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# Sand-based Soil Properties and Green Bean (*Phaseolus vulgaris* L.) Yield as Affected by Biochar and Foliar Application of Three Distinct Types of Iron

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**Abstract**

PLANT GROWTH is hindered by the infertility of sandy soil, which lacks organic matter and essential nutrients. Beans, in particular, require iron, a vital micronutrient necessary for photosynthesis and chlorophyll synthesis. Biochar has been shown to significantly enhance soil fertility. This study was conducted over two growing seasons, 2022/2023 and 2023/2024, to evaluate the effects of three different types of iron applied as a foliar spray at a concentration of 50 mg/L specifically iron oxide nanoparticles ($Fe_2O_3$), ferrous sulphate ($FeSO_4$), and iron chelate (Fe-EDDHA) in combination with three rates of biochar fertilizer (0.0, 1.5, and 3.0 tons per feddan). The study aimed to assess various parameters, including vegetative growth (plant height, number of branches per plant, and fresh and dry weight per plant), green pod yield, the physical quality of pods (length and weight), and the nutritional value of both bean leaves and pods (including nitrogen, phosphorus, potassium, and iron). Additionally, the chemical quality of the pods was analyzed, looking at protein, total carbohydrates, and fiber content. Results indicated that all treatments had a significant impact on these parameters. Notably, except for soil salinity, which improved with the application of biochar, the soil properties (including soil interaction, organic matter, and bulk density) also showed improvement after the bean harvest as the rates of biochar fertilizer increased from zero to three tons per feddan. The study concluded that applying 3.0 tons of biochar per feddan and foliar spraying of iron nanoparticles at a concentration of 50 mg/L was the most effective treatment. This combination significantly influenced all measured parameters, while the lowest values were observed when no biochar was added, and no foliar iron was applied.

**Keywords:** Bean, Biochar, Iron oxide nanoparticles, Ferrous sulphate, and Iron chelate.

## Introduction

In Egypt, green beans (*Phaseolus vulgaris* L.) are a significant economic legume crop and are vital to human nutrition due to their low cost and high protein, mineral, amino acid, and vitamin content (Kerlous, 1997, Abdel-Hakim et al., 2012, Salah et al. 2018, and Hashim et al., 2025). The edible green pods and dry seeds are highly sought after by the market and eaten as cooked vegetables that are high in minerals (phosphorus, calcium, manganese, magnesium, potassium, and iron), fiber, carbohydrates, and proteins (Marzouk et al., 2019). This crop produces 23,411,172 tons annually on an area of roughly 1,586,086 hectares worldwide (FAOSTAT, 2021). Snap beans face numerous challenges when grown in recently reclaimed sandy soil, including erratic rainfall, low organic matter content, and nutrient deficiencies. A lot of farmers use mineral fertilizer in large quantities or organic fertilizers to get around this issue (Stewart et al., 2005 and Galal et al., 2024).

Many plants have trouble surviving in sand soil, which usually have poor water and nutrient holding capacity and high hydraulic conductivity. To create biochar, a solid black carbon residue, biomass (such as field crop residues, forest residues, manure, or urban waste) must thermally decompose in an oxygen-limited environment (Lehmann et al., 2006 and Abuzaid et al., 2025). The potential of biochar to

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improve soil quality and increase crop yields makes it a common soil amendment in agricultural soil (Sohi et al., 2010). The usual range of biochar application rates in the field is 0.5 to 100 Mg/ha (4%, w/w) (Major et al., 2010, Karhu et al., 2011, Arthur et al., 2015, Jeffery et al., 2015, and Zhao et al., 2016). Important indicators for evaluating the physical quality of soil are soil hydraulic properties, which are directly related to crop growth and yield as well as the storage and movement of materials (such as water, air, and nutrients) in the soil (Reynolds et al., 2009, Cullotta et al., 2016). Biochar has two advantages over other organic materials: it is more stable against degradation and has a higher capacity to hold onto nutrients. Through the improvement of microbial flora, moisture-holding capacity, and cation-exchange capacity, biochar improves the physical and chemical characteristics of the soil (Mensah & Frimpong, 2018 and Elhakem et al., 2025).

Plant metabolism depends on the optimal uptake of micronutrients like iron, which is involved in numerous metabolic and enzymatic processes, including hormone and DNA synthesis, electron transport, and nitrogen fixation (Fernandez et al., 2008 and Sheta et al., 2025). Some soil typically has a deficiency in the available form of iron, $Fe^{2+}$, because iron is primarily found in the insoluble form of $Fe^{3+}$, especially in high pH and aerobic soils (Ye et al., 2015). Conventional fertilizers like sulphates and iron chelates don't help with these issues because they tend to leach and contaminate the groundwater table (Galicia et al., 2011). For this reason, the application of iron nanoparticles to crops growing in soils with alkaline pH and high calcium carbonate content is very important, because these problems are common in many crops of agricultural importance. An alternative application of this element is foliar fertilization, which is rapidly absorbed through the leaf epidermis and can be accessed from other parts of the plant via xylem and phloem (Nasiri et al., 2010). It also has a more immediate and targeted response than soil fertilization, as nutrients can be applied during critical stages of plant growth (Fernandez et al., 2015). One workable solution to plants' micronutrient needs is the foliar application of micronutrients (Wang et al., 2010). In recent years, Nanofertilizers have been introduced because of ongoing advancements in fertilizer technology. A successful method of managing plant nutrition is the delivery of nutrients to plants using nanotechnology techniques (Solanki et al., 2015, Ghorbanpurit et al., 2017, and Taha et al., 2024). Fertilizer materials are synthesized and formulated into extremely fine particles (1–100 nm) to create nanofertilizers. The characteristics of these nutrients differ from those of large-scale nutrient presence, and this technology is being used in a variety of fields outside fertilizers application. One benefit of using fertilizers in nanoform is that they release nutrients more slowly over an extended period, which reduces soil nutrient loss and groundwater and soil pollution (Nadiri and Danesh-Shahraki, 2013). The remarkable capacity of nanofertilizers to greatly improve plant growth and yields is remarkable. In striking contrast to traditional fertilizers, nanofertilizer require remarkably lower concentrations for foliar application. Thus, iron deficiency can be effectively corrected by these remarkable nano-iron particles, particularly in arid and water-scarce regions, improving the general health of plants. Additionally, when it comes to boosting the growth and nutritional status of green beans, the application of nano fertilizers, including nano-iron, represents an unmatched strategy, outperforming traditional methods by an astounding margin of up to 30%. Beyond just green beans, nanofertilizer have a remarkable effect on the growth and, ultimately, yield of numerous other common beans (Abd El-Ghany et al., 2021, El-Gioushy et al., 2021, Mahmoud et al., 2022 and Salama et al., 2022).

This study aimed to investigate the effects of different biochar application rates (0.0, 1.5, and 3.0 tons/feddan) and foliar application of three iron formulations ($Fe_2O_3$ nanoparticles, $FeSO_4$, and Fe-EDDHA at 50 mg/L) on vegetative growth parameters, green pod yield, physical quality, nutritional composition of leaves and pods post-harvest soil properties.

## **Materials and Methods**

This study investigated the effects of foliar iron applications and biochar amendments on vegetative growth parameters, physical and chemical properties of green beans (*Phaseolus vulgaris* L. cv. Bronco), and post-harvest soil characteristics in sandy soil.

### ***Experimental Details***

Location: Village 1, Matay City, Minia Governorate, Egypt

Duration: Two consecutive growing seasons (2022/2023 and 2023/2024).

Experimental Design: Split-plot design with four replicates comprising nine treatments:

Main plots: Biochar application rates (0.0, 1.5, and 3.0 ton/feddan)

Sub-plots: Foliar iron treatments (50 mg/L of):

- Iron oxide nanoparticles ($Fe_2O_3$ NPs)
- Ferrous sulphate ($FeSO_4$)
- Iron chelate (6.0% Fe-EDDHA)

### ***Site Characteristics***

Soil properties: Initial physical and chemical characteristics were analyzed following Klute (1986) and Page et al. (1982), respectively (presented in Table 1)

Irrigation: Surface irrigation using Nile-derived water from Bahr Youssef Canal, stored in reservoirs and delivered via a pumping system.

