

Optimizing Carrot Production through Organic Amendments: Enhancing Soil Fertility and Crop Performance in Alkaline Soils



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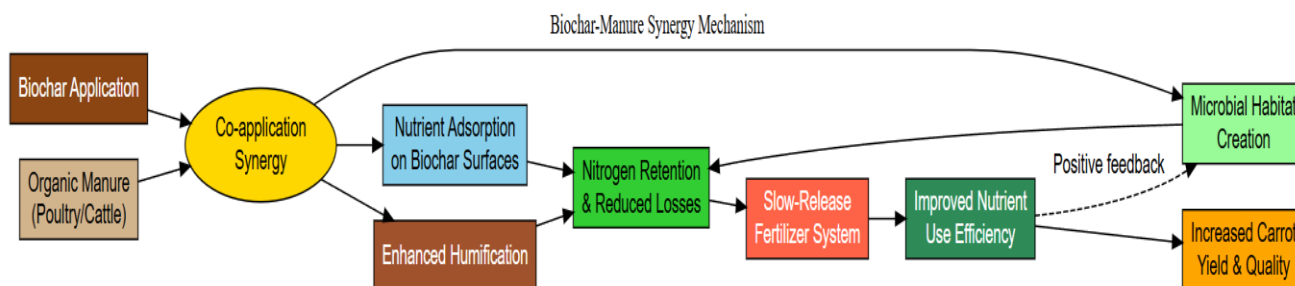
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Abstract

This study investigated the effects of various organic amendments on soil properties and carrot (*Daucus carota* L.) growth in a pot experiment. Five treatments were evaluated: control (T0, 100% chemical fertilizer), charcoal (T1, 1% + 50% fertilizer), cattle dung (T2, 2.5% + 50% fertilizer), poultry manure (T3, 2.5% + 50% fertilizer), and compost (T4, 2% + 50% fertilizer). Results demonstrated that organic amendments significantly enhanced soil fertility by increasing organic matter content (1.6-fold), total nitrogen (1.8-fold), available phosphorus (2.1-fold), and exchangeable potassium (1.7-fold) compared to control. Poultry manure (T3) emerged as the most effective treatment, producing the highest shoot length (16 cm), root fresh weight (25 g), and dry matter accumulation. The amendments also moderately reduced soil pH from 8.81 to 7.92, improving nutrient availability in alkaline conditions. These findings conclusively demonstrate that partial substitution of chemical fertilizers with organic amendments, particularly poultry manure, enhances soil health and carrot productivity while reducing dependence on synthetic inputs, offering a sustainable approach for vegetable production in alkaline soils.



Graphical Abstract

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1. Introduction

Carrots (*Daucus carota* L.) are a globally significant root vegetable, renowned for their culinary versatility and exceptional nutritional profile. As a rich source of β -carotene, the precursor to vitamin A, they are fundamental for eye health and immune function (Tripathi, 2021). Their value is further enhanced by their content of fibrous proteins, vitamins like B6 and K1, minerals such as potassium and calcium, and a suite of antioxidants, contributing to benefits that include reduced cancer risk and better management of blood sugar levels due to their low glycemic index (Banerjee et al., 2020). This robust nutritional composition solidifies the carrot's role as a vital vegetable for human diets worldwide. However, the cultivation of carrots, particularly in developing nations like Pakistan, faces a significant paradox: despite its potential for high profitability as a short-interval crop, the actual yield per unit area consistently falls below the global average (Ahmad, Mazhar, Ali, Batool, & Ahmad, 2016). This yield gap is largely attributed to suboptimal agricultural practices, with inefficient and unsustainable soil fertility management being a primary concern (Muendo & Tschirley, 2004).

Conventional carrot production has heavily relied on synthetic fertilizers to meet nutrient demands. While effective in boosting short-term yields, the intensive and often imbalanced use of these chemical inputs leads to a cascade of detrimental effects, including soil degradation, loss of organic matter, and environmental pollution through nutrient leaching (Bitew & Alemayehu, 2017). For smallholder farmers, the spiraling cost of these fertilizers makes them economically inaccessible, thereby threatening both livelihoods and food security (Bationo et al., 2020). This untenable situation necessitates a pivot towards more sustainable and economically viable nutrient management strategies, where the utilization of locally available organic resources presents a promising pathway. Organic amendments, such as animal manures, are foundational to this approach. Their value extends beyond mere nutrient supply; they are a primary source of organic carbon, the cornerstone of soil health (Kwiatkowska-Malina, 2018). Incorporating materials like poultry manure or cattle manure improves soil physical properties by reducing bulk density, enhancing porosity and aeration, and increasing water-holding capacity—all critical factors for the development of a robust root system in carrots (Kwiatkowska-Malina, 2018).

