



Differential Efficacy of Farmyard Manure and Cow Manure in Ameliorating Salinity Stress: Integrated Assessment of Spinach Growth, Soil Health, and Enzymatic Recovery

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Abstract

Soil salinity is one of the major threats to food security in the world because it drastically reduces the growth of crops and interferes with the major processes in soil. This study compared the relative performance of two organic amendments that are readily available, namely farmyard manure (FYM) and cow manure in alleviating salinity stress on spinach (*Spinacia oleracea* L.) planted in the pot. This involved a thorough evaluation, which incorporated the measurements of the growth of plants, the carbon cycle in the soil and several important enzymatic functions. A comparison between four treatments was done: none as control, saline, which had EC greater than 4.0 dS/m, and saline manure treatment in the form of cow manure or FYM at 5% (w/w). Findings revealed that spinach growth was severely inhibited by salinity as the root length, shoot length, fresh and dry weight were found to be 38-63% lower than the non-saline control. Both organic amendments significantly alleviated salinity stress but FYM consistently outperformed cow manure in all parameters. FYM increased root length by 162% and dry matter accumulation to be on par with the non-saline control. The soil health indicators also exhibited impressive recovery: the soil organic carbon, the dissolved organic carbon and the microbial biomass carbon improved by 175, 128 and 45% in FYM-amended soil in comparison to the saline control. Enzyme activity, including urease, phosphatase, β -glucosidase and catalase, was restored at 78-100% of normal by FYM as opposed to 61-80% by cow manure. The Multivariate analysis showed that the parameters of plant growth, especially root and shoot length, were the major causes of separation of treatments. FYM has enhanced performance owing to its stabilized and humified organic matter that offers sustained amelioration in the soil structure, supplies nutrients, and offer microbial habitation. The conclusion of this paper is that FYM is a more efficient and sustainable amendment to restore saline soils providing a viable and environmentally friendly measure to increase the output and renew the soil biomass Capacity.

1. Introduction

Salinity in soil is a severe form of abiotic stress that is threatening global agricultural productivity and imposing a detrimental impact on about 20 % of all irrigated lands globally and leading to enormous losses in crop quality and yield (FAO, 2021). High concentrations of chloride (Cl⁻) and sodium (Na⁺) ions cause disturbance of critical physiological and biochemical pathways in plants and result in osmotic distress, ion toxicity, and nutritional disorders (Isayenkova and Maathuis, 2019). Spinach (*Spinacia oleracea* L.) is a healthy leafy crop that is mainly susceptible to salinity because it is a short-cycle crop containing a lot of minerals of high value. Its growth, biomass, and chlorophyll content is

highly inhibited by saline conditions, and it is an ideal model crop to study the mitigation of salinity (Sarker et al., 2023).

In addition to the effects of salinity on the physiology of plants, salinity has a significant adverse effect on the health and biological processes of soil. It compromises the soil structure, decreases the content of organic matter, and most importantly it suppresses the functioning of the microbes and the accompanying enzymatic functions that regulate nutrient cycling. The essential soil enzymes, including dehydrogenase, urease, phosphatase and β -glucosidase, which are part of the nitrogen, phosphorus, and carbon mineralization process, are severely inhibited when the soils are stressed by salt (Yan et al., 2022). This inhibition forms a vicious cycle: when the plants grow poorly, the organic input

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becomes low, which reduces the biological stability and productivity of the soil further. Use of organic amendments has been largely recommended as a sustainable approach towards the rehabilitation of saline soils. Organic manures have been found to increase soil physical characteristics, increase cations exchange capacity, and may interfere directly with toxic ions, and have the potential to displace harmful ions (Ahmed et al., 2023). Two amendments that are most readily available, as well as commonly used, are farmyard manure (FYM) and cow manure. Although both are good sources of organic carbon and nutrients, their nature and stability vary radically. FYM is widely a composted combination of animal dung, urine and bedding material, which results in more stabilized and humified organic matter. Conversely, fresh cow manure contains more carbon that is labile and easily decomposable (Laxminarayana et al., 2022). It is postulated that these differences have different effects on the biological recovery of soil and, therefore, on plant growth in the presence of stress (Sohaib et al., 2023).

Yet, the ability to make a comparatively clear insight into the impact of these two widespread amendments on the interdependence of the triad of saline soil characteristics, the enzymatic vigor, and the spinach yield is not thoroughly discussed. Majority of the studies are dedicated either to plant reactions or to the discrete soil parameters. The existing research gap is the quantitative restoration of the enzyme activities, the functional driver of soil fertility, and the consequences of such a restoration process in agronomic performance of a salt-sensitive crop, such as spinach. Thus, the present study was aimed at exploring and comparing the effectiveness of farmyard manure and cow manure in alleviating salinity stress on spinach in pot. Additionally, the specific objectives were to evaluate the effects on measure their impacts on: (1) major agronomic variables (growth, biomass, chlorophyll content), (2) key soil health variables (SOC, DOC, MBC), and (3) the activity of key soil enzymes that are involved in nutrient cycling. This study will allow achieving a comprehensive evaluation of the processes of salinity amelioration and determine the most efficient organic amendment to boost the productivity and biological stability of salt-impacted soils.

2. Materials and Methods

2.1. Experimental Site and Soil Collection

The pot experiment was conducted in a net house at the Experimental Farm of Mian Channu, Punjab Pakistan. Naturally saline soil was collected (0-20 cm depth) from a fallow agricultural field from Uchkera Village, Faisalabad Pakistan, a known salt-affected area. A composite sample was prepared, air-dried, and passed through a 2-mm sieve for potting. A representative sub-sample was analyzed for initial physicochemical properties (Table 1) following standard methods (Sparks et al., 1996).