### *Methods Used in Agriculture*

Dry maize stalks from the experimental farm at Village No. 1, West Matay, Minya Governorate, Egypt, were collected to make biochar. The maize stalks were chopped into pieces that were 5–10 cm long and burned at a temperature of 400 °C without air. A stainless-steel mill was then used to grind the biochar that was produced. A few of these biochar's chemical characteristics are displayed in Table 2 according to Page et al. (1982). In the experimental plot, biochar was added to the soil and thoroughly mixed before being planted at rates of 0.0, 1.5, and 3.0 tons/feddan for each treatment independently.

During soil preparation, 100 kg/feddan of calcium superphosphate (15% $P_2O_5$) was applied as fertilizer. During the growing seasons, nitrogen was added at 150 kg/feddan in the form of ammonium sulphate (20.6% N) and 50 kg/feddan in the form of potassium sulphate (48% $K_2O$).

Application of three different forms of iron micronutrients [Iron oxide nanoparticles ($Fe_2O_3$), ferrous sulphate ($FeSO_4$), and iron chelate (6.0% Fe-EDDHA) topically at a concentration of 50 mg/L are sprayed foliar onto leaves. Three sprays were applied to the plants: the first was applied 25 days after planting, and the second and third were applied 15 days apart. El-Gamhouria Company for Chemicals, Zagazig branch, Egypt, provided the ferrous sulphate and iron chelate.

### *Characterization of Nanofertilizers*

The iron oxide ($FeO_3$) nanofertilizer employed in this work was made by wet chemical techniques and came in the form of magnetic and semiconductor iron oxide nanoparticles (maghemite ($\gamma$-$FeO_3$). Scanning electron microscopy (SEM) (Figure 1) and transmission electron microscopy (TEM) (Figure 2) were used to determine the size and form. The manufacturer's information indicates that the nanoparticles are 99.7% pure and have an average size of less than 50 nm (Figure 3). The Plant Pathology Research Institute's Nanotechnology Lab, Agricultural Research Centre, Giza, Egypt provided the iron oxide nanoparticles ($FeO_3$).

### *Cultivation*

All bean seeds were treated with Rhizobium phaseoli bacteria prior to sowing. Rhizobium was acquired from the Soil, Water, and Environment Research Institute's Microbiology Department in Giza. In each season, the first week of September saw the sowing of green bean seeds (Bronco cultivar). The experiment's plot measured 10.5 m² (3.0 m x 3.5 m). After 15 days of germination, the plants were thinned to two plants in each hole, separated by 20 cm. As in the district, other culturally recommended methods of producing beans were carried out.

### *Data Collection and Analysis Methods*
### *Plant Growth Measurements*

At 60 days post-planting (10-50% flowering stage), five random plants per plot were sampled to assess:

- Plant height (cm)
- Branch number per plant
- Fresh leaf weight (g/plant)
- Dry leaf weight (g/plant) (oven-dried at 70°C to constant weight)

### *Yield Component Analysis*

At maturity, five plants per subplot were evaluated for:

- Average pod length (cm)
- Average pod weight (g/plant)
- Marketable yield (ton/feddan)

### *Leaf and Pod Chemical Analysis*

*Leaf Analysis:*

- Dried samples (70°C) were digested using $H_2SO_4$-$H_2O_2$ (Bremner & Malvaney, 1982)
- Nutrient quantification:
  - Total N: Spectrophotometric analysis (Novozamsky et al., 1984)
  - P: Colorimetric method (Wilde et al., 1985)
  - K: Flame photometry (Black, 1985)
  - Fe: Atomic Absorption Spectroscopy (Perkin-Elmer, 1982)
  - Chlorophyll content (Gavrilenko & Zigalova, 2003)

*Pod Quality Analysis:*

- Crude protein (%N × 6.25)
- Total carbohydrates
- Crude fiber
  (Analyzed according to AOAC, 2005 standards)

### *Post-Harvest Soil Analysis*

Surface soil samples (0-30 cm depth) were analyzed for:

- pH (1:2.5 soil:water)
- Electrical conductivity (dS/m)
- Organic matter content
- Bulk density (g/cm³)
  (Klute, 1986 methods)

### *Experimental Design:*

All measurements were conducted with four replicates, with means calculated for statistical analysis.

*Analyses of Statistics*

The statistical analysis was subjected to the method described by Snedecor and Cochran (1989). The treatment means were compared by using the Duncan Multiple Range Test at a 5% probability level.

## Results

*Effects of Biochar and Foliar Iron on Bean Growth Parameters*

Enhancing growth characteristics is essential for improving bean crop productivity. Data from the 2022/2023 and 2023/2024 growing seasons (Table 3) demonstrate the effects of different biochar application rates (0.0, 1.5, and 3.0 tons/feddan) and foliar iron treatments (sulfate, chelate, and nano forms) on key growth parameters: plant height (cm). number of branches per plant, leaf fresh weight (g/plant) and leaf dry weight (g/plant). Significant differences ($P < 0.05$) were observed among biochar treatments in both seasons. The highest growth performance was recorded at 1.5 and 3.0 tons/feddan, surpassing the control (0.0 tons). 3.0 tons/feddan was the most effective rate, suggesting that higher biochar applications enhance nutrient availability for bean plants.

*Effects of Iron Formulations and Biochar on Bean Growth Performance*

The experimental results (Table 3) revealed significant treatment effects ($P < 0.05$) of foliar iron applications on all measured growth parameters: Plant height (cm), Branch number per plant, Leaf fresh weight (g/plant), Leaf dry weight (g/plant).

*Iron Form Comparison*

Nano-iron ($Fe_2O_3$ NPs at 50 mg $L^{-1}$) consistently outperformed both chelated (Fe-EDDHA) and sulfur-based ($FeSO_4$) forms. Nano-treated plants showed 15-22% greater growth metrics compared to other iron forms at equivalent concentrations. The optimal treatment combination (3.0 tons of biochar/feddan + nano-iron) was produced. Maximum vegetative growth values 25-30% improvement over control (no biochar, no iron). This combination significantly ($P < 0.05$) enhanced all measured traits.

*Yield and Its Constituent Parts*

During the 2022/2023 and 2023/2024 seasons, Table 4 displays the yields and their components of bean production, expressed in terms of pod length (cm) and pod weight (g), as well as green pod yield. These measurements were influenced by the application of biochar fertilizers at rates of 0.0, 1.5, and 3.0 tons per feddan, along with various forms of iron (nano, chelated, and sulphate) sprayed on the plants.

The data in Table 4 indicate that increasing the biochar fertilizer application from zero to three tons per feddan significantly affected the yield characteristics and their components. Specifically, the highest averages for pod length and pod weight, as well as marketable yield measured in tons per feddan, were achieved when applying biochar at a rate of three tons per feddan. In contrast, lower yields were observed with the zero and 1.5 tons per feddan treatments.

The characteristics of yield components and the marketable green pod yield significantly increased due to the three treatments of foliar spraying iron in different forms (nano, chelated, and sulphate), as shown in Table 4. During the growth seasons of 2022/2023 and 2023/2024, the treatment involving the application of nano iron at a rate of 50 mg $L^{-1}$ recorded the highest values for both yield components and marketable pod yield. This increase was particularly noteworthy compared to the other forms of iron spraying. Table 4 presents comparisons of the average values of crop components and green pod yield based on the combination of foliar iron application and biochar. The data clearly indicate that all rates of biochar and foliar applications of various iron forms significantly stimulated the values of yield components and marketable pod yield. Specifically, using 3.0 tons of biochar per feddan along with topical application of iron in nano form during both growing seasons resulted in the highest average values.

*Content of Minerals (as a percentage of dry weight) in the Beans' Leaves and Pods*

During the 2022/2023 and 2023/2024 growing seasons, Tables 5 and 6 illustrate the impact of applying biochar fertilizer and foliar spraying with iron in its different forms, whether sulphur, chelated, or nano, on the concentration of certain nutrients, including nitrogen, phosphorus, potassium, and iron, in the beans' leaves and pods.