Chemically, the gradual decomposition of these materials releases a spectrum of essential nutrients while also boosting the soil's cation exchange capacity, allowing it to retain nutrients more effectively (Gideon, 2024). Biologically, the influx of organic carbon energizes the soil microbiome, stimulating microbial populations essential for nutrient cycling and pathogen suppression (Amini & Asoodar, 2015). Despite this well-understood value, a critical challenge persists in the lack of localized, crop-specific

recommendations for the application of these organic amendments.

More recently, biochar has emerged as a particularly potent soil conditioner with the potential to complement traditional organic fertilizers. Produced through the pyrolysis of organic biomass, this carbon-rich, porous material offers unique advantages, including a highly stable structure that enables long-term carbon sequestration and improves soil physics by lowering bulk density and enhancing water retention (Lehmann & Kleber, 2015). Its large surface area allows it to act as a "nutrient sponge," adsorbing ammonium and nitrates to reduce leaching losses and synchronize nutrient release with plant uptake (Mandal et al., 2016).

However, a key limitation of biochar is its typically low inherent nutrient content (Badu et al., 2019), which has led to the investigation of its synergistic potential with organic manures. Indeed, research indicates that co-applying biochar with manure can reduce nitrogen losses during decomposition and enhance the humification process, thereby creating a more effective, slow-release fertilizer system (Steiner, Das, Melear, & Lakly, 2010). Despite the individual promise of these amendments, significant knowledge gaps remain, particularly within the context of carrot production in regions like Pakistan. The literature presents conflicting results on the efficacy of biochar, with some studies reporting significant yield increases and others showing neutral or even negative effects (Spokas et al., 2012). Furthermore, direct, comparative studies evaluating the impact of poultry manure, cattle manure, compost, and biochar—both individually and in combination—on carrot growth and fundamental soil health indicators are notably scarce. There is, therefore, a pressing need for empirical evidence to determine which amendment, or combination thereof, most effectively enhances productivity and soil quality. This study is designed to systematically investigate the role of these carbon-based materials in cultivating a sustainable and productive carrot agrosystem, providing much-needed data to guide farmers and policymakers towards more resilient agricultural practices.

It is hypothesized that the application of all carbon-based amendments will significantly improve the growth, yield, and quality of carrots compared to an unamended control, with poultry manure expected to produce the most substantial yield response due to its high and readily mineralizable nutrient content. It is hypothesized that all amendments will lead to a significant increase in soil organic carbon percentage, with biochar and compost expected to induce the most pronounced and persistent increase due to their stable, carbon-rich structures that are resistant to rapid decomposition. It is hypothesized that combined treatments of biochar with organic manures will exhibit synergistic effects, resulting in significantly greater carrot yield and higher soil organic carbon than the application of any single amendment alone, as the combination is expected to leverage the nutrient supply of the manure with the superior physical and chemical conditioning properties of the biochar.

To evaluate and compare the effects of different carbon-based soil amendments, specifically poultry manure, cattle manure, biochar, and compost, on the growth, yield, and quality parameters of carrots (*Daucus carota* L.). To determine the influence of these amendments on soil health by measuring their respective effects on the soil's organic carbon percentage following the crop cycle. To assess the potential synergistic effects of combining biochar with organic manures on carrot productivity and soil carbon content, comparing these combinations against the amendments applied individually.

2 Materials and Methods

2.1 Experimental Site, Design, and Soil Collection

A pot experiment was conducted during the winter season of 2022-2023 at the warehouse of the Institute of Soil and Environmental Science (ISES), University of Agriculture, Faisalabad (UAF). The objective was to examine the impact of various organic amendments on carbon sequestration and the growth and yield of carrots. The soil for the experiment was collected from the farm area of ISES. It was subsequently sun-dried, and large aggregates were carefully crushed. The soil was then sieved to achieve a uniform consistency before being used to fill the pots (Sparks, Page, Helmke, & Loeppert, 2020). The experiment was arranged in a Complete Randomized Design (CRD) with five treatments and four replications each, resulting in a total of twenty experimental units (Steel & Torrie, 1981). Each pot was filled with 15 kg of the prepared soil.

2.2 Collection and Preparation of Organic Amendments

The organic amendments used in this study included cattle manure, poultry manure, compost, and charcoal. Cattle manure and poultry manure were collected from the animal farm and poultry shed of UAF, respectively. The collection sites were visited at four-day intervals to gather fresh materials, which were then carefully placed in polythene bags and transported to the experimental site. Compost was procured from a local fertilizer dealer in Faisalabad. Charcoal, acting as a biochar, was produced locally through the pyrolysis of firewood at temperatures below 700°C in a limited oxygen environment (Lehmann & Kleber, 2015). Prior to application, all organic materials were sun-dried in the open air to remove moisture. Once thoroughly dried, each amendment was weighed to the required ratio as per the experimental plan using an electronic balance.