2.2. Organic Amendments and Experimental Design

Two organic amendments were used: i) Farmyard Manure (FYM): Well-decomposed FYM (dung, urine, litter mixture aged for 6 months) was collected from the university livestock farm and ii) Cow Manure: Fresh cow dung was collected from healthy dairy cattle, sun-dried, and powdered. Both amendments were air-dried, ground, and sieved (2 mm). Their chemical composition was analyzed (Table 2). The experiment was arranged in a Completely Randomized Design (CRD) with four treatments, each replicated five times (n=5):

- **T1: Normal Soil Control (Non-saline)** – Normal fertile soil ($EC < 2 \text{ dS m}^{-1}$).
- **T2: Saline Soil Control** – Unamended saline soil.
- **T3: Saline Soil + Cow Manure** – Saline soil amended with cow manure at 5% w/w (equivalent to $\sim 10 \text{ t ha}^{-1}$).
- **T4: Saline Soil + FYM** – Saline soil amended with FYM at 5% w/w (equivalent to $\sim 10 \text{ t ha}^{-1}$).

2.3. Pot Preparation and Spinach Cultivation

Earthen pots (30 cm height, 25 cm diameter) were filled with 5 kg of the respective soil-amendment mixtures. The amendments were thoroughly incorporated three weeks before sowing to allow for stabilization. Spinach (*Spinacia oleracea* L.) cv. [e.g., Bloomsdale] seeds were sown directly, with five seeds per pot. After germination, seedlings were thinned to three uniform plants per pot. Pots were irrigated with distilled water to maintain soil moisture at approximately 80% of field capacity by weight, monitored using a portable soil moisture meter (e.g., HH2 Moisture Meter, Delta-T Devices, UK). No chemical fertilizers were applied. Weeds were removed manually.

2.4. Data Collection

2.4.1. Plant Growth and Yield Parameters

At 45 days after sowing (DAS), at the marketable maturity stage, plants were carefully uprooted. Root Length (cm) & Shoot Length (cm): Measured from the base of the stem to the tip of the longest leaf and root using a ruler. Fresh Weight (g plant^{-1}): Determined immediately after harvest. Dry Weight (g plant^{-1}): Recorded after oven-drying plant samples at 70°C to constant weight (48-72 h). SPAD Value: Chlorophyll content index was measured on the youngest fully expanded leaf using a handheld SPAD-502 chlorophyll meter (Konica Minolta, Japan) at 40 DAS. Five readings per plant were averaged.

2.4.2. Soil Sampling and Analysis

Post-harvest, soil samples were collected from the rhizosphere of each pot, air-dried, and sieved for chemical and enzymatic analyses. Soil pH and EC: Measured in a 1:2.5 soil:water suspension (Sparks et al., 1996). Soil Organic Carbon (SOC, %): Determined by the Walkley-Black wet oxidation method (Nelson & Sommers, 1996). Dissolved

Table 1: Initial physicochemical properties of the experimental soil.

Property	Value	Method/Reference
Soil Texture	Sandy clay loam	Hydrometer method (Gee & Bauder, 1986)
pH (1:2.5 soil: water)	8.2 ± 0.2	Glass electrode pH meter
EC (dS m ⁻¹ , 1:2.5 extract)	4.5 ± 0.3	Conductivity meter
Organic Carbon (%)	0.35 ± 0.05	Walkley-Black method (Nelson & Sommers, 1996)
Available N (mg kg ⁻¹)	45 ± 5	Alkaline permanganate method (Subbiah & Asija, 1956)
Available P (mg kg ⁻¹)	8 ± 1	Olsen's method (Olsen et al., 1954)
Exchangeable Na ⁺ (cmol ⁺ kg ⁻¹)	5.8 ± 0.4	Flame photometry after ammonium acetate extraction

Table 2: Chemical composition of the organic amendments used.

Parameter	Farmyard Manure (FYM)	Cow Manure
Organic Carbon (%)	22.5 ± 1.5	35.0 ± 2.0
Total N (%)	0.8 ± 0.1	1.2 ± 0.2
C:N Ratio	28:1	29:1
Total P (%)	0.4 ± 0.05	0.5 ± 0.07
Total K (%)	1.2 ± 0.1	0.9 ± 0.1
EC (dS m ⁻¹)	2.8 ± 0.2	3.5 ± 0.3
pH (1:5)	7.8 ± 0.2	8.0 ± 0.2

Organic Carbon (DOC, mg kg⁻¹): Extracted with 0.5 M K₂SO₄ (1:5 w/v) for 1 h, filtered, and analyzed using a TOC analyzer (Shimadzu, Japan) (Jones & Willett, 2006). Microbial Biomass Carbon (MBC, µg g⁻¹): Estimated by the chloroform fumigation-extraction method (Vance et al., 1987), using a K_c factor of 0.45.

2.4.3. Soil Enzyme Assays

Enzyme activities were determined on field-moist soil samples stored at 4°C and analyzed within one week. Dehydrogenase Activity (µg TPF g⁻¹ soil day⁻¹): Based on the reduction of 2,3,5-triphenyltetrazolium chloride (TTC) to triphenylformazan (TPF) during a 24-h incubation at 37°C (Casida et al., 1964). Urease Activity (µg NH₄⁺-N g⁻¹ soil h⁻¹): Measured by incubating soil with urea solution and quantifying the released ammonium using the indophenol blue method (Kandeler & Gerber, 1988). Phosphatase Activity (µg PNP g⁻¹ soil h⁻¹): Estimated by incubating soil with *p*-nitrophenyl phosphate (pNPP) as substrate and measuring the released *p*-nitrophenol (pNP) colorimetrically at 400 nm (Tabatabai & Bremner, 1969). β-Glucosidase Activity (µg PNP g⁻¹ soil h⁻¹): Assessed using *p*-nitrophenyl-β-D-glucopyranoside as substrate (Eivazi & Tabatabai, 1988).