About adding biochar fertilizer to the soil and how it affects the levels of certain nutrients, like iron, phosphorus, potassium, and nitrogen, in the leaves at 60 days of age (heading stage) and the bean pods at harvest as well as the values for protein content. The concentration of the elements under analysis and protein increased significantly at both the 60-day and harvest stages when the rates of biochar fertilizer addition were increased from 0.0 to 3.0 ton/feddan.

According to the information in Tables 5 and 6, foliar spraying with iron in its three forms had a significant impact on the amounts of nitrogen, phosphorus, potassium, and iron in green bean leaves and pods. In comparison to the foliar spray treatments of iron sulphate and chelated iron at the same concentration, the foliar spraying treatment employing nano iron at a rate of 50 mg/L produced the highest values of nitrogen, phosphorus, potassium, and iron concentrations in leaves and pods.

As the table illustrates, the results demonstrated the positive impact of combining iron foliar spray with biochar fertilizer. The results show that the levels of nitrogen, phosphorus, potassium, and iron in bean leaves and pods were all considerably impacted by the treatments that were being studied. High concentration of iron, phosphorus, phosphorus, and nitrogen were found in bean leaves and pods, during both growing seasons when combined biochar was applied to the soil at a rate of 3.0 tons per feddan with a treatment of 50 mg/L nano iron.

*Green Plants' and Pods' Chemical Makeup Content of Carbohydrates, Fiber, and Protein (as a percentage of dry weight)*

The information in Table (7) showed how the total carbohydrates and fibers and protein content of bean plants during the 2022/2023 and 2023/2024 growth seasons were affected by biochar fertilizer and foliar spraying with iron in its three forms: sulphur, chelated, and nano.

The addition of biochar fertilizer had a significant impact on total carbohydrates, fibers, and protein content during the 2022/2023 and 2023/2024 growing seasons, according to the statistical analysis of the data in the same table. In comparison to the 1.5 ton/feddan of biochar and the 0.0 ton/feddan biochar treatment, the data also demonstrated that the addition of 3 ton/feddan of biochar fertilizer produced the highest values of carbohydrates, fibers, chlorophyll, and protein contents. This reflects that increasing biochar fertilizer from 0.0 to 3 ton/feddan in sandy soils improves the quality characteristics of the bean crop.

Foliar spraying with iron in its three forms, sulphur, chelated, and nano had a significant impact on total carbohydrates, fibers, and protein content during both growing seasons, according to data in Table (7) regarding the chemical quality of the pods. Comparing 50 mg/L of iron in nano form to chelated iron and iron sulphate at the same concentration, the best values for carbohydrates, fiber, and protein content were observed. This is explained by how crucial the use of nano fertilizers has become in the agricultural industry lately.

Table (7) makes it evident that the quality of chemical pods was significantly impacted by the combination of foliar spraying with iron in all three forms and biochar fertilizer. The bean plant's percentage of total carbohydrates, fibers, and protein showed the highest value when 3.0 tons/feddan of biochar fertilizer when combined with 50 mg/L. of nano iron.

*Characteristics of the Soil Following Harvest*

Following bean harvest, Table 8 displays a few physical and chemical characteristics of the soil, including bulk density, conductivity, and reaction. According to the data, applying biochar fertilizer from 0 to 3 tons/feddan resulted in a decrease in pH and bulk density values, but an increase in electrical conductivity and organic matter percentage.

The results clearly demonstrate that the properties of the studied soil did not respond to the interaction between biochar fertilizer and foliar spraying of iron. In terms of the effect of foliar spraying of iron in its three forms, the data indicated that all of the physical and chemical properties of the studied soil were not affected by foliar spraying of iron in its three forms.

## **Discussion**

In Egypt, growing beans on sand soils, especially in recently reclaimed desert regions, presents significant obstacles such as low organic matter, poor water retention, and iron (Fe) deficiency that is made worse by calcareous conditions and high pH. This study shows that bean productivity on these marginal soils can be increased by combining foliar iron sprays (ferrous sulphate, chelated iron, and nano-iron) with biochar (made from local agricultural waste, such as dry maize stalks). These findings emphasize context-specific trade-offs in nutrient management while remaining in line with Egypt's National Strategy for Sustainable Agriculture.

The findings of the study indicate that the addition of 3 tons of biochar fertilizer per feddan enhances the growth of bean plants by improving soil characteristics and supplying the required nutrients. Biochar improves soil porosity, which enhances the soil's capacity to hold onto water and nutrients. These two factors are critical for plant growth in arid and semi-arid regions (Lehmann and Joseph, 2024). Furthermore, Glaser et al. (2022) discovered that biochar contributes to better soil aeration, which promotes plant root development and lowers the risk of root diseases. According to Atkinson et al. (2020), biochar improves the soil's capacity to exchange cations, which enhances the nutrients' availability to plants.

The fact that biochar has enough of the organic acids that the soil releases during mineralization may be the reason for its capacity to lower soil pH (Geng et al., 2022). Furthermore, because biochar is an acidifier, it releases certain organic acids during its breakdown, which reduces soil reactivity (Bedassa, 2021). They added that hydrochloric acid ($H_2CO_3$), which is formed when the carbon dioxide produced during the breakdown of biochar dissolves in soil moisture led to further reduces the pH of soil. It's probable that biochar's beneficial effect on bulk density resulted from both reducing the density of soil particles and increasing the volume of micropore space, according to Niraj and Mahat (2011).

Certain vital nutrients for plants, including calcium, phosphorus, and potassium, are found in biochar and can help to enhance plant growth (Schmidt et al., 2023). By decreasing leaching or stabilization, biochar enhances the availability of nutrients in soil (Major et al., 2021). Bean plants' capacity to absorb water and nutrients can be enhanced by adding biochar to the soil (Merkeb et al., 2024). By increasing the biomass of bean plants, biochar can result in higher crop yields (Jeffery et al., 2020). By lowering environmental stressors like salt and water stress, biochar has improved plants' capacity to thrive in challenging environments (Mukherjee et al., 2021).

Incorporating three tons of biochar into the soil improves soil fertility and nutrient availability, which impacts the chemical makeup of green bean plants and their pods, particularly the amount of carbohydrates and fiber. The absorption of nutrients (like potassium and phosphorus) necessary for photosynthesis-based carbohydrate synthesis is improved by biochar. Ephruim et al. (2024) found that applying rice husk biochar (500–600 °C) at a dose of 10 tons/ha increased the amount of total carbohydrates (starch and sugars) in pods by 8–12%. This result is in line with their findings. Furthermore, because degrading microbes are more active in rich clay soils, Abriz et al. (2021) and Deshoux et al. (2023) observed a slight decrease (3–5%) in simple sugars (like glucose).

The process by which increasing the fiber content of biochar improves the availability of calcium and magnesium to the bean plant, which in turn promotes the formation of plant cell walls. Utilizing wood biochar (700°C) in sandy soil results in a 10-15% increase in fiber in pods because of better silicon absorption, which increases the soil's hardness (Kumari et al., 2022). Pre-fertilized clay soil did not exhibit a statistically significant change in fiber content (Su et al., 2024, Khan et al., 2024, and Demirkaya et al., 2025). The ideal dosage, according to some research, is 5–15 tons/ha. Pod formation may be adversely affected by high doses (>20 tons) that inhibit nitrogen uptake (Sheffield et al., 2024).

Green bean growth, yield, and nutritional quality were all improved by iron nanoparticles more effectively than by ferrous sulphate or chelated iron. Iron nanoparticles (10–100 nm) avoid soil–root interactions by penetrating the stomata and epidermis directly. The efficiency of foliar absorption is enhanced by their small size and large surface area (Rui et al., 2016). By releasing $Fe^{2+}/Fe^{3+}$ ions gradually, polymer-coated iron nanoparticles (like chitosan) lessen oxidative stress and leaf burn (Giglou et al., 2022). Compared to $FeSO_4$ (20%) and Fe-EDTA (25%), iron nanoparticles raise the amount of chlorophyll in iron-deficient beans by 35–40% (Zhang et al., 2024). Improved auxin synthesis results in a 30% increase in root biomass (Reddy et al., 2024). The nutritional quality was improved by iron nanoparticles, which raised grain iron content by 50% and pod yield by 22–28% (Merkeb et al., 2024). Because of the balanced distribution of iron, pod deformation was decreased (Aslam et al., 2024). Catalase (CAT) and superoxide dismutase (SOD) enzyme activity was 20% higher in plants treated with iron nanoparticles, reducing oxidative stress during drought (Ullah et al., 2024). In pods, iron nanoparticles boosted protein synthesis by 15%, whereas iron dioxide led to nitrate buildup because of insufficient absorption (Dedejani et al., 2021).

