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ORGANIC AMENDMENTS AS A STRATEGY TO ENHANCE SOIL CARBON SEQUESTRATION AND SPINACH PRODUCTIVITY

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Keywords
Spinach; Soil carbon sequestration; Organic amendments; Soil health; Plant growth; Nutrient management

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Abstract
Spinach is a key leafy vegetable crop in Pakistan, valued for its nutritional benefits and economic importance. However, climate change and rising atmospheric CO_2 *levels pose challenges to agricultural productivity and ecosystem stability. Soil organic matter is crucial for maintaining soil ecosystem functions, regulating biogeochemical cycles, and enhancing carbon sequestration.To assess the effects of organic amendments on carbon sequestration and spinach productivity, an experiment was conducted using residual soil and organic manures. The treatments included: control (recommended fertilizers only), 1% organic amendment + 50% recommended fertilizers, 2% organic amendment + 50% recommended fertilizers, 1% organic amendment alone, and 2% organic amendment alone. The experiment followed a Completely Randomized Design (CRD) with five treatments and three replications at the Institute of Soil and Environmental Sciences, University of Agriculture, Faisalabad.Results indicated that organic amendments significantly (*$p < 0.05$*) improved both soil carbon sequestration and spinach yield compared to the control. The 2% organic amendment treatment showed the greatest benefits, enhancing soil organic carbon, water use efficiency, infiltration rate, and porosity, while reducing bulk density. Overall, the application of 2% organic amendment was most effective in promoting soil health, increasing carbon storage, and improving spinach growth, supporting sustainable crop production and soil management under changing climatic conditions.*

INTRODUCTION
Spinach (*Spinacia oleracea* L.), belonging to the *Chenopodiaceae* family, is a highly nutritious leafy vegetable that originates from Central Asia. It is a cool-season crop with a quick growth period, typically taking 30 to 35 days to mature in temperate regions. Spinach grows best in temperatures between 15-20 °C (Raimondo *et al.*, 2023). Spinach is richly appreciated for its nutritional density, such as vitamins (A, C, K, folic acids), and major minerals like phosphorus, iron, calcium, magnesium, and zinc (Pandey *et al.*, 2024). Spinach may be consumed raw in abundance of iron and antioxidants.Soil fertility and health are vital for spinach cultivation and overall agricultural productivity. Soil organic matter (SOM) plays an important role in sustaining soil structure and fertility by serving as a nutrient reservoir, enhancing water storage, and promoting soil aggregation (Shivangi *et al.*, 2024). Soil fertility reduction from intensive farming, poor nutrient management and excessive application of chemical fertilizers is a serious issue. Pakistani soils are inherently lacking in nitrogen (N) and phosphorus (P) but potentially high in potassium

(K) with prevalence of mica minerals fertility carbon and crop productivity, resulting in long-term

Table: 3.1 Characteristics of soil and applied organic matter

Determination	Values
Texture	Sandy clay loam
pH of soil	7.86
EC of soil	1.73 dS m^{-1}
Organic matter	0.53%
CO_3^{2-}	0
HCO_3^-	6
$Ca^{2+} + Mg^{2+}$	30.6
N	0.04
P	7 mg/kg
C	0.31
Saturation percentage	30.1%
pH of cow dung	10.5
EC of poultry manure	7.25 dS m^{-1}
EC of cow dung	10.2 dS m^{-1}
pH of press mud	8.1
EC of press mud	0.42 dS m^{-1}
pH of poultry manure	7.1

(Sajjad *et al.*, 2024). Organic amendments such as farmyard manure, compost and crop residues are recommended as sustainable options to improve soil health and enhance crop yields.

Organic amendments improve physical, chemical and biological soil properties through the increase of soil organic carbon (SOC), stimulation of microbial activity and enhancement of the availability of nutrients (Rashid *et al.*, 2020). Organic amendments enhance soil structure by improving aggregation, decrease bulk density and enhance water-holding capacity, which subsequently supports improved root development and nutrient uptake for plants (Adekiya *et al.*, 2023). Additionally, they improve physical, chemical and biological properties by increasing soil organic carbon, stimulating microbial activity, enhancing nutrient availability and improving soil structure and water retention which together support healthy plant growth (Zani *et al.*, 2003).

Soil carbon sequestration is the capturing and storing of atmospheric CO_2 in soil organic matter emerged as a significant strategy to tackle climate change. The atmospheric CO_2 concentration alone has increased from 275 ppm to 385 ppm since the dawn of the industrial era (Wu *et al.*, 2024). The soil contains around three times more carbon than the atmosphere and is therefore a major carbon sink (Jat *et al.*, 2022). Organic amendments affect soil carbon storage and thus minimizing climate change effects (Shakeel *et al.*, 2021).