2.5. Statistical Analysis

All data were subjected to one-way Analysis of Variance (ANOVA) using statistical software (e.g., SAS 9.4, SAS Institute Inc., Cary, NC, USA, or R 4.3.1). Treatment means were compared using Fisher's Least Significant Difference (LSD) test at a 5% probability level ($p < 0.05$). Graphs were prepared using GraphPad Prism 9.0 (GraphPad Software, San Diego, CA, USA).

3. Results and Discussion

3.1. Plant Growth and Biomass Parameters

Organic amendments had a significant ($p < 0.05$) negative impact on the growth of spinach (Figure 1). Both amendments improved all the measured parameters compared to the saline control, which was more effective in most measures Farmyard Manure (FYM). The salinity-stressed physiology was found to be severely suppressed by the saline soil control (Isayenkov & Maathuis, 2019). The 38 and 33% root and shoot length, 63 and 57% fresh and dry weight reductions respectively of the non-saline control were indicative of the dual osmotic and ionic toxicity stresses which disrupted water uptake, nutrient homeostasis and photosynthetic complex. This was physically established through intense chlorosis and burnt leaves. Both amendments reserved the negative effects of salinity though in varying efficiency mechanisms. Cow Manure gave great recovery especially to root architecture, which went up by 125%

compared to the saline control, even more than the non-saline control, by 38%. This is in line with the reports indicating that fresh organic amendments can quickly promote root growth by releasing nutrients instantly and enabling microbial activities (Laxminarayana et al., 2022). The shoot length and dry weight had rebounded to levels that were statistically equal to the non-saline control, and this indicates that it is effectively able to restore the fundamental growth processes. Nevertheless, the most extensive improvements were determined in FYM treatment. It gave the highest values on root length (162% increase compared with saline control) and dry weight (7.3 g/plant) which was equal to the non-saline control. This can be explained by the fact that FYM is more stabilized and humified. FYM with a high degree of compost levels has greater proportions of stable humic substances that enhance the aggregation stability of soils and the establishment of a more favorable physical environment to allow continued root exploration (Tejada et al., 2006). Moreover, nutrient release was slower and more gradual in FYM which might have facilitated better sustained growth and proportionality of dry matter over the fresh cow manure which was more volatile. The values of SPAD were also in the same direction, with FYM registering the highest value (39.0) in saline treatments- 62.5% higher than the saline control. This means that it would preserve more of the chlorophyll content and photosynthetic ability, which is important in spinach since it is a leafy vegetable. The 13% gap between FYM and non-saline optimum indicates that, although FYM may significantly reduce salt stress, there may still be some level of ionic interference.

3.2. Soil Salinity (EC) and Mitigation of Integrated Stress.

The amendments had a different salinity reduction capacity killing capacity as measured by EC of soils after harvest period. The EC of over 4.0 dS/m was lowered to about 3.0 dS/m using Cow Manure and further to 2.5 dS/m using FYM. It is possible to explain this higher reduction by FYM by the following factors: 1) increased leaching as a result of improved soil structure and increased infiltration, 2) high exchange capacity of cations carried out by humified organic matter replacing Na^+ and 3) potential solubility of solids in soluble complex of salts and humic acids (Wong et al., 2009). This amelioration was a direct translation of this physical-chemical into visual plant health. Cow Manure treatment demonstrated moderate greening and less necrosis in plants compared to the FYM treatment where plants exhibited improved chlorophyll retention and less apparent salt injury which resembled normal non-saline control plants. The combined improvement where FYM had improved both below-ground (root length) and above-ground (biomass, chlorophyll) parameters and had best lowered the soil EC, shows the importance of FYM as an integrated soil amendment in saline soils. The outstanding root development response of both saline treatments especially compared with the non-saline control is worth paying attention to. This stress induced overcompensation may represent a compensatory

growth response under stress conditions in root exploration to reach patchy nutrient resources in the amended recovering saline soil- a phenomena that has been observed in other studies by using organic amendments under stress conditions (Rietz and Haynes, 2003).

3.3. Soil Health and Carbon Dynamics

The organic amendments also contributed to the improvement of the major pools of soil carbon and FYM had a better performance in all parameters (Figure 2). The saline control had a soil organic carbon (SOC) of 0.4, whereas the cow manure and FYM had 0.9 and 1.1 respectively (125 and 175 % increase). This is especially important because saline soils are characterized by low organic matter levels attributed to low levels of plant inputs and fast decomposition (Wong et al., 2009). The greater accumulation of SOC in FYM is a reflection of the more recalcitrant carbon fractions that were not mineralized easily, to promote longer-term carbon retention than the more reactive carbon in cow manure. The readily available fraction of carbon, dissolved organic carbon (DOC) was also higher in the presence of cow manure (1100 mg C kg⁻¹) and FYM (1230 mg C kg⁻¹) as compared to the saline control (540mg C kg⁻¹). This increased DOC pool has various roles: that of providing an instant source of energy to salt-stressed microbial communities, of chelating toxic ions, and of giving rise to stable humus (Jones & Willett, 2006). The increased DOC in the soil with FYM indicates the possibility of increased beneficial processes consequently contributing to the further growth of plants. The treatment gradient of microbial biomass carbon (MBC) was evident with lesser values of 650 mg C kg⁻¹ in the saline control, and 750 mg C kg⁻¹ in the cow manure and 940 mg C kg⁻¹ in the FYM. This 44.6% higher microbial biomass in the presence of FYM than in cow manure reflects the fact that the quality of carbon plays a significant role in the recovery of the microbial activity in saline soils. The mixture of FYM is probably helping to maintain a more varied and more robust microbial community that could be active and resilient to less favorable environments (Yan et al., 2022). The positive correlation between SOC, DOC, and MBC leads to the restoration of soil health: as the SOC increases, it enhances the soil structure; as the DOC increases, it stimulates the activity of soil microbes; and as the MBC increases, it stimulates the nutrient mineralization and enzyme synthesis.