A novel approach to improving crop resilience and productivity, particularly in nutrient-poor or stressed agroecosystems, is the combined application of biochar and foliar spraying three distinct types of iron micronutrients on leaves at 50 mg/l [(Iron oxide nanoparticles (Fe2O3) Fe-NPs, ferrous sulphate FeSO4, and iron chelate (Fe-EDDHA)]. Plant growth and development benefited from the interaction between biochar and foliar application of iron in its three forms: sulphur, chelated, and nano. According to Abriz et al. (2021), foliar iron applications can give plants a direct source of iron, while biochar can boost the amount of iron in the soil. When combined, the two can improve plants' uptake and utilization of iron. According to Mehmood et al. (2022), the combination of biochar and foliar iron treatments can enhance plant growth by increasing biomass production, leaf area, and root growth. Additionally, Geetha et al. (2022) found that iron and biochar can work together to boost antioxidant activity in plants, potentially enhancing plant health and preventing oxidative stress. According to Ephrium et al. (2024), foliar iron applications can give microorganisms involved in nutrient cycling a source of iron, while biochar can enhance nutrient cycling in soil. The two can work together to improve the availability and cycling of nutrients.

## Conclusions

The integration of biochar (3 tons per feddan) and foliar nano-iron (50 mg/L) provides a sustainable solution for enhancing bean productivity in Egypt's reclaimed sandy soils while minimizing environmental impacts. Reduced Dependency on Chemical Fertilizers. Biochar improves soil fertility, which decreases the need for synthetic inputs. Additionally, the high efficiency of nano-iron reduces the requirements for iron fertilizers. Enhanced Crop Performance: This approach maximizes bean yield and quality in marginal soils, improves nutrient uptake, and increases resilience to stress. Socioeconomic Advantages: Higher yields lead to increased profitability for farmers and support Egypt's goals for food security. Recommendation for Middle Egypt: To achieve optimal results in newly reclaimed lands, farmers should implement the following practices: - Soil amendment: Apply 3 tons of biochar per feddan, preferably sourced from local maize residues. - Foliar application: Use 50 mg/L of $Fe_2O_3$ nanoparticles during critical growth stages. This integrated approach aligns with sustainable agricultural practices while addressing the challenges of the region's soil conditions. Future studies should explore the long-term effects on soil health and the economic feasibility of scaling these methods.

*List of abbreviations*

$FeSO_4$: Ferrous sulphate

Fe-EDDHA: Iron chelate

Fe-NPs: Iron oxide nanoparticles

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*Conflicts of interest*

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**Table 1. Physical and chemical analysis for soil field experiments conducted in 2022/2023 and 2023/2024 seasons.**

| Soil properties | 2022/2023 season | 2023/2024 season |
|---|---|---|
| **Physical properties** | | |
| **Particle size distribution:** | | |
| **Clay%** | 10.00 | 10.15 |
| **Silt%** | 15.32 | 15.00 |
| **Fine sand%** | 26.43 | 25.72 |
| **Coarse sand%** | 48.25 | 49.13 |
| **Texture grade** | Sand loam | Sand loam |
| **Bulk density (g cm$^{-3}$)** | 1.35 | 1.41 |
| **Chemical properties** | | |
| **Ph** | 8.16 | 8.13 |
| **EC, soil paste dS m$^{-1}$** | 1.10 | 1.12 |
| **Organic matter%** | 0.32 | 0.34 |
| **$CaCO_3$%** | 1.7 | 1.6 |
| **Available N mg kg$^{-1}$** | 13.34 | 14.00 |
| **Available P mg kg$^{-1}$** | 5.78 | 6.05 |
| **Available K mg kg$^{-1}$** | 154.87 | 155.67 |
| **Available Fe mg kg$^{-1}$** | 5.2 | 5.8 |
| **Available Mn mg kg$^{-1}$** | 4.8 | 4.0 |
| **Available Zn mg kg$^{-1}$** | 3.23 | 3.05 |
| **Available Cu mg kg$^{-1}$** | 1.03 | 1.08 |

**Table 2. Some characteristics of the utilized biochar.**

| The characteristics of biochar | Values |
|---|---|
| **pH** | 8.15 |
| **EC dS m$^{-1}$** | 2.72 |
| **Organic carbon (g kg$^{-1}$)** | 493 |
| **CEC (cmol$^{+}$ kg$^{-1}$)** | 45.4 |
| **Total N (%)** | 1.42 |
| **Total P (%)** | 0.76 |
| **Total K (%)** | 1.41 |
| **Total Ca (%)** | 0.82 |
| **Total Mg (%)** | 0.53 |
| **Bulk density (g cm$^{-3}$)** | 0.64 |
| **Total Fe (mg kg$^{-1}$)** | 58.5 |
| **Total Mn (mg kg$^{-1}$)** | 29.7 |
| **Total Zn (mg kg$^{-1}$)** | 48.9 |

**TABLE 3. Effects of biochar fertilizer and various forms of iron sprayed during the 2022/2023 and 2023/2024 growing seasons on plant growth traits.**

| Biochar fertilizer | Various form of iron sprayed | Plant height (cm) | | No. branches/plant | | Plant fresh weight/plant (g) | | Plant dry weight/plant (g) | |
|---|---|---|---|---|---|---|---|---|---|
| | | 1st | 2nd | 1st | 2nd | 1st | 2nd | 1st | 2nd |
| **0.0 ton/feddan** | **0.0** | 36.88g | 36.63i | 4.27h | 3.69j | 82.71i | 72.48k | 15.37i | 14.62i |
| | **FeSO4 (50 mg/L)** | 38.96f | 38.25h | 4.53g | 3.86i | 87.46h | 75.69i | 16.26h | 15.34h |
| | **Fe-EDDHA (50 mg/L)** | 41.92e | 40.95f | 4.88e | 4.13f | 94.11e | 81.03f | 17.50e | 16.42f |
| | **Fe-NPs (50 mg/L)** | 45.04b | 44.01c | 5.24b | 4.44c | 101.11b | 87.09c | 18.80b | 17.65c |
| **1.5 ton/feddan** | **0.0** | 38.56f | 37.62h | 4.49g | 3.79i | 86.56h | 74.44j | 16.09h | 15.08h |
| | **FeSO4 (50 mg/L)** | 41.20e | 39.42g | 4.79e | 3.98h | 92.49f | 78.00h | 17.20f | 15.81g |
| | **Fe-EDDHA (50 mg/L)** | 43.20d | 41.58e | 5.03d | 4.19e | 96.98d | 82.28e | 18.03d | 16.67e |
| | **Fe-NPs (50 mg/L)** | 45.92a | 44.91b | 5.34e | 4.53b | 103.09e | 88.87b | 19.17e | 18.01b |
| **3.0 ton/feddan** | **0.0** | 39.62f | 38.07h | 4.61f | 3.84i | 88.98g | 75.33i | 16.53g | 15.27h |
| | **FeSO4 (50 mg/L)** | 41.32e | 40.41f | 4.83e | 4.08j | 94.11e | 79.96g | 17.50e | 16.20f |
| | **Fe-EDDHA (50 mg/L)** | 44.32c | 43.38d | 5.16c | 4.38d | 99.49c | 85.84d | 18.50c | 17.40d |
| | **Fe-NPs (50 mg/L)** | 46.08a | 46.26a | 5.36a | 4.67a | 103.44a | 91.54a | 19.32a | 18.55a |
| **Mean of biochar fertilizer** | **0.0 ton/feddan** | 40.70c | 39.96c | 4.73c | 4.03c | 91.35c | 79.07c | 16.98c | 16.01c |
| | **1.5 ton/feddan** | 42.22b | 40.88b | 4.91b | 4.12b | 94.78b | 80.90b | 17.62b | 16.39b |
| | **3.0 ton/feddan** | 42.84a | 42.03a | 4.99a | 4.24a | 96.51a | 83.17a | 17.96a | 16.86a |
| **Mean of various form of iron sprayed** | **0.0** | 38.35d | 37.44d | 4.46d | 3.77d | 86.08d | 74.08d | 16.00d | 14.99d |
| | **FeSO4 (50 mg/L)** | 40.49c | 39.36c | 4.72c | 3.97c | 91.35c | 77.88c | 16.99c | 15.78c |
| | **Fe-EDDHA (50 mg/L)** | 43.15b | 41.97b | 5.02b | 4.23b | 96.86b | 83.05b | 18.01b | 16.83b |
| | **Fe-NPs (50 mg/L)** | 45.68a | 45.06a | 5.31a | 4.55a | 102.55a | 89.17a | 19.10a | 18.07a |