The increasing cost and environmental damage caused by excessive chemical fertilizer use highlights the need for sustainable practices. While organic amendments are cost- effective and improve nutrient cycling, their slow nutrient release may not fully meet the rapid demands of spinach (Ahmad *et al.*, 2023). Therefore, combining organic amendments with recommended NPK doses was chosen to optimize yield and harness nutrient synergy, ensuring both

immediate and sustained nutrient availability. However, we recognize that this integrated approach can also increase greenhouse gas emissions compared to sole organic use, underscoring the importance of careful nutrient management to balance productivity with environmental impacts. This study examined these combined effects on soil fertility, nutrient availability, and spinach growth. Despite extensive evidence on the benefits of organic amendments, limited research has specifically evaluated their comparative effects on soil carbon sequestration and spinach productivity under semi-arid conditions in Pakistan. Therefore, this study tested the hypothesis that integrating organic and inorganic amendments would significantly improve soil fertility, enhance spinach growth and yield, and increase soil organic carbon content compared to sole inorganic fertilization.
sequestration mainly by increasing SOC and reducing**1.**

2. Materials and Methods

greenhouse gas emissions. Increased SOC improves soil

2.1. Site Description

The experiment was conducted during the winter season of 2022 at the Institute of Soil and Environmental Science, University of Agriculture Faisalabad, Pakistan. The experimental site is situated in a semi-arid region characterized by hot temperatures and low rainfall during the kharif season, followed by cool and dry weather in the rabi season. Spinach was harvested at 45 days after sowing, with subsequent harvests at 21-day intervals. The experiment was conducted over a single growing season, during which three harvests were taken. These climatic conditions are considered suitable for growing cool-season crops such as spinach (*Spinacia oleracea* L.), which require moderate temperatures for optimal growth and nutrient uptake. The soil at the experimental site was classified as sandy clay loam according to USDA soil taxonomy.

2.2. Soil Preparation and Analysis

Prior to initiating treatments, composite soil samples were collected from the experimental plots to establish baseline soil characteristics. The samples were air-dried at room temperature, gently crushed to break clods, passed through a 2 mm sieve, and homogenized to ensure consistency in further analyses. This preparation facilitated the precise assessment of key physicochemical properties, which are essential for understanding soil fertility status and monitoring changes due to amendments.

Soil pH was measured in a 1:1 soil-to-water suspension using a calibrated pH meter to assess soil reaction, as pH affects nutrient availability and microbial activity. Electrical conductivity (EC), an indicator of soil salinity, was determined using a conductivity meter and expressed in dS m^{-1}. High EC levels can negatively influence plant growth by reducing water and nutrient uptake. Soil texture was analyzed by the hydrometer method to quantify proportions of sand, silt, and clay, which collectively influence water retention, aeration, and nutrient-holding capacity. Bulk density was determined using the clod method (g cm^{-3}), providing an indication of soil compaction and porosity, both of which affect root development and infiltration rates.

Cation exchange capacity (CEC) was measured using the ammonium acetate method and expressed in cmol kg^{-1} to evaluate the soil's capacity to retain nutrient cations essential for crop growth. Organic matter content was assessed by the Walkley-Black dichromate oxidation method and expressed as a percentage. Total nitrogen content was determined using the Kjeldahl digestion and distillation method (g kg^{-1}), while available phosphorus was measured by the Olsen method (mg kg^{-1}), which involves extraction with sodium bicarbonate. Soil organic carbon (SOC), a key index of soil fertility and carbon sequestration potential, was derived from organic matter estimations.

2.3. Experimental Treatments

The study utilized a Completely Randomized Design (CRD) comprising five treatments and

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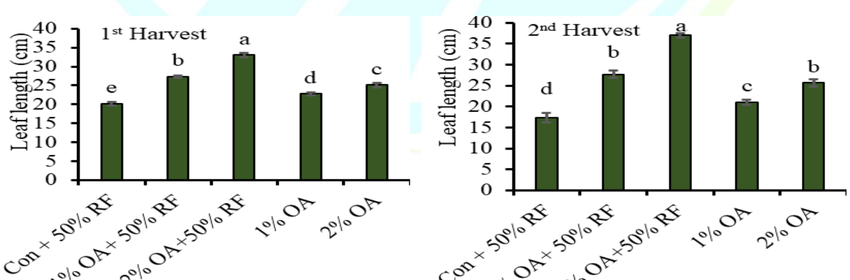
three replications to ensure statistical rigor and minimize experimental error. Treatments consisted of various combinations of organic amendments—poultry manure, cow dung, and press mud— applied singly or in combination with recommended doses of chemical fertilizers. The control treatment received no fertilizer inputs to allow a clear comparison with conventional and integrated nutrient management practices. Organic amendments were sourced locally to reflect commonly available materials used by farmers in the region. Poultry manure and cow dung were collected from nearby livestock farms, while press mud, a by-product of the sugar industry, was obtained from a sugar mill in Faisalabad. All materials were dried under shade to prevent nutrient loss due to prolonged sun exposure, then ground and sieved to achieve uniform particle size for consistent application. The nutrient composition of the amendments was analyzed prior to application and was as follows: poultry manure (2.5% N, 1.8% P_2O_5, 1.2% K_2O), cow dung (0.8% N, 0.6% P_2O_5, 0.5% K_2O), and press mud (1.2% N, 1.0% P_2O_5, 0.9% K_2O). The precise nutrient profiles enabled accurate assessment of their comparative effects on soil properties and crop performance. The rationale for combining organic amendments with 50% recommended NPK fertilizer was to optimize nutrient availability and spinach yield under semi-arid conditions, where nutrient deficiencies are common. Previous studies have demonstrated that integrating organic and mineral fertilizers can improve nutrient use efficiency, support rapid early growth, and sustain soil fertility over time. While sole organic amendments contribute to carbon sequestration, the combined approach was adopted to meet both short-term crop nutritional requirements and longer-term soil health objectives.

