all treatments with the World Health Organization (WHO) permissible limit, showed that Fe concentration was 2 to 3 times higher in all the treatments than the permissible limit of 425 mg/kg. This implies that regular intake of *T. triangulaire* may pose a health threat to human. There was no significant difference (P>0.05) in the mean shoot and root Fe concentration between treatments. This indicates that *T. triangulaire* will accumulate about the same level of iron in the control, homogeneous and heterogeneous treatments. However, homogeneous root Fe concentration was 0.19 times higher than control and 0.07 times higher than the heterogeneous while the homogeneous shoot Fe concentration was 0.35 times higher than control and 0.25 times higher than heterogeneous.

Fig. 2 compared root and shoot concentrations between treatments. The root Fe concentration of the control, homogeneous and heterogeneous treatments were 30.4%, 36.1% and 33.5% were higher than the shoots respectively. The shoot Fe concentrations between treatments were 10 to 40% lower than the roots. This showed that *T. triangulaire* accumulate about 60% of the Fe in the roots and translocates about 10 to 40% of Fe from the roots to the shoots depending on the distribution of Fe in the soil with up to 20 to 30% translocation of Fe in the homogenous and heterogenous treatments and 10% less in the control.

Table 1. Shoot and root iron concentration of *T.triangulaire* in the control, homogenous and heterogenous treatments

Treatment	Iron Concentration mg/kg (mean ±SEM)
Root	
Control	1263±153
Homogenous	1504±178
Heterogenous	1393±140
Shoot	
Control	904±174
Homogenous	1401±117
Heterogenous	1045±95
WHO	425 (Akubugwo et al., 2012)

Key: SEM =Standard Error of the Mean; WHO= World Health Organization

The concentration factor (CF) which is a measure of uptake in the control, homogeneous and heterogeneous were 0.1118, 0.1498 and 0.1258 respectively. This indicates that Fe uptake is also similar irrespective of treatments.

It also indicates that this plant is an accumulator of Fe and exhibited tolerance and affinity for Fe in varied soil treatments.

4. DISCUSSION

The result of this study showed no significant difference in iron uptake between the control, homogeneous, and heterogeneous treatments for waterleaf. The concentration factors indicated waterleaf's capacity to acquire iron efficiently across variable soil conditions. The observed early flowering and the higher number of flowers in the heterogenous treatment than the control and homogenous treatments may indicate that Fe plays a role in plant reproduction, however, the mechanism behind this is not completely known. Iron is a cofactor for various enzymes involved in chlorophyll synthesis, electron transport, and DNA replication, all of which are essential for plant growth and reproduction [20].

The study found slightly higher iron concentrations in the shoots and roots of plants grown in the homogeneous treatment compared to the heterogeneous and control treatments. This suggests that while heterogeneity did not majorly impede total uptake, the variability in iron distribution may have had subtle impacts on absorption and translocation.

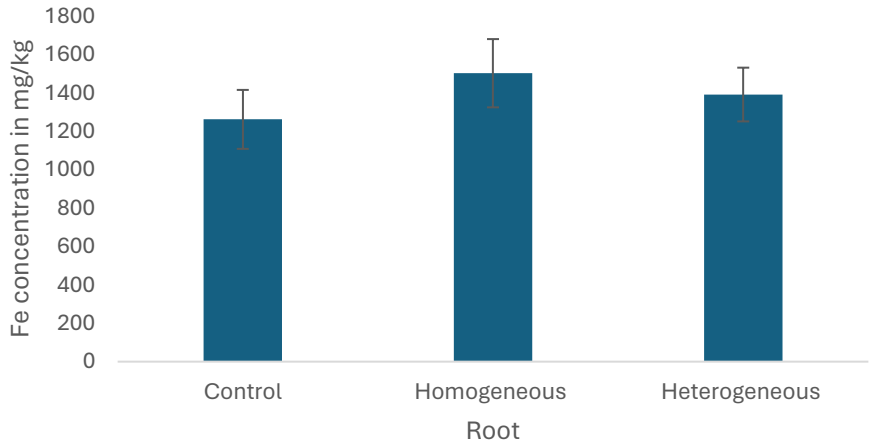

Fig. 1. Comparison of root Fe concentration between treatments
Error bars represent 2 standard errors on the mean