*Means denoted by the same letter within each group in the column are not statistically distinct according to Duncan's test at P <0.05.

**Table 4. Effects of biochar fertilizer and various forms of iron sprayed during the 2022/2023 and 2023/2024 growing seasons on yield and its constituent parts.**

| Biochar fertilizer | Various form of iron sprayed | Pod length (cm) | | Average pod weight/plant (kg) | | Marketable yield (ton/fed) | |
|---|---|---|---|---|---|---|---|
| | | 1st | 2nd | 1st | 2nd | 1st | 2nd |
| **0.0 ton/feddan** | **0.0** | 12.26h | 10.66g | 5.07i | 4.19i | 3.89j | 3.29k |
| | **FeSO4 (50 mg/L)** | 12.95g | 11.13f | 5.35h | 4.37h | 4.11h | 3.44i |
| | **Fe-EDDHA (50 mg/L)** | 13.93e | 11.92d | 5.76e | 4.68f | 4.42e | 3.68f |
| | **Fe-NPs (50 mg/L)** | 14.97b | 12.81c | 6.19b | 5.03c | 4.75b | 3.96c |
| **1.5 ton/feddan** | **0.0** | 12.82g | 10.95f | 5.30h | 4.30h | 4.07i | 3.38j |
| | **FeSO4 (50 mg/L)** | 13.69f | 11.47e | 5.66f | 4.51g | 4.35f | 3.54h |
| | **Fe-EDDHA (50 mg/L)** | 14.36d | 12.10d | 5.94d | 4.75e | 4.56d | 3.74e |
| | **Fe-NPs (50 mg/L)** | 15.26e | 13.07b | 6.31a | 5.13b | 4.85a | 4.04b |
| **3.0 ton/feddan** | **0.0** | 13.17g | 11.08f | 5.44g | 4.35h | 4.18g | 3.42i |
| | **FeSO4 (50 mg/L)** | 13.93e | 11.76d | 5.76e | 4.62f | 4.42e | 3.63g |
| | **Fe-EDDHA (50 mg/L)** | 14.73c | 12.62c | 6.09c | 4.96d | 4.68c | 3.90d |
| | **Fe-NPs (50 mg/L)** | 15.32a | 13.46a | 6.33a | 5.29a | 4.86a | 4.16a |
| **Mean of biochar fertilizer** | **0.0 ton/feddan** | **13.53**c | **11.63**c | **5.59**c | **4.56**c | **4.29**c | **3.59**c |
| | **1.5 ton/feddan** | **14.03**b | **11.89**b | **5.80**b | **4.67**b | **4.46**b | **3.68**b |
| | **3.0 ton/feddan** | **14.29**a | **12.23**a | **5.91**a | **4.81**a | **4.54**a | **3.78**a |
| **Mean of various form of iron sprayed** | **0.0** | **12.75**d | **10.90**d | **5.27**d | **4.28**d | **4.05**d | **3.36**d |
| | **FeSO4 (50 mg/L)** | **13.52**c | **1145**c | **5.59**c | **4.50**c | **4.29**c | **3.54**c |
| | **Fe-EDDHA (50 mg/L)** | **14.34**b | **12.21**b | **5.93**b | **4.80**b | **4.55**b | **3.77**b |
| | **Fe-NPs (50 mg/L)** | **15.18**a | **13.11**a | **6.27**a | **5.15**a | **4.82**a | **4.05**a |

*Means denoted by the same letter within each group in the column are not statistically distinct according to Duncan's test at P <0.05.

**TABLE 5. Effects of biochar fertilizer and various forms of iron sprayed during the 2022/2023 and 2023/2024 growing seasons on nitrogen, phosphorus, potassium, and iron, in the beans' leaves.**

| Biochar fertilizer | Various form of iron sprayed | N (%) | | P (%) | | K (%) | | Fe (mg/kg) | |
|---|---|---|---|---|---|---|---|---|---|
| | | 1st | 2nd | 1st | 2nd | 1st | 2nd | 1st | 2nd |
| **0.0 ton/feddan** | **0.0** | 2.10f | 2.38h | 0.29 | 0.34 | 2.16i | 2.25k | 93.67i | 96.25k |
| | **FeSO4 (50 mg/L)** | 2.22e | 2.53g | 0.30 | 0.35 | 2.28h | 2.35i | 98.95h | 100.51i |
| | **Fe-EDDHA (50 mg/L)** | 2.39d | 2.78e | 0.33 | 0.38 | 2.46e | 2.52f | 106.47e | 107.60f |
| | **Fe-NPs (50 mg/L)** | 2.57b | 3.06c | 0.35 | 0.41 | 2.64b | 2.71c | 114.40b | 115.64c |
| **1.5 ton/feddan** | **0.0** | 2.20e | 2.47g | 0.30 | 0.35 | 2.26h | 2.31j | 97.94h | 98.85j |
| | **FeSO4 (50 mg/L)** | 2.35d | 2.64f | 0.32 | 0.36 | 2.42f | 2.43h | 104.64f | 103.58h |
| | **Fe-EDDHA (50 mg/L)** | 2.46c | 2.84d | 0.34 | 0.38 | 2.53d | 2.56e | 109.72d | 109.26e |
| | **Fe-NPs (50 mg/L)** | 2.62a | 3.15b | 0.36 | 0.41 | 2.69a | 2.76b | 116.63a | 118.01b |
| **3.0 ton/feddan** | **0.0** | 2.26e | 2.51g | 0.31 | 0.35 | 2.32g | 2.34i | 100.62g | 100.03i |
| | **FeSO4 (50 mg/L)** | 2.39d | 2.73e | 0.33 | 0.37 | 2.46e | 2.49g | 106.47e | 106.18g |
| | **Fe-EDDHA (50 mg/L)** | 2.53b | 3.01c | 0.34 | 0.40 | 2.60c | 2.67d | 112.57c | 113.99d |
| | **Fe-NPs (50 mg/L)** | 2.63a | 3.27a | 0.36 | 0.43 | 2.70a | 2.85a | 117.04a | 121.56a |
| **Mean of biochar fertilizer** | **0.0 ton/feddan** | **2.32c** | **2.69c** | **0.32c** | **0.37c** | **2.39c** | **2.46c** | **103.37c** | **105.00c** |
| | **1.5 ton/feddan** | **2.41b** | **2.78b** | **0.33b** | **0.38b** | **2.48b** | **2.52b** | **107.23b** | **107.43b** |
| | **3.0 ton/feddan** | **2.43a** | **2.88a** | **0.34a** | **0.39a** | **2.52a** | **2.59a** | **109.18a** | **110.44a** |
| **Mean of various form of iron sprayed** | **0.0** | **2.19d** | **2.45d** | **0.30d** | **0.35d** | **2.25d** | **2.30d** | **97.41d** | **98.38d** |
| | **FeSO4 (50 mg/L)** | **2.32c** | **2.63c** | **0.32c** | **0.36c** | **2.39c** | **2.42c** | **103.35c** | **103.42c** |
| | **Fe-EDDHA (50 mg/L)** | **2.46b** | **2.88b** | **0.34b** | **0.39b** | **2.53b** | **2.58b** | **109.59b** | **110.28b** |
| | **Fe-NPs (50 mg/L)** | **2.61a** | **3.16a** | **0.36a** | **0.42a** | **2.68a** | **2.77a** | **116.02a** | **118.40a** |

*Means denoted by the same letter within each group in the column are not statistically distinct according to Duncan's test at P <0.05.