2.4. Data Collection and Laboratory Analyses

The study evaluated a range of soil fertility indicators and plant growth parameters throughout the cropping period. Soil pH, EC, texture, bulk density, CEC, organic matter, total nitrogen, available phosphorus, and SOC were measured both before treatment application and after harvest to monitor changes induced by amendments. In addition to soil analyses, spinach growth parameters were recorded, including plant height (cm), leaf fresh weight (g $plant^{-1}$), and root fresh weight (g $plant^{-1}$). These parameters served as proxies for crop response to improved nutrient availability and soil condition.

Measurements followed established standard procedures to ensure data reliability. For example, pH and EC were measured immediately after preparing soil suspensions to avoid temporal fluctuations. The hydrometer method involved dispersing soil particles in a sodium



hexametaphosphate solution to accurately determine textural class. Bulk density samples were carefully collected to avoid compaction, and SOC assessments followed Walkley-Black oxidation with external heating to maximize recovery of organic carbon fractions.

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Statistical Analysis

All experimental data were subjected to analysis of variance (ANOVA) using Statistix 8.1 software. Treatment means were compared using the least significant difference (LSD) test at a significance threshold of $p < 0.05$. This statistical approach facilitated robust evaluation of treatment effects on soil and plant variables.

3. Results and Discussion

Agronomic attributes of spinach

3.1. Leaf lengths in two consecutive harvests

The treatment with organic matter (OM) and recommended fertilizers enhanced the length of spinach leaves more than the control treatment. In the case of the first harvest, the recorded highest leaf length (40 cm) was at 2% organic manure and 50% recommended fertilizers, in agreement with the findings of Adekiya *et al.* (2020), who depicted that improving soil properties and nutrients availability through manuring can increase plant biomass and improvements with the use of organic fertilizers. The addition of nitrogen in combination with organic amendments enhances nutrient retention in soil, improving plant growth. Jakhro *et al.* (2017) and Shaheen *et al.* (2014) emphasized the combined beneficial effects of organic and inorganic fertilizers offering better growth conditions. This study illustrated that integration of organic matter with

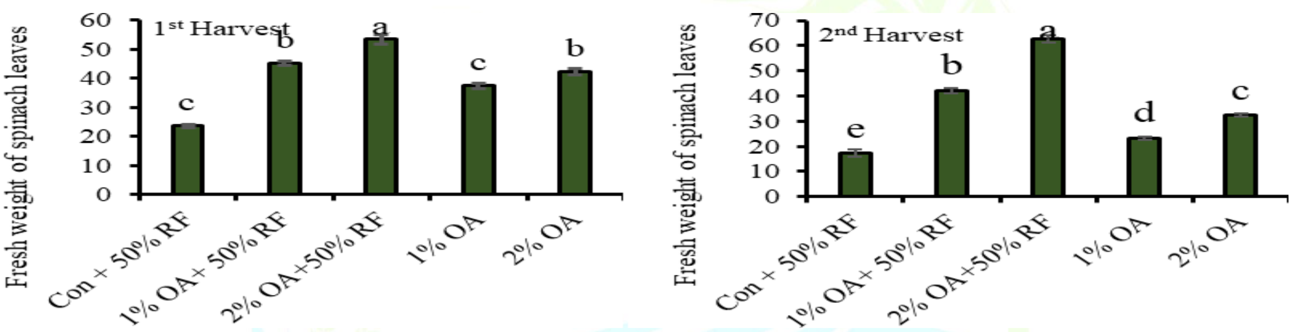

Figure 2:
Impact of different organic amendments on leaf fresh weight (g) of spinach in two consecutive harvests. Columns showed the mean of four replicates, whereas bar shows the standard error among treatment replicates. Columns with similar letters indicate non-significant relation among the treatments at $p<0.05$ leafy length. Hashmi *et al.* (2019) also attributed that spinach growth increased due to mixed application organic matter with fertilizers.