2.3 Experimental Treatments

The treatments were designed to assess the impact of different organic matters, each applied in combination with a reduced dose of fertilizer, on carrot development and production. The specific treatments were as follows: T0 (Control: 0% organic matter + 100% recommended fertilizer), T1 (1% charcoal + 50% fertilizer), T2 (2.5% cattle dung + 50% fertilizer), T3 (2.5% poultry manure + 50%

fertilizer), and T4 (2% compost + 50% fertilizer). All percentages are expressed on a weight-by-weight basis.

2.4 Soil Analysis Prior to Experiment

A comprehensive analysis of the initial soil was conducted to determine its physicochemical properties. Soil texture was determined by the hydrometer method (Gee & Or, 2002). The pH and electrical conductivity (EC) of a saturated soil paste were measured using a pH and EC meter, respectively (Sparks et al., 2020). Soil bulk density was assessed using the clod method (Blake & Hartge, 1986). The water holding capacity was determined by conventional methods (Reynolds & Topp, 2008). Soil organic matter and the percentage of organic carbon were analyzed using the Walkley and Black method (Nelson & Sommers, 1982). Available phosphorus was extracted with 0.5 M NaHCO₃ (Olsen, 1954) and measured spectrophotometrically (Rayment & Lyons). Extractable potassium was determined using a flame photometer after extraction with ammonium acetate (Helmke & Sparks, 1996). Total nitrogen was analyzed by the Kjeldahl method (Bremner, 1996). The initial soil was characterized by a pH of 8.81, an EC of 10.35 dS m⁻¹, and a CEC of 13.2 cmolc kg⁻¹.

2.5 Analysis of Organic Amendments

The chemical properties of the key organic amendments were also analyzed before application. The pH and EC of the manures were determined in a 1:5 (w/v) suspension with water (Sparks et al., 2020). The pH of poultry manure and cattle dung was found to be 7.08 and 10.41, respectively. Their electrical conductivity was measured at 7.22 dS m⁻¹ for poultry manure and 10.1 dS m⁻¹ for cattle dung.

2.6 Determination of Soil Physical Properties

Several soil physical properties were measured using standard procedures. The infiltration rate was determined using a double-ring infiltrometer (Reynolds & Topp, 2008). The rings were driven 10 cm into the soil, filled with water, and the rate of water infiltration was recorded until a constant rate was achieved.

2.7 Calculations for Carbon Stock and Sequestration

Carbon stock and carbon sequestration were calculated at the conclusion of the experiment. The carbon stock was calculated using the formula: Carbon stock (tons ha⁻¹) = concentration of soil carbon (%) * soil bulk density (g cm⁻³) * soil depth (Sarwar et al.) (Pearson, 2007). Carbon sequestration was determined as the difference between the final soil carbon content and the initial soil carbon content (Benbi & Senapati, 2010).

2.8 Plant Growth and Agronomic Parameters

At the time of crop harvest, carrot plants were carefully uprooted from the pots. They were washed with distilled water and gently dried with blotting paper before measurements were taken. The following agronomic

parameters were recorded: root length and leaf length (measured with a meter rod), fresh weight of roots, shoots, and the entire plant, and the dry weight of roots and shoots. For dry weight determination, plant samples were oven-dried at 65°C until a constant weight was achieved. All weights were measured using an electronic balance.

2.9 Plant Tissue Analysis

The nutritional content of the plant tissues was analyzed to assess nutrient uptake. For phosphorus determination, dried plant samples were digested in a tri-acid mixture ($\text{HNO}_3\text{:HClO}_4\text{:H}_2\text{SO}_4$ in a 5:2:1 ratio). The phosphorus concentration in the digestate was determined calorimetrically using a spectrophotometer after developing a blue complex with ammonium molybdate and ascorbic acid. Potassium in the plant digestate was directly measured using a flame photometer calibrated with potassium standards (Helmke & Sparks, 1996). Total nitrogen in the plant samples was determined using an Automatic Kjeldahl apparatus, which involved digestion, distillation, and titration (Bremner, 1996).

2.10 Statistical Analysis

All collected data were processed and organized using Microsoft Excel. Statistical analysis was performed using Statistics 8.1 software. Analysis of variance (ANOVA) was applied to the data to determine the significance of the treatment effects (Steel et al., 1997). Where the F-test showed significant differences, the Least Significant Difference (LSD) test was employed at a 5% probability level to compare the means of the various treatments.