3.4. Integrated Mechanisms and Practical Implications

The excellent performance of FYM can be explained by the fact that an integrated amelioration mechanism helps to deal with various salinity constraints at the same time. Its organic matter is humified physically and thus improves the structure of the soil, which increases water infiltration as well as leaching of salts (Sajjad et al., 2025). It is chemically active to give cation exchange sites and organic acids which chelate and replace toxic Na^+ ions. It also supports different microbial communities which increase nutrient cycling and generate growth promoting substances (Rietz and Haynes,

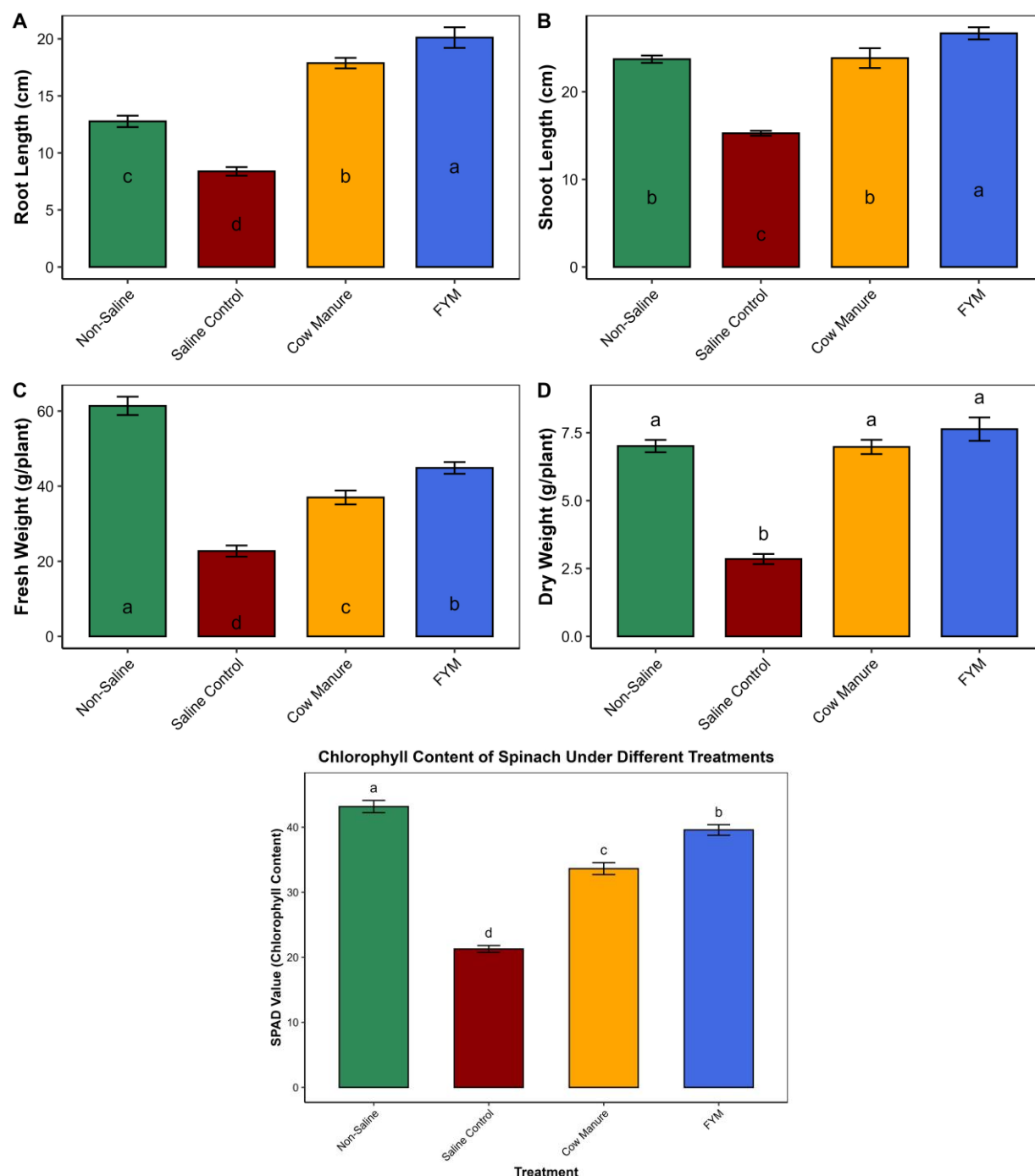


Figure 1: Effect of different soil treatments on growth parameters of spinach cultivated under saline conditions. Values represent means of experimental measurements for root length, shoot length, fresh weight, dry weight, and SPAD value across four treatment groups: Non-Saline control, Saline Control (no amendment), Cow Manure-amended saline soil, and FYM (Farmyard Manure)-amended saline soil.