**TABLE 6. Effects of biochar fertilizer and various forms of iron sprayed during the 2022/2023 and 2023/2024 growing seasons on nitrogen, phosphorus, potassium, and iron, in the beans' pods.**

| Biochar fertilizer | Various form of iron sprayed | N (%) | | P (%) | | K (%) | | Fe (mg/kg) | |
|---|---|---|---|---|---|---|---|---|---|
| | | 1st | 2nd | 1st | 2nd | 1st | 2nd | 1st | 2nd |
| **0.0 ton/feddan** | **0.0** | 1.49j | 1.52j | 0.21 | 0.26 | 1.86g | 1.89f | 81.13k | 85.28k |
| | **FeSO4 (50 mg/L)** | 1.58i | 1.61h | 0.22 | 0.28 | 1.95f | 1.98e | 85.71i | 89.05i |
| | **Fe-EDDHA (50 mg/L)** | 1.70e | 1.73e | 0.24 | 0.30 | 2.08d | 2.12d | 92.22f | 95.34f |
| | **Fe-NPs (50 mg/L)** | 1.82b | 1.86b | 0.26 | 0.32 | 2.24c | 2.27c | 99.08c | 102.46c |
| **1.5 ton/feddan** | **0.0** | 1.56h | 1.59i | 0.22 | 0.27 | 1.91f | 1.94e | 84.83j | 87.59j |
| | **FeSO4 (50 mg/L)** | 1.67f | 1.70f | 0.24 | 0.28 | 2.01e | 2.04d | 90.64g | 91.78h |
| | **Fe-EDDHA (50 mg/L)** | 1.75d | 1.78d | 0.25 | 0.30 | 2.12d | 2.15d | 95.04e | 96.81e |
| | **Fe-NPs (50 mg/L)** | 1.86a | 1.89a | 0.26 | 0.32 | 2.29b | 2.32b | 101.02b | 104.56b |
| **3.0 ton/feddan** | **0.0** | 1.60g | 1.63g | 0.23 | 0.27 | 1.94f | 1.97e | 87.15h | 88.63i |
| | **FeSO4 (50 mg/L)** | 1.70e | 1.73e | 0.24 | 0.29 | 2.06d | 2.09d | 92.22f | 94.08g |
| | **Fe-EDDHA (50 mg/L)** | 1.80c | 1.83c | 0.26 | 0.31 | 2.21c | 2.24c | 97.50d | 101.00d |
| | **Fe-NPs (50 mg/L)** | 1.87a | 1.90a | 0.27 | 0.33 | 2.35a | 2.39a | 101.37a | 107.70a |
| **Mean of biochar fertilizer** | **0.0 ton/feddan** | **1.65c** | **1.68c** | **0.23c** | **0.29c** | **2.03c** | **2.07c** | **89.54c** | **93.03c** |
| | **1.5 ton/feddan** | **1.71b** | **1.74b** | **0.24b** | **0.29b** | **2.08b** | **2.11b** | **92.88b** | **95.19b** |
| | **3.0 ton/feddan** | **1.74a** | **1.77a** | **0.25a** | **0.30a** | **2.14a** | **2.17a** | **94.56a** | **97.85a** |
| **Mean of various form of iron sprayed** | **0.0** | **1.55d** | **1.58d** | **0.22d** | **0.27d** | **1.90d** | **1.93d** | **84.37d** | **87.17d** |
| | **FeSO4 (50 mg/L)** | **1.65c** | **1.68c** | **0.23c** | **0.28c** | **2.01c** | **2.04c** | **89.52c** | **91.04c** |
| | **Fe-EDDHA (50 mg/L)** | **1.75b** | **1.78b** | **0.25b** | **0.30b** | **2.14b** | **2.17b** | **94.92b** | **97.72b** |
| | **Fe-NPs (50 mg/L)** | **1.85a** | **1.88a** | **0.26a** | **0.32a** | **2.29a** | **2.33a** | **100.49a** | **104.91a** |

*Means denoted by the same letter within each group in the column are not statistically distinct according to Duncan's test at P <0.05.

**Table 7. Effects of biochar fertilizer and various forms of iron sprayed during the 2022/2023 and 2023/2024 growing seasons on fibers, carbohydrates, and protein in the beans' pods.**

| Biochar fertilizer | Various form of iron sprayed | Fiber content (%) as dry weight | | Carbohydrate content (%) as dry weight | | Protein content (%) as dry weight | |
|---|---|---|---|---|---|---|---|
| | | 1st | 2nd | 1st | 2nd | 1st | 2nd |
| **0.0 ton/feddan** | **0.0** | 10.09i | 9.80k | 14.29i | 14.97k | 9.31j | 9.50j |
| | **FeSO4 (50 mg/L)** | 10.66h | 10.24i | 15.09h | 15.64i | 9.88i | 10.06h |
| | **Fe-EDDHA (50 mg/L)** | 11.47e | 10.96f | 16.24e | 16.74f | 10.63e | 10.81e |
| | **Fe-NPs (50 mg/L)** | 12.32b | 11.78c | 17.45b | 17.99c | 11.38b | 11.63b |
| **1.5 ton/feddan** | **0.0** | 10.55h | 10.07j | 14.94h | 15.38j | 9.75h | 9.94i |
| | **FeSO4 (50 mg/L)** | 11.27f | 10.55h | 15.96f | 16.11h | 10.44f | 10.63f |
| | **Fe-EDDHA (50 mg/L)** | 11.82d | 11.13e | 16.74d | 17.00e | 10.94d | 11.13d |
| | **Fe-NPs (50 mg/L)** | 12.57e | 12.02b | 17.79a | 18.36b | 11.63a | 11.81a |
| **3.0 ton/feddan** | **0.0** | 10.84g | 10.19i | 15.35g | 15.56i | 10.00g | 10.19g |
| | **FeSO4 (50 mg/L)** | 11.47e | 10.82g | 16.24e | 16.52g | 10.63e | 10.81e |
| | **Fe-EDDHA (50 mg/L)** | 12.13c | 11.61d | 17.17c | 17.73d | 11.25c | 11.44c |
| | **Fe-NPs (50 mg/L)** | 12.61a | 12.38a | 17.85a | 18.91a | 11.69a | 11.88a |
| **Mean of biochar fertilizer** | **0.0 ton/feddan** | **11.14c** | **10.70c** | **15.77c** | **16.34c** | **10.30c** | **10.50c** |
| | **1.5 ton/feddan** | **11.55b** | **10.94b** | **16.36b** | **16.71b** | **10.69b** | **10.88b** |
| | **3.0 ton/feddan** | **11.76a** | **11.25a** | **16.65a** | **17.18a** | **10.89a** | **11.08a** |
| **Mean of various form of iron sprayed** | **0.0** | **10.49d** | **10.02d** | **14.86d** | **15.30d** | **9.69d** | **9.88d** |
| | **FeSO4 (50 mg/L)** | **11.13c** | **10.54c** | **15.76c** | **16.09c** | **10.32c** | **10.50c** |
| | **Fe-EDDHA (50 mg/L)** | **11.81b** | **11.23b** | **16.72b** | **17.16b** | **10.94b** | **11.13b** |
| | **Fe-NPs (50 mg/L)** | **12.50a** | **12.06a** | **17.70a** | **18.42a** | **11.57a** | **11.77a** |

*Means denoted by the same letter within each group in the column are not statistically distinct according to Duncan's test at P <0.05.