3. Results

3.1. Effect of Organic Amendments on Carrot Growth Parameters

The application of various organic amendments significantly influenced the growth and biomass of carrot plants, as detailed in Figure 1. Figure 1a (Shoot Length) demonstrates a clear positive effect of organic treatments on the aerial growth of carrots. All amendment treatments (T1: Charcoal, T2: Cattle dung, T3: Poultry manure, T4: Compost) resulted in a greater shoot length compared to the control (T0). Notably, treatment T3 (Poultry manure) produced the tallest shoots, with a mean length of approximately 16 cm, followed closely by T2 (Cattle dung). The T1 (Charcoal) and T4 (Compost) treatments also showed a marked improvement over the control but were less effective than the manure-based amendments. In Figure 1b (Root Length), a similar trend was observed, where organic amendments enhanced root development. Treatment T3 (Poultry manure) again yielded the best results, producing the longest roots. The control group (T0) consistently showed the lowest values for both shoot and root length, highlighting the limitation of relying solely on chemical fertilizers for optimal growth. The impact on biomass accumulation is shown in Figure 1c (Shoot Fresh Weight) and Figure 1d (Root Fresh

Weight). The fresh weight of both shoots and roots was substantially increased by the addition of organic matter. For shoot fresh weight (Figure 1c), T3 (Poultry manure) and T2 (Cattle dung) treatments resulted in the highest biomass, significantly outperforming the control. A parallel effect was seen in root fresh weight (Figure 1d), a critical yield parameter for carrots. Treatment T3 (Poultry manure) produced roots with the highest fresh weight, indicating its superior efficacy in promoting the economic yield of the crop. Treatment T4 (Compost) also showed a substantial improvement in root biomass over the control. In summary, the results from Figure 1 consistently show that the integration of organic amendments, particularly poultry manure (T3), with a reduced dose of chemical fertilizer led to statistically superior growth and yield outcomes in carrots compared to the full dose of chemical fertilizer alone (T0).

3.2. Effect of Organic Amendments on Plant Biomass Accumulation

The dry weight of plant biomass, a key indicator of net primary production and nutrient assimilation, was significantly affected by the different soil amendment treatments, as illustrated in Figure 2. Figure 2a (Dry Weight of Shoots) shows that the accumulation of dry matter in the shoots was markedly enhanced by the application of organic amendments. All treatments incorporating organic matter (T1-T4) resulted in a higher shoot dry weight compared to the control (T0), which relied solely on chemical fertilizer. Among the organic treatments, T3 (Poultry manure) produced the highest shoot dry mass, indicating its superior ability to support vegetative growth. This was followed by T2 (Cattle dung) and T4 (Compost), which also showed substantial improvements over the control. Treatment T1 (Charcoal) resulted in a more moderate but still significant increase in shoot dry weight compared to T0. A more pronounced and economically critical effect was observed in Figure 2b (Dry Weight of Carrot Roots). The dry weight of the roots, which represents the harvested portion of the crop, was profoundly influenced by the treatments.

Consistent with the trend for fresh weight and shoot growth, treatment T3 (Poultry manure) yielded the highest root dry weight, significantly outperforming all other treatments. This confirms that the benefits of poultry manure amendment directly translate into the development of the marketable product. Treatments T2 (Cattle dung) and T4 (Compost) also resulted in a significantly greater root dry mass than the control, while T1 (Charcoal) showed an intermediate effect. In conclusion, the data from Figure 2 demonstrate that the integration of organic amendments, particularly poultry manure, with a reduced chemical fertilizer dose not only promotes overall plant growth but also specifically enhances the accumulation of dry matter in the economically valuable root portion of the carrot plant.