2003). It is this complex treatment that resulted in plants treated with FYM showing a small amount of salt damage and equal growth parameters as non-salty conditions. The outstanding root development reaction in amended treatments- especially that of the surpassing over the non-

saline control- could be a compensatory reaction to stress. In order to acquire patchy nutrient resources in the recovering saline soil, plants probably put more resources into root exploration as a strategy to exploit the abiotic stress reported in other research on organic amendments. This would

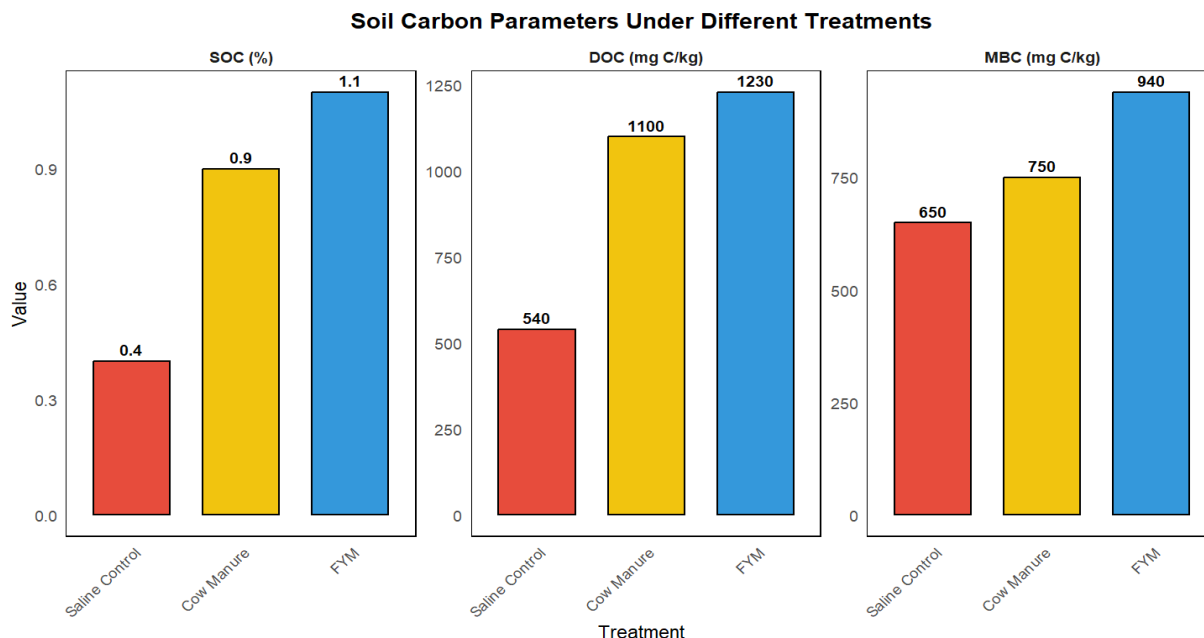


Figure 2: Soil carbon parameters under different organic amendment treatments in saline soil.

increase the root system to boost water and nutrient uptake and reinforce above-ground growth (Shakeel et al., 2021). In practical terms, the findings have significant implications to the management of saline soils. Although both amendments are positive, FYM proposes more sustainable changes as it has a stabilized carbon level. Cow manure gives faster returns to a situation needing immediate productivity increase in really saline soils, whereas in the long run, FYM is the best choice to enhance the health of the land and its stability. Amendment selection must be based on availability, cost, and management goals, but FYM is the more all-inclusive option as far as converting saline soils into efficient agricultural systems.

3.5 Enzyme Response to Salinity and Amendments

The activities of soil enzymes were highly sensitive to salinity stress as well as organic amendments (Table 3). Saline soil control exhibited extreme inhibition of all the enzymes, urease by 62.5 %, phosphatase by 40.9 %, β -glucosidase by 61.1 % and catalase by 71.4 % principally relative to non-saline conditions. This general inhibition fits into the known mechanisms of high salt levels denaturing the enzyme proteins and breaking the microbial communities that generate them (Rietz & Haynes, 2003). Organic amendments selectively recovered enzyme activities with Farmyard Manure (FYM) having better efficacy. The response of urease activity, which is important in the mineralization of nitrogen, in saline control (45 $\mu\text{g NH}_4\text{-N/g soil/h}$) was found compared to FYM (53.3% recovery to normal levels) salinity (69 $\mu\text{g NH}_4\text{-N/g soil/h}$). This improvement is especially remarkable to spinach, a nitrogen-sensitive leafy crop, because the better urease activity, the

better endows organic sources of nitrogen (Sajjad et al., 2024). Phosphatase activity demonstrated greatest recovery and FYM treatment reached the same level of (110 $\mu\text{g PNP/g soil/h}$) of phosphatase as was found under non-salty conditions. Even cow manure recorded 88 $\mu\text{g PNP/g soil/h}$, which is high (80) recovery. The resilience of this enzyme could be related to its role in cellulose breakdown and carbon cycling that are essential nutrients, the availability of which in saline soils is usually low because they are precipitated by magnesium and calcium ions (Yan et al., 2022). β -Glucosidase, a cellulose-breaking enzyme, involved in carbon cycling, showed an increase of up to 77.8% of normal activity in saline control and fertilized soil (35 $\mu\text{g PNP/g soil/h}$). This recovery justifies the noted gains on soil organic carbon pools by the fact that the biomass gains greater β -glucosidase activity to make organic amendments available to plants. FYM (3.4 $\mu\text{l O}_2\text{/g soil/min}$) recovered catalase activity which alleviates oxidative stress in soils remarkably, reaching 97.1% of normal activity. This close restoration suggests that the oxidative stress commonly caused by salinity has been mitigated, which produces a better environment to the microbial and plant root systems.