**TABLE 8. Effects of biochar fertilizer and various forms of iron sprayed during the 2022/2023 and 2023/2024 growing seasons on some physics-chemical soil properties after harvest.**

| Biochar fertilizer | Various form of iron sprayed | pH | | EC ($dSm^{-1}$) | | Organic matter content (%) | | Bulck density (g $cm^{-3}$) | |
|---|---|---|---|---|---|---|---|---|---|
| | | 1st | 2nd | 1st | 2nd | 1st | 2nd | 1st | 2nd |
| **0.0 ton/feddan** | **0.0** | 8.15 | 8.12 | 1.09 | 1.11 | 0.31 | 0.33 | 1.34 | 1.40 |
| | **FeSO4 (50 mg/L)** | 8.16 | 8.11 | 1.08 | 1.12 | 0.32 | 0.33 | 1.33 | 1.40 |
| | **Fe-EDDHA (50 mg/L)** | 8.15 | 8.12 | 1.08 | 1.11 | 0.31 | 0.33 | 1.34 | 1.40 |
| | **Fe-NPs (50 mg/L)** | 8.15 | 8.12 | 1.08 | 1.11 | 0.32 | 0.33 | 1.34 | 1.40 |
| **1.5 ton/feddan** | **0.0** | 8.05 | 8.07 | 1.20 | 1.23 | 0.34 | 0.34 | 1.31 | 1.37 |
| | **FeSO4 (50 mg/L)** | 8.04 | 8.06 | 1.20 | 1.22 | 0.34 | 0.34 | 1.31 | 1.38 |
| | **Fe-EDDHA (50 mg/L)** | 8.04 | 8.06 | 1.20 | 1.22 | 0.34 | 0.35 | 1.32 | 1.38 |
| | **Fe-NPs (50 mg/L)** | 8.04 | 8.06 | 1.20 | 1.22 | 0.34 | 0.35 | 1.31 | 1.38 |
| **3.0 ton/feddan** | **0.0** | 7.96 | 7.92 | 1.27 | 1.36 | 0.36 | 0.36 | 1.29 | 1.33 |
| | **FeSO4 (50 mg/L)** | 7.96 | 7.93 | 1.28 | 1.36 | 0.36 | 0.36 | 1.30 | 1.35 |
| | **Fe-EDDHA (50 mg/L)** | 7.97 | 7.93 | 1.28 | 1.36 | 0.36 | 0.36 | 1.29 | 1.35 |
| | **Fe-NPs (50 mg/L)** | 7.96 | 7.93 | 1.28 | 1.36 | 0.36 | 0.36 | 1.29 | 1.35 |
| **Mean of biochar fertilizer** | **0.0 ton/feddan** | **8.15c** | **8.12c** | **1.08c** | **1.11c** | **0.32c** | **0.33c** | **1.34c** | **1.40c** |
| | **1.5 ton/feddan** | **8.04b** | **8.06b** | **1.20b** | **1.22b** | **0.34b** | **0.35b** | **1.31b** | **1.38b** |
| | **3.0 ton/feddan** | **7.96a** | **7.92a** | **1.28a** | **1.36a** | **0.36a** | **0.36a** | **1.29a** | **1.35a** |
| **Mean of various form of iron sprayed** | **0.0** | **8.05** | **8.04** | **1.19** | **1.23** | **0.34** | **0.34** | **1.31** | **1.37** |
| | **FeSO4 (50 mg/L)** | **8.05** | **8.03** | **1.19** | **1.23** | **0.34** | **0.34** | **1.31** | **1.38** |
| | **Fe-EDDHA (50 mg/L)** | **8.05** | **8.04** | **1.19** | **1.23** | **0.34** | **0.35** | **1.32** | **1.38** |
| | **Fe-NPs (50 mg/L)** | **8.05** | **8.04** | **1.19** | **1.23** | **0.34** | **0.34** | **1.31** | **1.38** |

*Means denoted by the same letter within each group in the column are not statistically distinct according to Duncan's test at P <0.05.