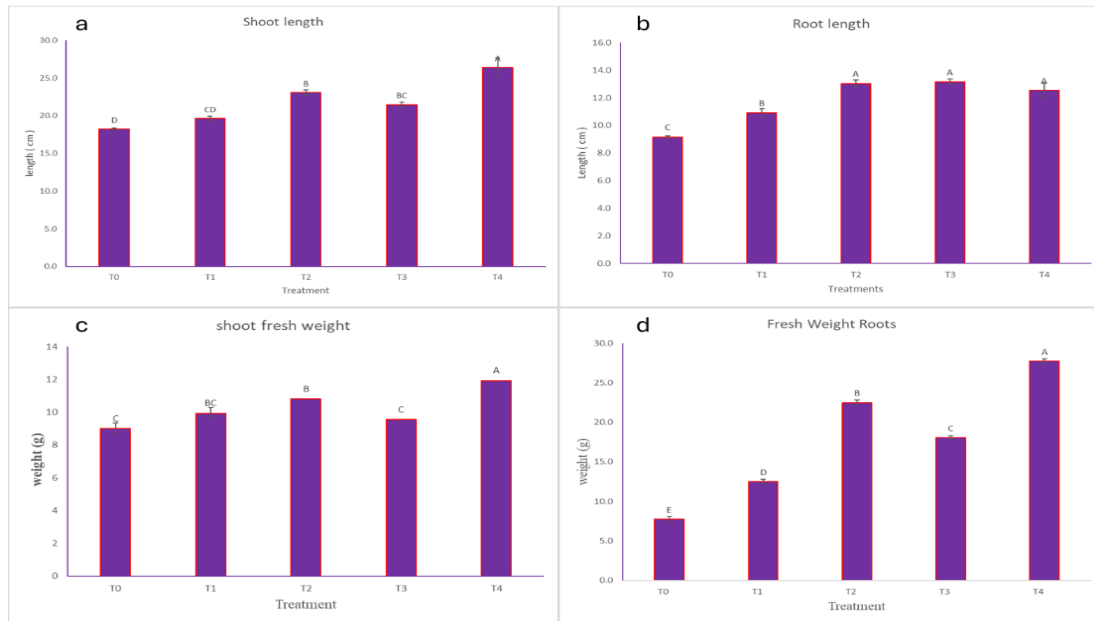


Figure 1: Effect of organic amendments on carrot growth parameters. Values are means of four replicates ($\pm$ standard error). Different lowercase letters above bars indicate significant differences among treatments according to the Least Significant Difference (LSD) test at $p < 0.05$. Treatments are: T0 (Control: 100% fertilizer), T1 (1% Charcoal + 50% fertilizer), T2 (2.5% Cattle dung + 50% fertilizer), T3 (2.5% Poultry manure + 50% fertilizer), T4 (2% Compost + 50% fertilizer).

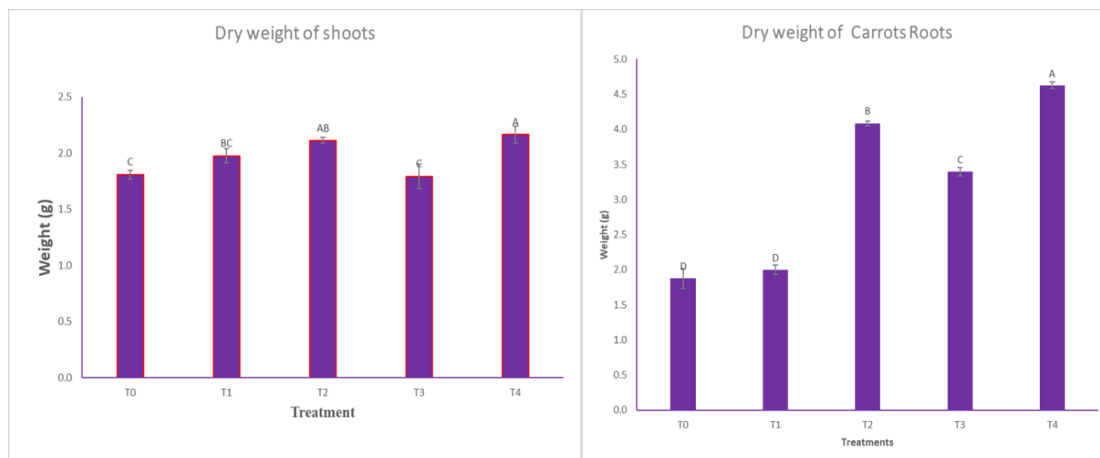


Figure 2: Effect of organic amendments on dry biomass accumulation of carrot plants. Values are means of four replicates ($\pm$ standard error). Different lowercase letters above bars indicate significant differences among treatments, as determined by the Least Significant Difference (LSD) test at $p < 0.05$. Treatments are as defined in Figure 1.

3.3. Effect of Organic Amendments on Soil Chemical Properties

The application of organic amendments significantly altered the chemical properties of the soil, with notable effects on organic matter content, nutrient availability, pH, and salinity, as presented in Figure 3. The incorporation of organic amendments led to a substantial increase in soil organic matter (SOM) compared to the control (T0). As shown in Figure 3a, all organic treatments (T1-T4) resulted in a higher percentage of organic matter, with treatment T3 (Poultry manure) showing the most pronounced effect,

achieving the highest SOM level. This was closely followed by T2 (Cattle dung). A corresponding and critical trend was observed for soil nitrogen (N) content in Figure 3b. The total N percentage in the soil was significantly enhanced by the organic amendments. Treatment T3 (Poultry manure) was the most effective, yielding the highest soil N content, which aligns with its high nitrogenous composition. This increase in SOM and N provides a direct explanation for the enhanced plant growth and biomass observed in the previous figures, as it indicates a greater reservoir of slow-release nutrients and improved soil health. The availability of essential macronutrients phosphorus (P) and potassium (K) was also

markedly improved. Figure 3c demonstrates that the available phosphorus in the soil was significantly higher in all organically amended treatments than in the control. Treatment T3 (Poultry manure) again resulted in the highest P availability, consistent with its known nutrient profile.

Similarly, Figure 3d shows that the exchangeable potassium content was greatest in the soils treated with T3 (Poultry manure) and T2 (Cattle dung). These increases are attributed to the direct nutrient contribution from the manures and the enhanced nutrient retention capacity of the soil from the added organic matter. The organic amendments also induced favorable changes in soil pH and electrical conductivity (EC). Figure 3e illustrates that all organic treatments caused a modest but consistent decrease in soil pH compared to the alkaline control (T0). This slight acidifying effect can help improve the availability of certain micronutrients in alkaline soils. Furthermore, as seen in Figure 3f, the soil EC, an indicator of soluble salt content, was maintained within an acceptable range across all treatments. While there were variations, the values did not reach levels that would be considered detrimental to plant growth, indicating that the amendments did not cause problematic salt accumulation. In summary, the results from Figure 3 confirm that the addition of organic amendments, particularly poultry manure (T3), effectively enhanced soil fertility by increasing organic matter, boosting the reserves of key primary nutrients (N, P, K), and moderately improving soil pH conditions.