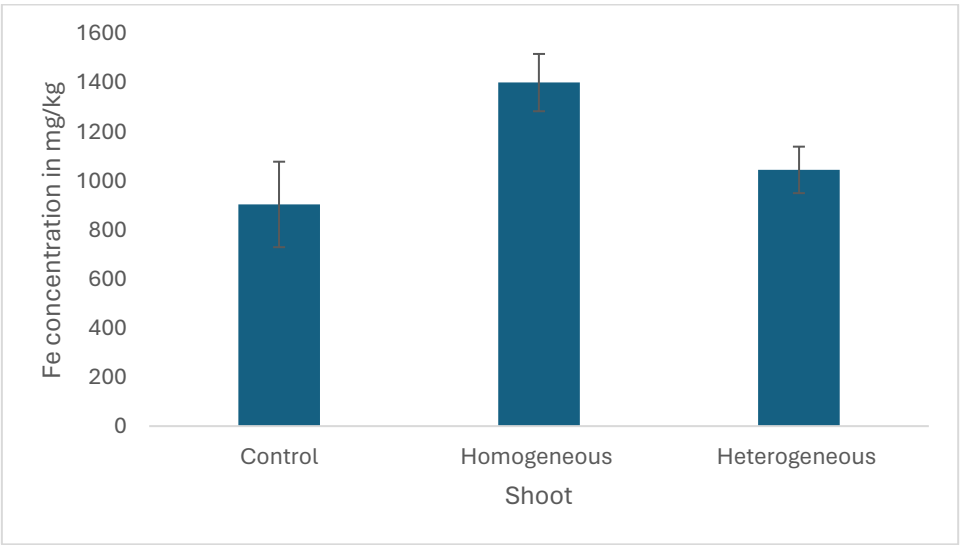

Fig. 2. Comparison of shoot Fe concentration between treatments
Error bars represent 2 standard errors on the mean

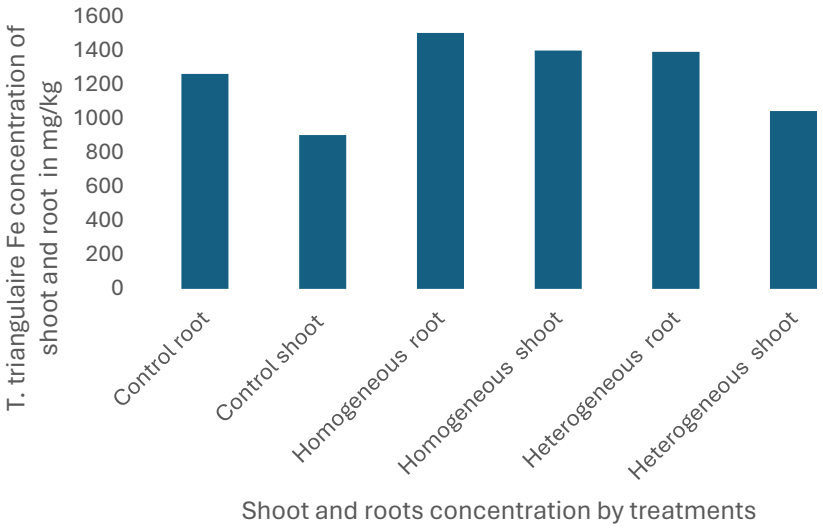

Fig. 3. comparison of roots and shoots Fe concentrations between treatments

The high iron concentrations observed even in the control treatment is a pointer to the adaptation of waterleaf root for tapping iron from native soil environments. This supports the inherent capacity of waterleaf to mobilize and take up iron from soils through root exudates and morphological changes in agreement with the report of Marschner, [20]. The mean plant concentration of Fe in the control treatment is an indication that the natural soil is rich in Fe and that plant has high affinity for Fe in varied soil concentrations. This may explain why water leaf is thought to be very rich in Fe consequently prescribed for persons with anaemia by most local populations in Nigeria.