3.6. Mechanisms and Functional Implications

The pattern in the recovery of the enzymes shows significant information about the soil functional restoration. Phosphatase and catalase were nearly fully recovered by FYM which indicates that these enzymes are especially sensitive to the enhanced physicochemical environment (lower EC, enhanced aeration) and microbial stimulation offered by stabilized organic matter. Otherwise, urease and β -glucosidase improved significantly, but residual

suppression was evident, perhaps because they remained susceptible to ionic effects or because of certain inhibitory substances present in saline soils. It is possible to explain the high performance of FYM on cow manure by a number of factors: Higher content of humic substances that may help to protect enzymes against salt denaturation, More balanced release of nutrients which support a multitude of diverse microbial enzyme producers and Better physical enhancement of the soil that is ideal in enzyme activity (Dick, 1997). The fact that catalase recovery using FYM is almost full is of particular importance as it suggests that the cascade of oxidative stresses, which is a common symptom of salinity, is mitigated. These improvements are agronomic in nature. The urease activity is improved to provide greater nitrogen nutrition to the nitrogen-demanding spinach crop. Enhanced phosphatase leads to availability of phosphorus within a system where fixation of phosphorus is a common occurrence. The b-glucosidase recovery is a sign of improved carbon cycling of the organic amendments added. Taken collectively, these enzymatic positives form a self-enhancing cycle, in which improved nutrient supply enhances plant growth, which in turn provides more root exudates on which to sustain further microbial and enzyme activity. The patterns of recovery of the enzymes also interpret the growth responses of the plants. Improved nitrogen (urease), phosphorus (phosphatase), and carbon (β -glucosidase), as well as a reduced oxidative stress (catalase), result in the formation of the most favorable spinach growth in the soil that was formerly salty. Such a combination is a biological recuperation that is crucial in changing saline soils that are subjected to stress to productive agricultural systems.

3.7: Principal component analysis and heatmap correlation for the competing factors

Principal Component Analysis showed that there were specific patterns of variable contributions to treatment discrimination (Figure 3). Root Length and Shoot Length were the parameters that had the greatest contribution to the principal component, which identified the parameters as the most significant in differentiating between the saline soil treatments and amendments. The contribution of the soil carbon parameters - DOC and MBC were moderate and indicated that though the dynamics of the soil carbon parameters were responsive to the amendments, the pattern of variations were not as strong as the patterns of reaction to the amendments of the direct growth of plants. In the same manner, SOC showed quantifiable, but a comparatively lower contribution as compared to the morphological parameters. Enzyme activities were contributing differently with b-Glucosidase and Phosphatase having moderate contributions, which were important in carbon and phosphorus cycling in the amended conditions. Conversely, the Urease activity showed the least contribution of the enzymatic parameters implying that the processes of nitrogen mineralization were not as varied between treatments or had different response patterns. Parameters of plant biomass

(Fresh weight and Dry weight) and SPAD values (chlorophyll content) had an intermediate contribution and thus, though the parameters reacted to treatments, they did not resolve as much of the total variance as the linear growth measures (root and shoot length).

Figure 3 showed the hierarchy of variable contributions, which gave important information on the main processes of the mitigation of salinity through organic amendments. The contributions of Root Length and Shoot Length suggest that the strongest treatment effects are manifested in the visible morphological modifications and not in the little biochemical changes. This is biologically sensible, since the initial treatment effect of plants under salinity stress would be growth inhibition, and recovery of this inhibition would be the most apparent effect. The role of root parameters in salinity amelioration is so significant and speaks to the role of responses at the below-ground level. The improved root growth does not only enhance the uptake of water and nutrients but also causes a rhizodeposition that in turn facilitates the observed increases in the carbon pools in the soil and the activities of the microbes, a positive feedback loop that promotes the improvements observed in the purported enhancement of soil carbon pools and enzyme activities. The intermediate effects of soil carbon parameters (DOC, MBC, SOC) indicate that although organic amendments enhanced the soil health, it took place at a different time or quantity than the response of plant growth. The carbon pools in soils can be slower to respond to amendments or threshold processes may exist where early carbon input would result in huge plant response but with only moderate alterations in quantifiable fractions of soil carbon. Specific attention should be paid to the diverse work of enzyme activities. The comparatively greater contribution made by Phosphatase to Urease could be because of a difference in sensitivity to salinity or amendment effects. Phosphorus is commonly critically low in the saline soils, precipitated by the calcium and magnesium ions, and the phosphatase activity is specifically sensitive to the soil conditioning. Conversely, changes in nitrogen may not be directly affected by the amendments or they may have involved more complicated regulatory mechanisms. The analysis of the contribution has significant practical significance to salinity management and monitoring. It implies that: i) Simple growth indices (root and shoot length) are most efficient markers of treatment effectiveness, iii) Soil carbon parameters can all contribute valuable information on long-term soil health recovery and iv) Enzyme functions should be considered in the context of particular nutrient constraints and treatment goals. The overall perspective resulting in PCA contribution analysis will be used to determine the effectiveness of the treatment of saline soils.