The treatment with 2% organic manure with 50% recommended fertilizer ranked maximum in leaf length at 37 cm in the second harvest, while control (T0) attained 17 cm. Such a trend corresponds with Parwada *et al.* (2020), who found that organic manure improved plant growth, including leaf length. Jakhro *et al.* (2017) also observed similarrecommended fertilizers enhances growth and leaf length in spinach.

3.2. Fresh weight of spinach leaves

Spinach leaf fresh weight was found to be greatly improved by the addition of organic matter (OM) and recommended fertilizers with both treatments showing improvement over the control in the two-harvest period. In 1st harvest, the control, which was treated with the full recommended fertilizers but no organic matter, had a leaf

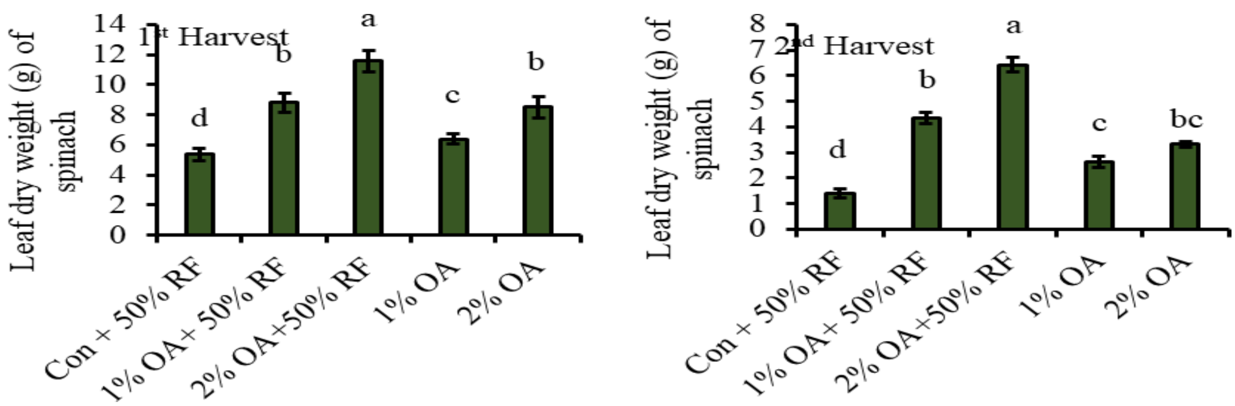

Figure 3: Impact of different organic amendments on leaf dry weught (g) of spinach in two consecutive harvests. Columns showed the mean of four replicates, whereas bar shows the standard error among treatment replicates. Columns with similar letters indicate non-significant relation among the treatments at $p<0.05$ fresh weight of 23 g, whereas the treatment that combined 2% organic matter with 50% recommended fertilizers produced the highest fresh weight of 53 g. This increase can be attributed to the combined action of organic matter and nitrogen fertilizers in enhancing soil microbial activity and nutrient availability. Kelley *et al.* (2022) illustrated that improvement of soil nutrient supply through compost promoted fresh weight. Furthermore, Khaliq *et al.* (2024) was supposed as combined application of organic amendments and nitrogen fertilizer raised leaf expansion and fresh weight.

Analogous trends were observed during the second harvest. The control showed a fresh leaf weight of 17 g, and the combination of 2% organic matter and fertilizers gave the maximum fresh weight of 62 g. The treatment with 1% organic matter and 50% recommended fertilizer produced an average weight of 42 g, while 2% organic matter alone gave

32 g. Sharma *et al.* (2024) noted that organic manure improved vegetative growth including fresh weight, while Thapa *et al.* (2021) underlined the fact that nitrogen from NPK fertilizers increased its fresh weight. These results further substantiate the complementary role of organic matter and fertilizers in improving the growth of spinach which strengthens the notion of using both for optimum yield.

3.3. Leaf dry weight (g) of spinach harvests

According to data observed in the first and second harvests, leaf dry weight of spinach increased remarkably due to the application of both organic matter and the recommended fertilizers (Figure 3). Thus, leaf dry weight was 5 g for the control treatment in the first harvest, but nitrogen fertilizer combined with organic matter gave a leaf dry weight of 11 g, which was significantly higher than that of control treatment. On the other hand, although their interaction was not statistically similar the combination of organic matter and fertilizers yielded a significantly better leaf dry weight compared to that of the control. Similar findings were observed by Fathi (2022) noted that increasing amounts of nitrogen would certainly promote increasing rates of photosynthesis leading to leaf growth and dry matter.

The second harvest showed the highest leaf dry weight in treatment T2 (2% organic manure + 50% recommended fertilizer) of 6.42 g, followed by treatment T1 (1% organic manure + 50% recommended fertilizer) with 4.35 g. Leaf dry weight in the control treatment (T0) was the least at 1.41 g. These results are in accordance with Arif and Amira, (2023) who discovered that the combined utilization of NPK fertilizers and organic amendments greatly improved shoot dry weight. The results of this study supported earlier work submitted by Sharma *et al.* (2024), Parwada *et al.* (2020) and Nazeer *et al.* (2024) all the researchers observed that applied fertilizers and organic manure improve yield and quality parameters. This supported the importance of combining organic amendments with chemical fertilizers for optimizing plant growth and dry matter accumulation.