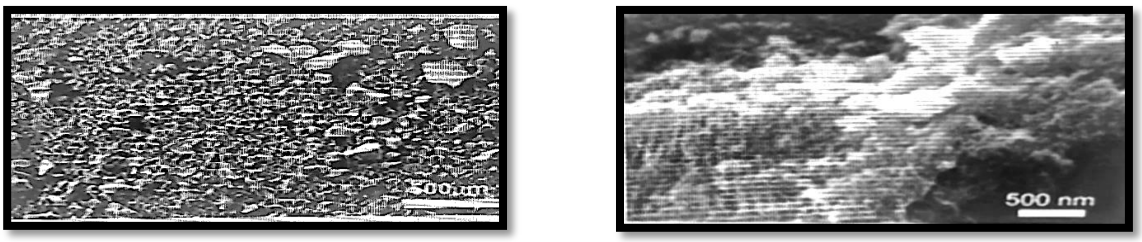


**Fig. 1. Morphology of the sample as seen by scanning electron microscopy (SEM).**

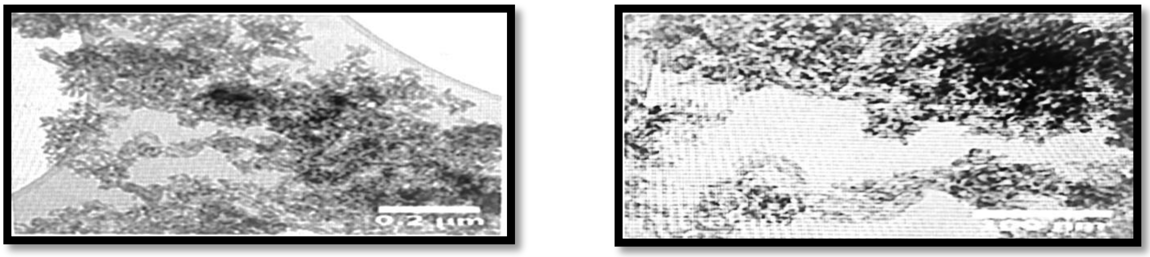


**Fig. 2. Morphology of the sample as seen by Transmission Electron Microscopy (TEM).**

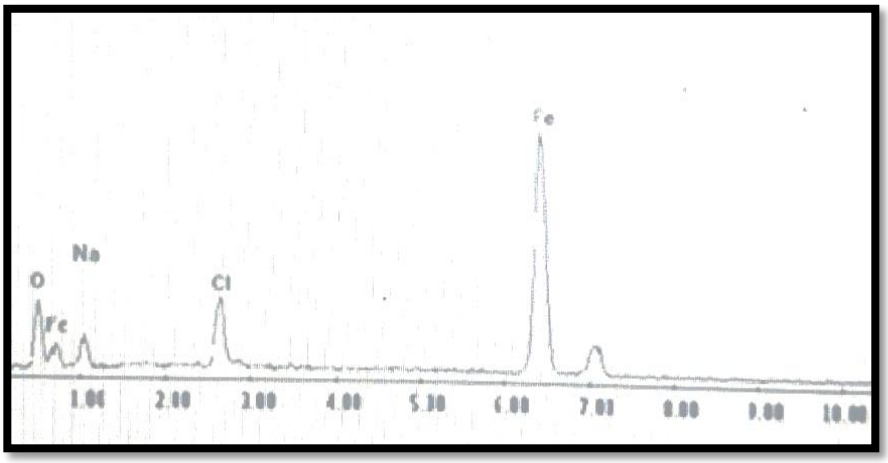


**Fig. 3. Using energy-dispersive X-ray spectroscopy (EDX) for elemental analysis (chemical characterization).**

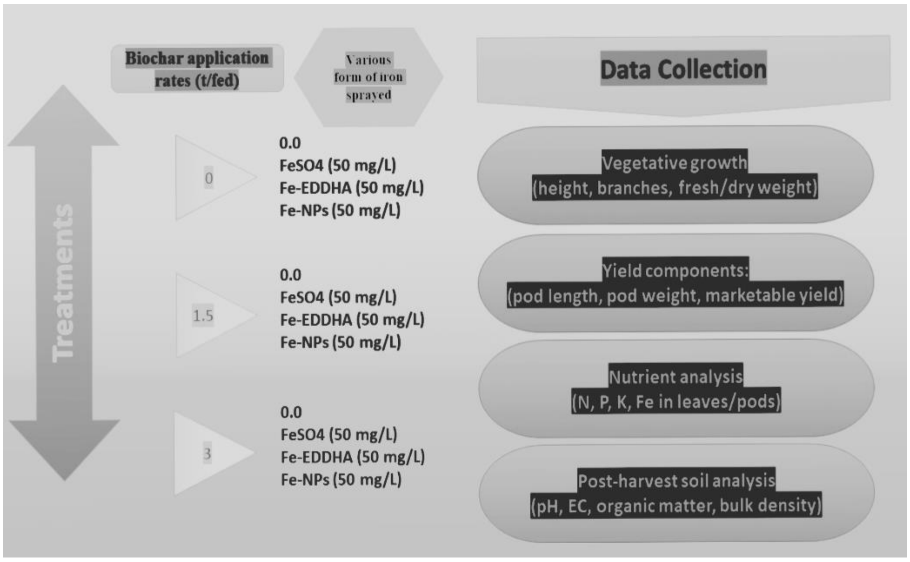


**Fig. 4. Flowchart for the study.**

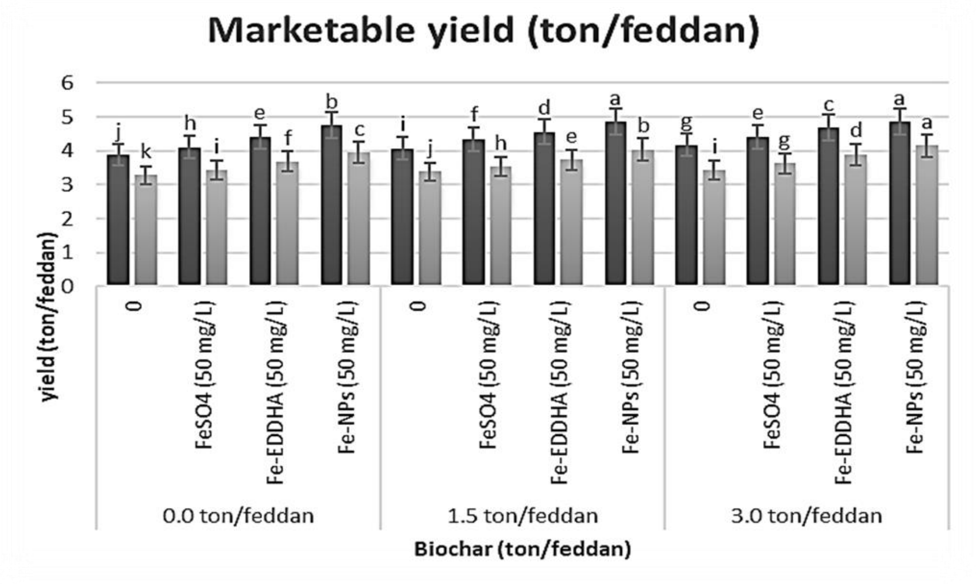


**Fig. 4. Effects of biochar fertilizer and various forms of iron sprayed during the 2022/2023 and 2023/2024 growing seasons on marketable yield of beans.**

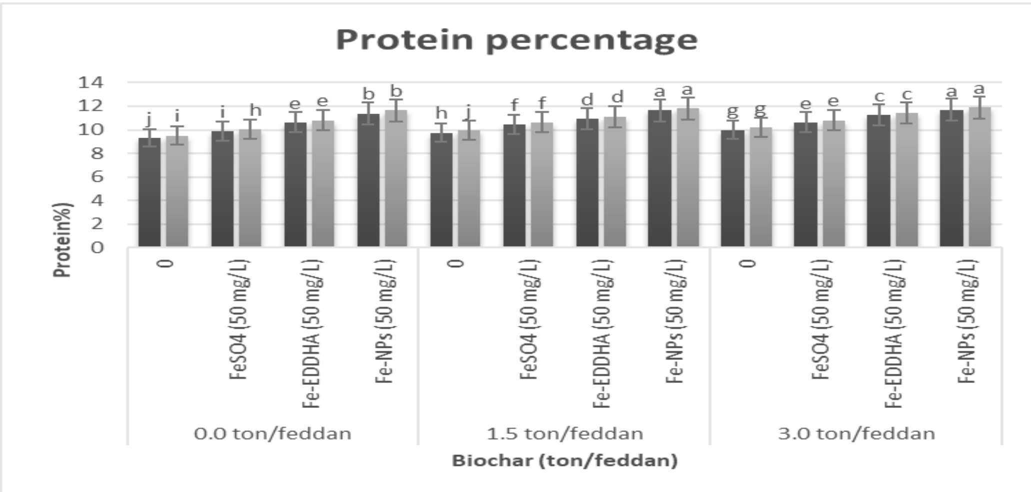


**Fig. 5. Effects of biochar fertilizer and various forms of iron sprayed during the 2022/2023 and 2023/2024 growing seasons on protein in the beans' pods.**

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# أثر استخدام الفحم الحيوي والرش الورقي لثلاثة أنواع متميزة من الحديد على خصائص التربة الرملية وانتاجية الفاصوليا الخضراء (*Phaseolus vulgaris* L.)

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**الملخص**

يصعب نمو النبات في التربة الرملية التي تفتقر إلى المواد العضوية والعناصر الغذائية الأساسية. حيث تتطلب الفاصوليا على وجه الخصوص عنصر الحديد، وهو عنصر غذائي حيوي ضروري لعملية التمثيل الضوئي وتخليق الكلوروفيل. ولقد ثبت علميا أن الفحم الحيوي يعزز بشكل كبير خصوبة التربة حيث أجريت هذه الدراسة خلال موسمي النمو ٢٠٢٢/٢٠٢٣ و ٢٠٢٣/٢٠٢٤ لتقييم تأثيرات ثلاثة أنواع مختلفة من الحديد (الرش الورقي للحديد بتركيز ٥٠ ملجم/لتر على وجه التحديد جزيئات أكسيد الحديد النانوميترية ($Fe_2O_3$) ، كبريتات الحديدوز ($FeSO_4$) ، والحديد المخلبى (Fe-EDDHA) مع ثلاث معدلات من سماد الفحم الحيوي (٠ ، ١,٥، ٣ طن/فدان). حيث تهدف الدراسة إلى تقييم معايير مختلفة ، بما في ذلك النمو الخضري (ارتفاع النبات ، عدد الأفرع لكل نبات ، الوزن الطازج والجاف لكل نبات)، ومحصول القرون الخضراء، والصفات الطبيعية للقرون (الطول والوزن)، والقيمة الغذائية لكل من أوراق الفاصوليا والقرون كما تم تقدير كلا من (النيتروجين والفوسفور والبوتاسيوم والحديد). بالإضافة إلى ذلك تم تحليل الصفات الكيميائية للقرون، كما تم حساب كلا من البروتين والكربوهيدرات الكلية ومحتوى الألياف.

أشارت النتائج إلى أن جميع المعاملات كان لها تأثير كبير على هذه المعايير. وباستثناء ملوحة التربة التي تحسنت مع تطبيق الفحم الحيوي، أظهرت خصائص التربة (بما في ذلك رقم الـpH والمادة العضوية والكثافة الظاهرية) تحسنا بعد حصاد محصول الفاصوليا حيث ارتفعت معدلات سماد الفحم الحيوي من صفر إلى ثلاثة أطنان لكل فدان. وخلصت الدراسة إلى أن اضافة ٣ طن من الفحم الحيوي لكل فدان والرش الورقي لجسيمات الحديد النانومترية بتركيز ٥٠ ملجم/ لتر كانت المعاملة الأكثر فاعلية. كما أثرت هذه المعاملة بشكل كبير على جميع الصفات التى تم دراستها ، بينما لوحظت أدنى القيم عند عدم إضافة الفحم الحيوي مع عدم استخدام الحديد الورقي.

**الكلمات الدالة:** الفاصوليا، البيوشار، اكسيد الحديد النانوميتريه، كبريتات الحديدوز، الحديد المخلبي.