3.8. Conceptual Framework and Integrated Mechanisms of Salinity Amelioration

Concurrent physical and chemical conditioning of the soil environment triggers the process of amelioration of

salinity stress on spinach using organic amendments. In the conceptual framework (Figure 4), cellular incorporation of

Table 3: Soil enzyme activities under different treatments

Enzyme	Normal Soil	Saline Control	Cow Manure	FYM
Urease ($\mu\text{g NH}_4\text{-N/g/h}$)	120 $\pm$ 10.2 a	45 $\pm$ 4.8 c	75 $\pm$ 6.5 b	95 $\pm$ 8.2 ab
Phosphatase ($\mu\text{g PNP/g/h}$)	110 $\pm$ 9.5 a	65 $\pm$ 6.2 c	88 $\pm$ 7.8 b	110 $\pm$ 9.3 a
β -Glucosidase ($\mu\text{g PNP/g/h}$)	90 $\pm$ 7.8 a	35 $\pm$ 3.5 c	55 $\pm$ 5.2 b	70 $\pm$ 6.4 ab
Catalase ($\mu\text{l O}_2\text{/g/min}$)	3.5 $\pm$ 0.3 a	1.0 $\pm$ 0.2 d	2.8 $\pm$ 0.25 b	3.4 $\pm$ 0.28 a

*Values are means $\pm$ SE. Different letters within rows indicate significant differences ($p < 0.05$).

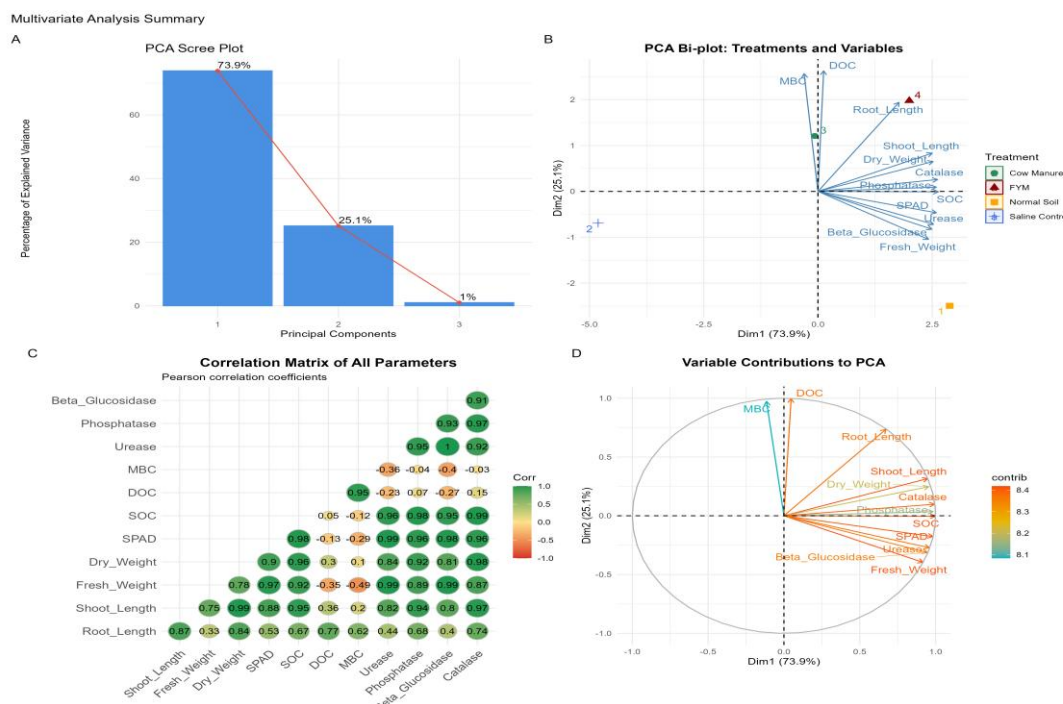


Figure 3. Variable contributions to Principal Component Analysis. Bar plot showing the relative percentage contribution of each measured parameter to the principal components derived from multivariate analysis. The height of each bar represents how much each variable contributes to explaining the variance in the dataset across all treatments.

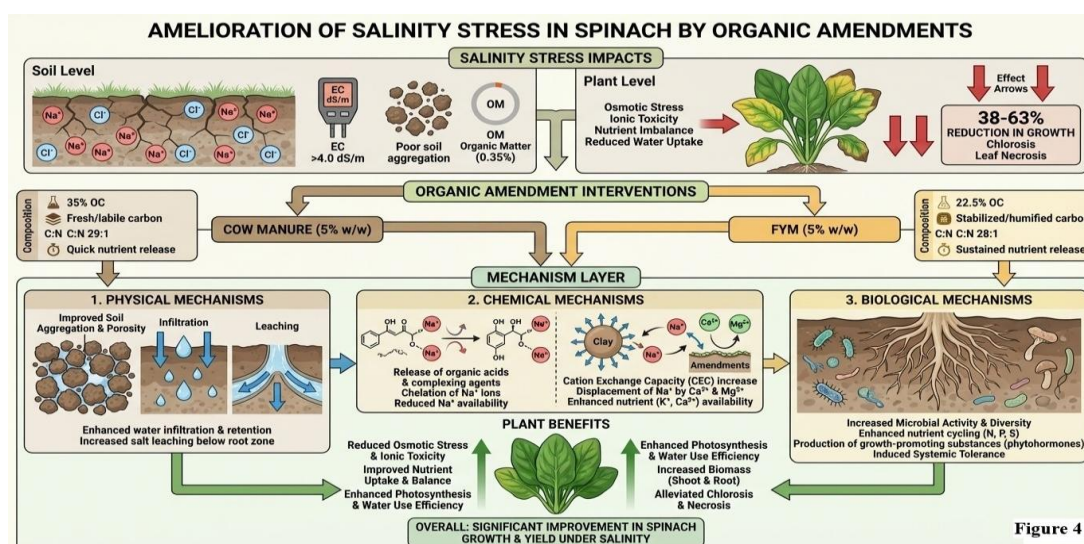


Figure 4. Conceptual framework of salinity mitigation through organic amendments. The diagram illustrates how farmyard manure (FYM) and cow manure physically, chemically, and biologically transform saline soil to restore spinach growth.