3.4. Root agronomic attributes of spinach harvests

The incorporation of organic fertilizers together with recommended synthetic fertilizers greatly influenced root fresh weight, dry weight and length of spinach owing to the synergistic effect of the treatments on plant growth (Figure 4). In terms of root fresh weight, the combination of 2% organic matter with 50% nitrogen fertilizer yielded the maximum root fresh weight of 32.33 g, significantly

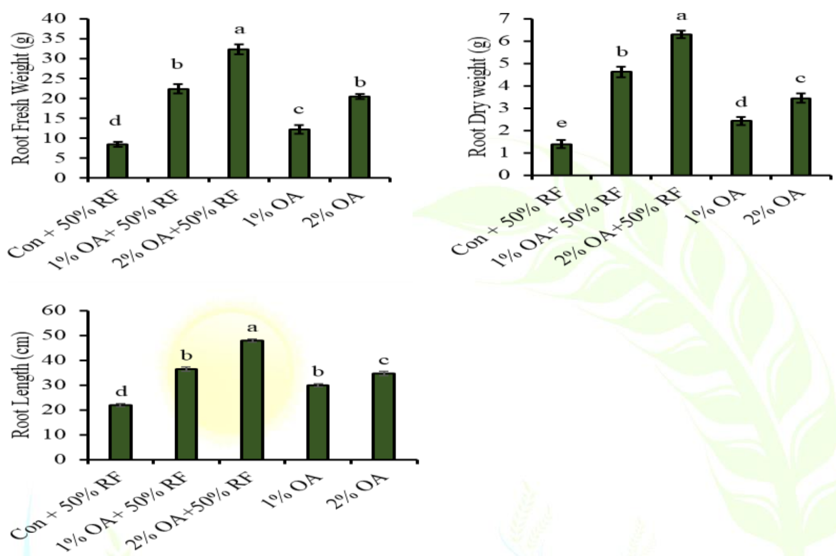

Figure 4: Impact of different organic amendments on root attributes of spinach in two consecutive harvests.

Columns showed the mean of four replicates, whereas bar shows the standard error among treatment replicate. Columns with

surpassing the control treatment of 8.47 g. In contrast, a considerable increase in fresh weight might be attributed to the increased availability of nutrients, especially nitrogen which is a highly crucial factor for root development (Nazeer *et al.*, 2020; Amin *et al.*, 2023),

For root dry weight improvement, the combined application of organic matter and nitrogen fertilizers was found to be very effective. Maximum root dry weight of 6.31 g was obtained with 2% organic manure and 50% recommended fertilizer, whereas the control showed a minimum of 1.39 g. This increase in root dry weight corresponds to findings of Pohan *et al.* (2021), who observed that organic manure enhanced root growth and overall biomass accumulation. Furthermore, Rahman *et al.* (2014) concluded that prolonged use of organic manures resulted in higher root dry weight,

indicating the long-term benefits of organic amendments.

Considerably, root behavior was similar. Its length surpassed that of the control by 48 cm through application of 50% fertilizer plus 2% organic manure, as compared to 22 cm of the control. This discovery is in line with those of Liu *et al.* (2024) and Donate *et al.* (2018), who have reported the improvement of root length as well as general growth under organic amendments and fertilizers, hence contributing to high productivity and yield in the plants.

3.5. Soil attributes under the influence of organic amendments

Organic amendments and recommended fertilizers significantly influenced soil pH, electrical

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conductivity (EC), organic matter and percentage organic carbon (Figure 5). The pH of soil generally decreased with the addition of organic matter and fertilizers and it was lowest at 6.6 for the treatment with 2% organic matter and 50% recommended fertilizer, compared with the control (7.3). This is due to the release of hydrogen ions during decomposition of organic matter, which acidifies the soil. These findings are consistent with Anwar *et al.* (2017), who reported that the use of organic amendments like cattle manure could affect soil pH and microbial activity.

With the application of organic amendments, there was an appreciable increase in electrical conductivity. The maximum in the electrical conductivity was recorded under the treatment of 2% organic matter + 50% fertilizer (3.21 ds m^{-1}) when compared with the control (1.61 ds m^{-1}). Machado *et al.* (2020) supported it with similar findings whereby manure application raises EC because of increase in soluble salts thus promoting soil microbial activity and nutrient availability.