4. Discussion

4.1 Synergistic Soil Fertility Enhancement through Biochemical and Physical Mechanisms

The pronounced increase in soil organic matter (SOM) following organic amendment application represents a fundamental improvement in soil quality that operates through multiple interconnected mechanisms. The incorporation of poultry manure, cattle dung, and compost introduces substantial quantities of organic carbon that serve as both a nutrient reservoir and a catalyst for biological activity (Lehmann & Kleber, 2015). The decomposition of these materials is mediated by a diverse consortium of soil microorganisms, including bacteria, fungi, and actinomycetes, which enzymatically break down complex organic compounds through processes such as ammonification and nitrification for nitrogen, and mineralization for phosphorus (Chen, Camps-Arbestain, Shen, Singh, & Cayuela, 2018). This microbial processing transforms nutrients from organic forms into plant-available inorganic ions, effectively creating a slow-release fertilizer system. Particularly noteworthy is the performance of poultry manure (T3), which typically possesses a favorable carbon-to-nitrogen (C:N) ratio that promotes efficient mineralization without inducing temporary nitrogen immobilization (Adekiya et al., 2020). The simultaneous improvement in cation exchange capacity (CEC) created by the increased SOM provides enhanced nutrient retention capabilities,

reducing leaching losses of cationic nutrients like ammonium (NH_4^+) and potassium (K^+) while maintaining their plant availability (Mandal et al., 2016). Furthermore, the decomposition process releases organic acids, including citric, oxalic, and malic acids, that chelate metal ions and solubilize fixed phosphorus compounds in alkaline soils, making previously unavailable phosphorus accessible to plants (Jones & Oburger, 2010) (Figure 4).

4.2 Integrated Plant Physiological Responses to Improved Rhizosphere Conditions

The remarkable enhancement in carrot growth parameters and yield under organic amendments, particularly with poultry manure, can be attributed to comprehensive improvements in rhizosphere dynamics that positively influence plant physiological processes. The improvement in soil physical properties through organic matter addition creates an optimal root environment by enhancing soil aggregation, reducing compaction, and increasing microporosity (Blanco-Canqui & Lal, 2004). This improved soil structure facilitates superior root penetration and proliferation, allowing the carrot plants to explore a greater soil volume for water and nutrients (Bengough, McKenzie, Hallett, & Valentine, 2011). The synchronized nutrient release from organic amendments matches the crop's developmental requirements more effectively than chemical fertilizers, preventing the boom-bust growth patterns associated with synthetic inputs (Sinclair & Rufty, 2012).

This steady nutrient supply supports continuous photosynthetic activity by maintaining optimal chlorophyll synthesis and photosynthetic efficiency, thereby increasing the production of photo assimilates (Lawlor, 2002). The increased availability of nitrogen, evidenced by the higher soil N content in amended treatments, directly supports amino acid and protein synthesis, while the improved phosphorus availability enhances energy transfer through ATP and supports root development (Marschner, 2011). The robust root system resulting from these improved conditions exhibits enhanced hydraulic conductivity and nutrient uptake capacity, creating a positive feedback loop that further supports shoot growth and ultimately directs more assimilates to the developing storage roots, resulting in the significantly higher fresh and dry weights observed (Lynch, 2019).

4.3 Soil System Reclamation and Sustainable Management Implications

The ameliorative effects of organic amendments on soil chemical properties extend beyond direct nutrient supply to include significant improvements in the overall soil health parameters critical for sustainable production. The modest but consistent reduction in soil pH observed in amended treatments represents a valuable corrective mechanism in alkaline soils, where high pH typically limits micronutrient availability (Bolan, Adriano, & Curtin, 2003). This pH moderation occurs through multiple pathways: the release of