stabilized organic matter, especially that of Farmyard Manure (FYM), is basically a factor in improving soil structure through the increase of the aggregation and porosity. This rearrangement of physical structures directly enhances the water infiltration and retention. The most vital process that occurs in critical succession is leaching of soluble salts (Na^+ and Cl^-) below the root zone as depicted by the downward arrows in the mechanism layer. At the same time, a strong chemical process occurs: the liberation of organic acids and complexing agents of the decomposing amendments bonds the toxic Na^+ ions (Na^+). Moreover, the high increase in CEC offers additional locations to store the nutrient and displacing Na^+ with the helpful cations such as Ca^{2+} and Mg^{2+} . These physical-chemical interactions are synergistic to decrease the EC of rhizosphere, an environment that is stressful (>4.0 dS/m) to about the optimal levels and directly alleviate the major causes of osmotic stress and ionic toxicity at the plant root interface. This improvement in the principal habitat of the soil promotes a powerful biological recovery chain, with the re-establishment of the soil microbiome as its central focus. The organic carbon, either more labile with cow manure or more stable with FYM, is a valuable substrate, and it triggers an increase in microbial activity and diversity. There are several downstream benefits of this reinvigorated microbial community. First, it promotes the increased recycling of important nutrients, mineralizing them to be utilized by plants and correcting the nutrient imbalances caused by salinity. Secondly, some groups of microbes synthesize growth stimulant compounds like phytohormones, which may cause spinach plant systemic tolerance. The layer of biological mechanisms, thus, turns the soil into a physically enhanced media into an actively aiding and self-sustaining ecosystem. The coordination of these mechanisms at the soil level is reflected in extensive physiological recovery and plant level growth promotion. It has decreased osmotic stress and Na^+ toxicity, and hence the plant can divert its metabolic energy to growth rather than survival. The better absorption and equilibrium of nutrients directly energize the cellular processes and production of chlorophyll, which overturns chlorosis. This is followed by increased photosynthesis and water use efficiency because the plant is no longer fighting with water shortage and ionic interference in its process of metabolism. This overall recovery can be graphically illustrated in the difference between the reduced water uptake and nutrient imbalance in the presence of stress to the enhancement of nutrient uptake and balance and the increase of photosynthesis in the conditions of amelioration. The quality and longevity of the carbon input is the cause of the different efficacy between cow manure and FYM as revealed in the framework. The stimulus by cow manure, especially with its fresh, volatile carbon and rapid nutrient release, is a quick but perhaps temporary boosting of the recovery process, which, in essence, jump-starts the recovery process. Conversely, FYM, having balanced, humified, carbon and continuous nutrient release, guarantees the longevity and stability of all the three layers of mechanistic.

It creates stronger soil aggregates, offers a more sustainable source of carbon to the microbes, and offers a stable flow of chelating agents and nutrients. It causes a more holistic and lasting change in the saline soil system which finally results. In better and more reliable growth and yield results of spinach recorded in the study, thus completing the circle between plant performance as a result of a soil intervention.

4. Conclusion

This research shows conclusively that organic amendments and especially well-composted farmyard manure presents an effective and long-term measure of reclaiming saline soils and regaining spinach production. The harsh depressive impacts of the salinity including reduced growth, chlorophyll loss, and biomass were significantly overturned by the application of amendments. It is evident that FYM was better than cow manure in not only salvaging the growth of plants but also promoting a deeper and stronger restoration of soil health. The processes that support this superiority are complex. The stabilized, humified carbon fractions of FYM improve the soil structure and facilitate the infiltration of water and leaching of salt, as well as generates a slow nutrient and energy release pool to the microbial communities. This, in its own turn, is the bionic activity of the soil biochemical equipment, since the activity of enzyme functions that are essential to the cycle of nitrogen, phosphorus, and carbon is restored almost entirely. The study shows that reclamation is an integrated cascade, in which amendments enhance the physical and chemical soil conditions, and this increases the microbial activity and enzyme functioning which results in better mineralization and Availability of nutrients that generate plant growth and biomass. Most importantly, the multivariate analysis has identified that the parameters of visible plant growth are the most sensitive indices of the very first recovery to enable the farmers to have convenient monitoring instruments that are low-cost. Nevertheless, the simultaneous recovery of both the carbon pool and enzyme functions in soils is necessary to guarantee the stability of the system over the long-term and prevent the further outbreak of the salinity problems. Thus, although fresh cow manure may have some beneficial temporary effects, FYM is the better long-term investment towards accelerating the conversion of saline soils into continuously productive and biologically dynamic agricultural systems. The study confirms the application of locally available, composted organic soil as a key to sustainable soil management in salty-prone areas to improve food security and ecological sustainability by using the cyclical method of agriculture. The optimization of application protocols and the analysis of long-term field scale performance and economic sustainability of these amendments in a variety of different cropping systems and salinity gradients should be the subject of future work.

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11. Conflict of Interest

The authors declare no conflict of interest.

12. Authors' Contribution

Amina: Writing Original Draft; Zahid Rashid: Conceptualization and Supervision; Muhammad Rehan and Asima Rashid: Conducting Experiment and Visualizations; Aleena Pervaiz: Writing Reviews and Suggestions in Experiment.

13. SDGs Addressed

This study directly contributes to SDG 2 (Zero Hunger) and SDG 15 (Life on Land) by providing a sustainable soil management strategy that enhances crop productivity in degraded saline lands and promotes soil health restoration through organic waste recycling.

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