On application of organic matter, soil organic matter was appreciably increased (1.21% to 2.23%) and organic carbon content also increased (0.63% to 1%). These findings were in line with studies by Zhang *et al.* (2022) and Pyakurel *et al.*

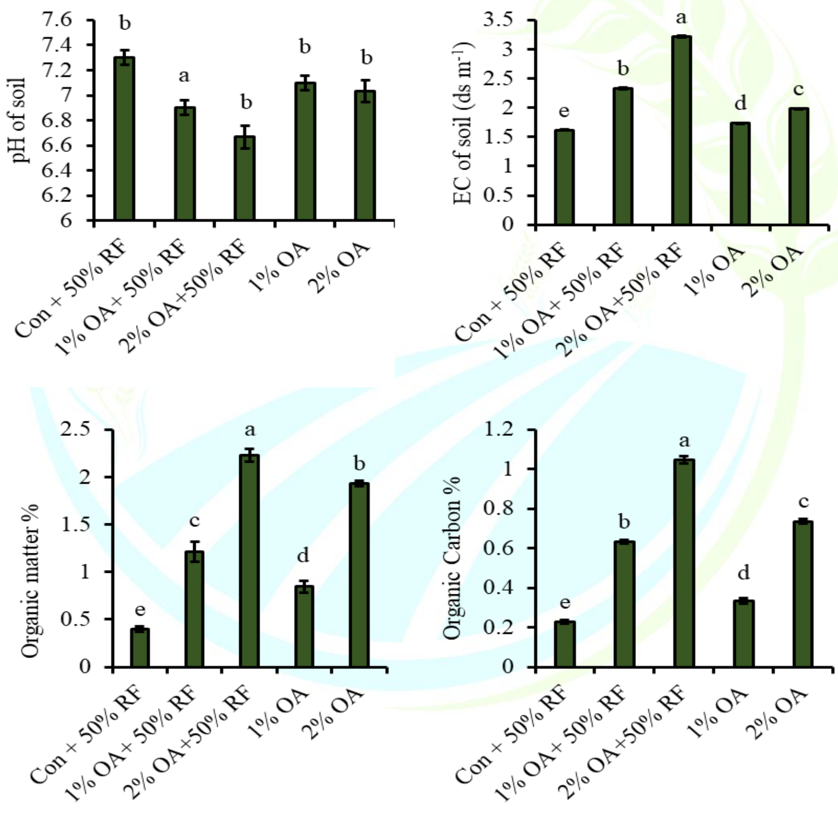

Figure 5: Impact of different organic amendments on soil attributes i) pH, ii) Electrical conductivity, iii) organic matter % and iv) organic carbon %. Columns showed the mean of four replicates, whereas bar shows the standard error among treatment replicates. Columns with similar letters indicate non-significant relation among the treatments at $p<0.05$

(2019) these researchers proved that organic amendments tend to enhance soil organic carbon and fertility over a longer time frame, underpinning the logical benefits of combining inorganic and organic fertilizers for sustainable soil management.

However, it should be noted that integrated nutrient management practices combining organic and inorganic inputs may also contribute to increased greenhouse gas emissions, particularly nitrous oxide, compared to sole organic applications. This potential trade-off highlights the need for careful nutrient management strategies and further research to quantify and mitigate emissions while maintaining productivity gains.

3.6. Impact of organic amendments on the total soil nitrogen and phosphorus contents

The synergistic application of organic amendments and recommended fertilizers affects the soil nitrogen and phosphorus concentrations prominently as evidenced by the study (Figure 6). Nitrogen concentration was highest in treatment T2 at 3.2%, with the mixing of 2% organic amendment with 50% of recommended fertilizers, whereas control treatment T0, which only recommended fertilizers, manifested a nitrogen concentration of 1.4%. The