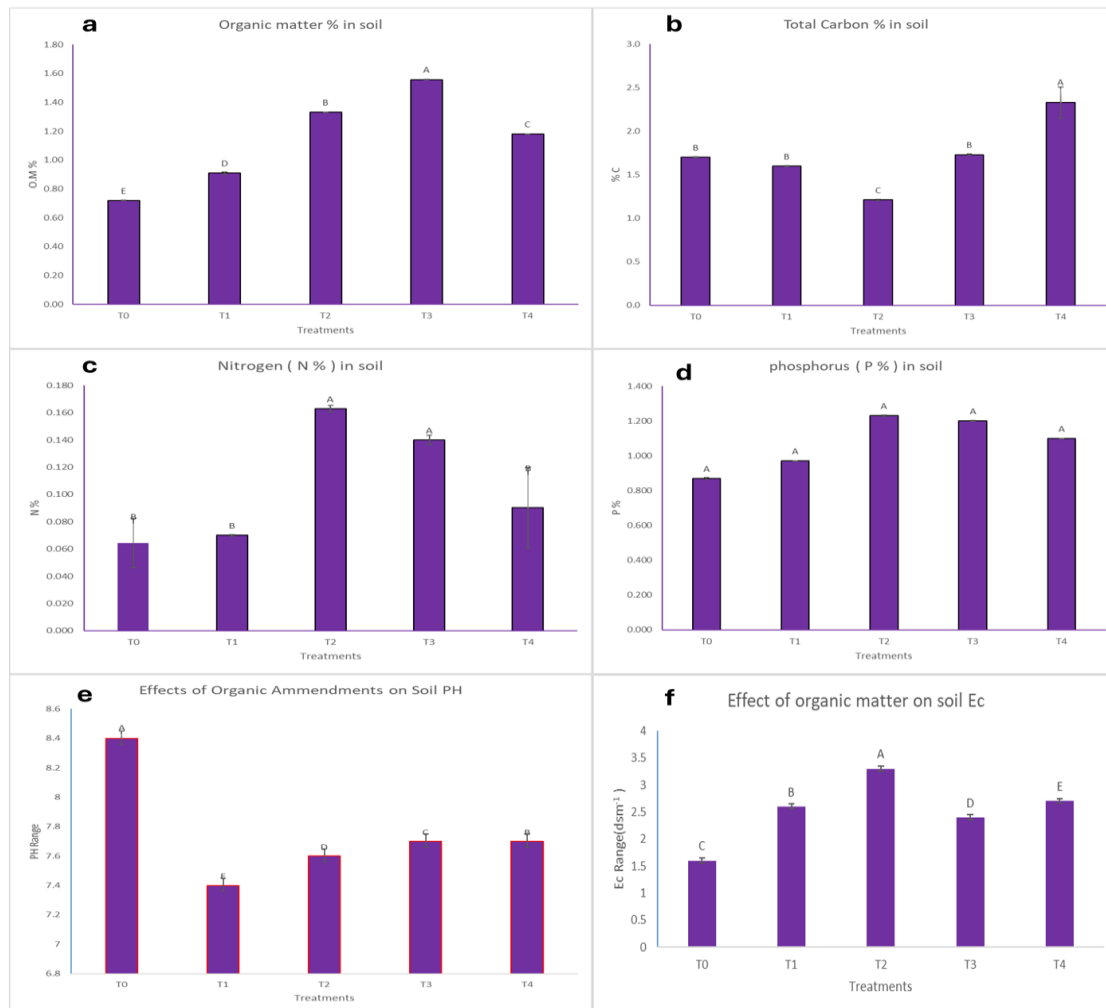


Figure 3: Impact of organic amendments on soil chemical properties post-harvest. (a) Soil organic matter content, (b) Total nitrogen content, (c) Available phosphorus, (d) Exchangeable potassium, (e) Soil pH, (f) Soil electrical conductivity (EC). Values are means of four replicates ($\pm$ standard error). Different lowercase letters above bars indicate significant differences among treatments, as determined by the Least Significant Difference (LSD) test at $p < 0.05$. Treatments are as defined in Figure 1.

CO_2 during microbial respiration forms carbonic acid; nitrification of ammonium releases H^+ ions; and organic acids produced during decomposition directly contribute protons to the soil solution (Yue et al., 2019). This slight acidification enhances the solubility and plant availability of essential micronutrients like iron, manganese, zinc, and copper, which are often deficient in high-pH soils (Rengel, 2015). The controlled increase in electrical conductivity (EC) observed in amended soils reflects the presence of soluble plant nutrients rather than problematic salt accumulation, as values remained within the non-saline range (Smith & Doran, 1997).

More importantly, the addition of stable organic compounds, particularly from the charcoal treatment, contributes to long-term carbon sequestration, improving the soil's carbon sink capacity while enhancing its water retention characteristics (Yu et al., 2019). These integrated improvements demonstrate that organic amendments

function as complete soil conditioners that simultaneously address chemical, physical, and biological limitations, offering a viable strategy for building soil resilience, reducing chemical fertilizer dependency, and establishing sustainable production systems, especially in resource-constrained agricultural environments where soil degradation presents significant challenges to food security (Lal, 2020).