The mechanisms governing iron acquisition in waterleaf merit further research. Study of genes and processes involved in strategies like rhizosphere acidification, ferric chelate reductase activity, and secretion of phytosiderophores could provide insights into waterleaf's iron efficiency [21].

Moreover, assessing growth, biomass allocation, and chlorophyll content would give a fuller picture of how iron heterogeneity influences waterleaf physiology beyond just uptake. Parameters like root proliferation in nutrient patches also need measurement [22,23,24].

Overall, this study constitutes an early step towards elucidating the linkages between soil chemical heterogeneity and plant mineral nutrition. Further field trials with geo-statistical characterization of soil variability could help generalize the findings. Nevertheless, the results highlight waterleaf's adaptability and hold useful implications for its sustainable cultivation [25].

The findings indicate that waterleaf can take up Fe efficiently across different soil conditions. This may be attributed to adaptive mechanisms such as increased root proliferation and exudation of organic acids in Fe deficient zones.

5. CONCLUSION

This study investigated the relationship between iron (Fe) heterogeneity in soil and its uptake by waterleaf (*Talinum triangulare*). The results showed that while there were slight variations in Fe uptake between the control, homogeneous, and heterogeneous treatments, these differences were not statistically significant.

Overall, the concentration factor for total Fe uptake were similar in all treatments. However, further studies with more pronounced heterogeneity levels and environmental variables are needed to conclusively determine if spatial variability affects waterleaf Fe nutrition. Field experiments could help validate the effects observed in controlled pot trials.

Nevertheless, this study provides initial evidence that waterleaf possesses resilience mechanisms enabling consistent Fe acquisition despite heterogeneous distribution in soil. This has positive implications for cultivation on diverse soil types with variability in Fe availability.

6. RECOMMENDATIONS

Based on the findings, the following are recommended:

Breeding programmes that could select waterleaf varieties with increased capacity for mobilizing and acquiring Fe from spatially variable soil environments that could enhance adaptation across diverse edaphic conditions is recommended.

Applying organic fertilizers may help overcome localized Fe deficiency by improving microbial Fe mobilization as organic acids released during decomposition can solubilize Fe in nutrient hotspots.

Adjusting pH through lime application in acidic soils can increase Fe availability. However, this should be implemented carefully to avoid over-liming.

Intercropping with species effective in nutrient mobilization could facilitate Fe uptake by waterleaf and aid nutrients cycling.

Adopting precision agriculture approaches to map *in-situ* variability in soil Fe can allow for targeted management in deficient zones.

Further studies could also evaluate interactions of Fe heterogeneity with other edaphic factors. Assessing impacts across field environments can help refine agronomic practices.

Finally, research on genetic and molecular mechanisms governing Fe efficiency merits more focus.

CONTRIBUTION TO KNOWLEDGE

This study provides new insights into the nexus between heterogeneous soil iron distribution and iron acquisition in waterleaf plants. These findings contribute to the scientific understanding of how adaptive traits can enhance nutrient uptake by plants despite variability in soil chemical forms and availability.

This knowledge can inform agricultural practices and plant programmes to enhance crop resilience to heterogeneous micronutrient supply, improving food production and nutritional outcomes.

The study also highlights the need for more research on plant micronutrient mobilization and uptake mechanisms in spatially variable soil environments. This can uncover genetic potential to further improve cultivation on marginal, nutrient deficient soils for sustainable food security.

Overall, the research advances the fields of agriculture, plant mineral nutrition, and agronomy by elucidating the multifaceted soil-plant relationships governing iron acquisition.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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