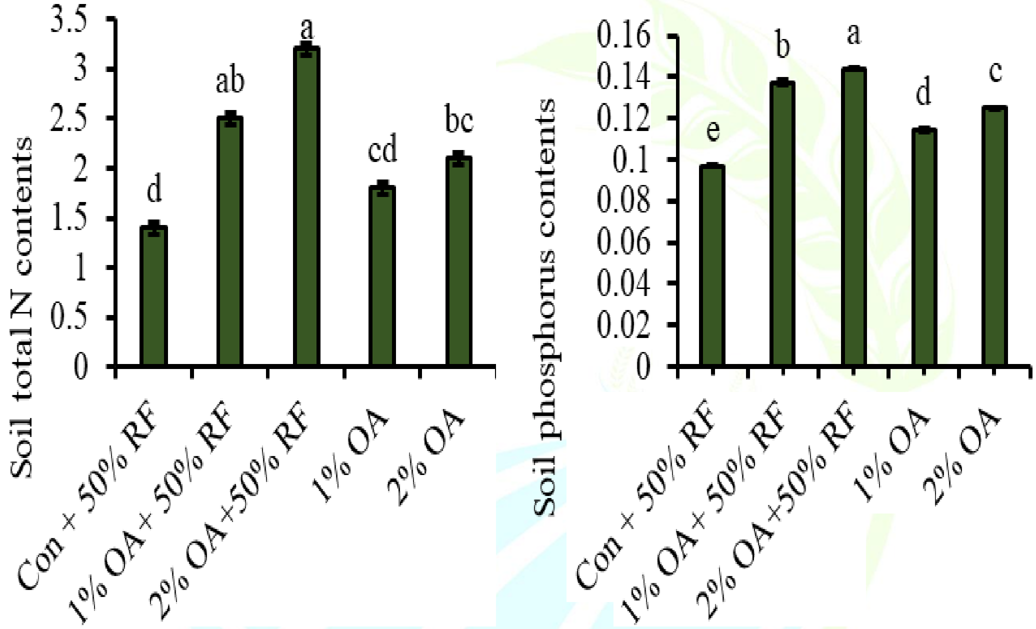

Figure 6: Impact of different organic amendments on soil attributes i) nitrogen, ii) phosphorus contents. Columns showed the mean of four replicates, whereas bar shows the standard error among treatment replicates. Columns with similar letters indicate non-significant relation among the treatments at $p<0.05$ considerable rise in nitrogen levels in treatments that involved the application of organic amendments may mainly be attributed to enhanced microbial activity and nutrient cycling due to organic materials. Organic amendments such as manure and compost, which fairly supply organic nitrogen, are thus made available in the soil through microbial action in the soil, which mineralizes it and thus releases it back into the soil.

These findings are consistent with Kim *et al.* (2023), who observed an increase in nutrient availability following the addition of manure and Machado *et al.* (2020), who reported elevated organic carbon and nitrogen content after the application of organic amendments. Variations in phosphorus levels were due to the faster release and higher initial availability from inorganic fertilizers, leading to quick uptake and potential fixation. In contrast, organic amendments released phosphorus more gradually through mineralization, sustaining soil P availability and uptake over time.

The addition of organic matter in conjunction with fertilizers greatly influences soil phosphorus content. The highest concentration of phosphorus was found in treatment T2 (2% organic amendment + 50% recommended fertilizers) at 0.144 ppm, followed by treatment T1 with 0.13

ppm. The lowest value belonged to the control treatment, which contained 4.54 ppm phosphorus. Organic amendments especially FYM are known to increase the availability of phosphorus through the production of organic acids during their decomposition and these acids are chelating agents that help release phosphorus from insoluble forms in soil. These results corroborate the findings of Pang *et al.* (2024) and Silva *et al.* (2023) who demonstrated the incorporation of organic amendments as they have increased available phosphorus in soil by solubilization of phosphorus. Hence, organic amendments in combination with recommended forms of fertilizer increase both nitrogen and phosphorus levels thus improving the overall factor of soil fertility and nutrient status which are essential for optimum growth of crops.

3.7. Correlation Patterns Between Soil Properties and Plant Growth Parameters

The correlation matrix illustrates the relationships among various soil physicochemical properties and plant growth parameters. Overall, soil pH exhibits strong and consistent negative correlations with nearly all other variables, suggesting that as soil pH increases, the availability of nutrients and plant growth performance tend to decline. For example, pH shows highly negative correlations with organic matter ($r = -0.97$), soil phosphorus ($r = -0.89$) and measures of leaf and root development (with correlation coefficients ranging from 0.89-0.99). Conversely, most plant growth parameters including leaf length (first and second measurements), root length, root dry weight, and both fresh and dry leaf weights are very strongly positively correlated with each other ($r \geq 0.90$), indicating that improved growth in one parameter is closely associated with increases in other growth traits. Electrical conductivity (EC) displays strong positive correlations with soil nutrients and plant growth indices, such as OM ($r = 0.90$) and root fresh weight ($r = 0.87$), implying that higher EC in this context may reflect greater nutrient availability rather than salinity stress. Additionally, soil nitrogen, phosphorus, organic matter, and organic carbon are highly interrelated ($r > 0.85$) and positively associated with plant growth variables, highlighting their collective importance in supporting biomass accumulation. Overall, this pattern of correlations suggests that better soil fertility, as indicated by higher organic matter and nutrients, is a key driver of enhanced plant growth, while increased pH may exert a limiting effect.

3.8 Principal Component Analysis (PCA) of Soil and Plant Growth Parameters

The principal component analysis (PCA) biplot revealed that the first principal component (F1) accounted for 94.9% of the total variability among the measured parameters, indicating that this axis captured the dominant patterns in the dataset. Most of the variables, including electrical conductivity, organic matter, organic carbon, soil nitrogen and phosphorus contents as well as all indicators of plant growth such as root length, root fresh and dry weights, and leaf lengths and weights at both harvests, were strongly projected in the positive direction of F1. This clustering suggests a high degree of positive association among these parameters, reflecting that improved soil fertility and organic matter content were closely linked to enhanced plant growth. In contrast, soil pH was oriented in the opposite direction