5. Conclusion

The integration of organic amendments with reduced chemical fertilizer rates significantly improved both soil health and carrot productivity. Poultry manure demonstrated superior performance in enhancing soil organic matter, nutrient availability, and plant growth parameters, followed by cattle dung and compost. The improvement in soil chemical properties, particularly the increase in nutrient content and moderate pH reduction, created favorable

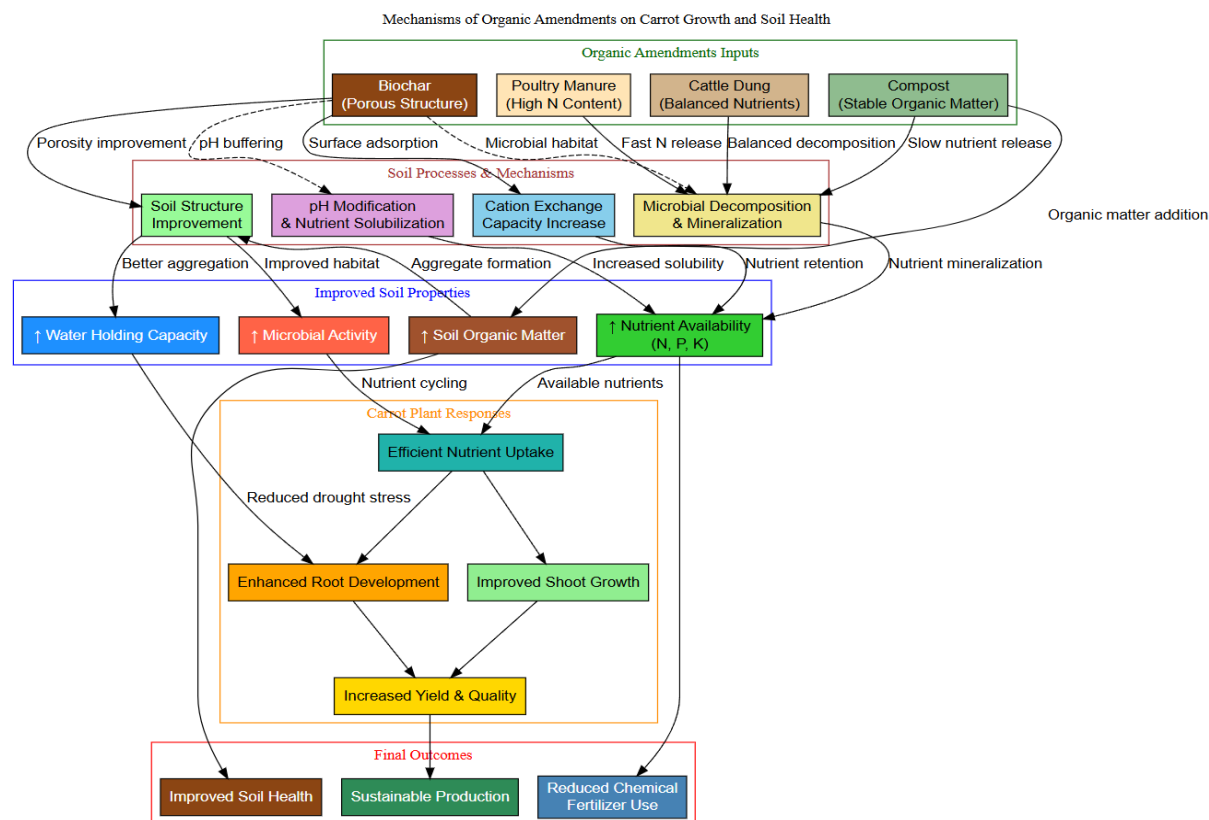


Figure 4: A mechanism-based illustration governing changes in soil and plant attributes.

conditions for carrot growth and development. The organic amendments served as complete soil conditioners, improving multiple aspects of soil fertility simultaneously while supporting sustainable crop production. This study establishes that a 50% reduction in chemical fertilizer combined with 2.5% poultry manure application represents an optimal strategy for carrot cultivation in alkaline soils, providing a viable pathway toward sustainable agricultural practices that maintain productivity while enhancing soil ecosystem services. Future research should focus on long-term field studies to validate these findings under diverse agro-climatic conditions and soil types. Investigating the economic viability of organic amendment applications would provide crucial information for farmer adoption. Research should also explore the synergistic effects of combined organic amendments and develop standardized application protocols for different cropping systems. Furthermore, studies on the microbial community dynamics and carbon sequestration potential of these amendments would enhance our understanding of their environmental benefits. The development of value chains for organic fertilizers and farmer training programs could facilitate wider adoption of these sustainable practices, ultimately contributing to climate-resilient agriculture and food security.

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8. Author's Contribution:

Amaan Ali: Investigations, Data Curation and Visualization, Writing Original Draft; **Muhammad Aamer Maqsood, Saddam Hussain:** Supervision, Writing reviews and corrections.

9. Conflict of Interest:

Authors declare no conflict of interest.

10. SDGs Addressed

SDG 2 (Zero Hunger) through enhancing sustainable food production and SDG 12 (Responsible Consumption and Production) by promoting sustainable soil management and reducing synthetic inputs. Other relevant goals include SDG 15 (Life on Land) for improving soil health and SDG 13 (Climate Action) through carbon sequestration in soil organic matter.

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