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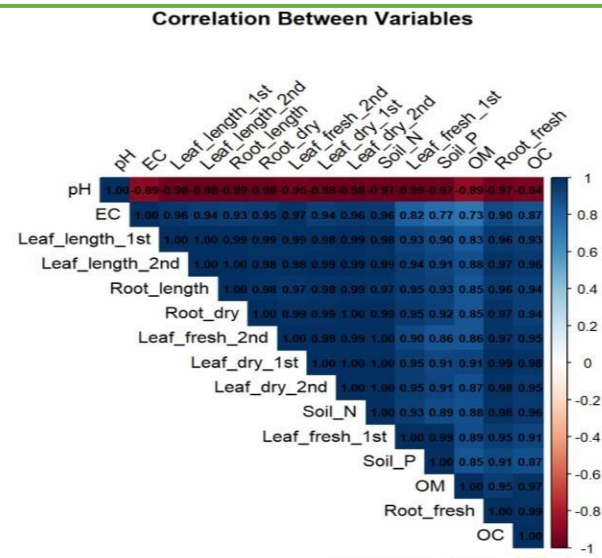

Figure 7: Correlation matrix showing the relationships among soil properties and plant growth parameters

along F1, highlighting its negative relationship with nutrient availability and biomass accumulation. The second principal component (F2) explained only 2.9% of the variation, indicating that differences along this axis were minimal and contributed little to the overall data structure. These findings emphasize that soil fertility indicators and plant growth traits are tightly correlated, while higher pH levels exert an antagonistic effect potentially limiting nutrient uptake and plant development.

3.9. Heatmap of Treatment Effects on Plant Growth and Soil Properties

The heatmap illustrates the effects of different treatments on plant growth parameters and soil characteristics. Treatments include organic amendments (OA) at 1% and 2%, with and without 50% rice fertilizer (RF), compared to a control. The intensity of the color indicates the magnitude of the measured variables, with darker colors representing higher values. Plant growth parameters such as leaf length, leaf fresh weight, and leaf dry weight particularly in the second measurement show significantly higher values under the combined treatment of 2% OA + 50% RF, indicating a strong positive impact on plant biomass and vigor. This treatment also enhances root length and root dry weight noticeably more than other treatments. In contrast, soil properties such as pH, EC, organic matter (OM), organic carbon (OC), soil nitrogen (N) and soil phosphorus (P) show relatively little variation across treatments, suggesting that the short-term impact on soil chemical properties is limited. Overall, the heatmap indicates that integrating organic amendments with partial chemical fertilizer considerably enhances plant growth parameters compared to control and sole applications of OA.

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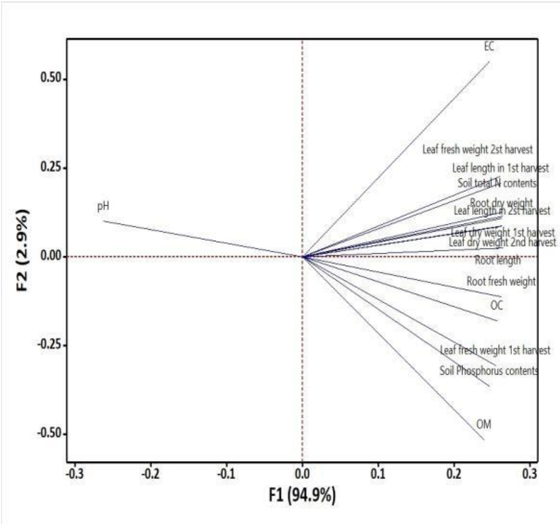

Figure 8: PCA biplot showing relationships among soil properties and plant growth parameters

3. Conclusion

When organic manure (press mud, cow dung, and poultry manure) is applied with nitrogenous fertilizers it supports the growth of spinach and ameliorates soil properties more effectively than control treatments. The results showed improvements in root length, leaf length, fresh and dry weights, and nutrient (N-P-K) uptake, with the highest values observed under 1% and 2% organic amendments. These treatments also enhanced soil organic carbon, water use efficiency, and overall soil porosity, while reducing bulk density and increasing infiltration rate. Combined application of organic amendments and recommended fertilizers modified soil pH and electrical conductivity, contributing to better soil fertility and crop performance.

These findings have broader implications for sustainable nutrient management policies and field-scale adoption, especially in semi-arid agricultural regions. Promoting integrated use of organic amendments through extension services and policy incentives could improve soil health, support climate change mitigation through carbon sequestration, and enhance food security.

Future research should consider long-term and multi- season field trials across different agro-ecological zones to assess the persistence of these benefits under varying climatic conditions. Additionally, integrating microbial bioinoculants with organic amendments could further improve nutrient availability, soil health, and crop productivity, and is recommended as a priority area for further investigation. While the combined use of organic amendments and fertilizers effectively improved soil fertility and spinach yield, future studies should also assess the greenhouse gas emission profiles of such integrated approaches to ensure their environmental sustainability.

4. Funding

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6. Conflict of Interest

The authors declare no conflict of interest.

7. SDGs Addressed

This article addressed the SDG2 (Zero hunger), SDG3 (Good health and well-being) SDG12 (Sustainable consumption and Production) and SDG14 (Life on land).

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