



Ameliorating Salinity and Water Deficit Stress in Spinach (*Spinacia oleracea* L.) through Farmyard Manure Application: Insights into Soil Reclamation and Physiological Resilience

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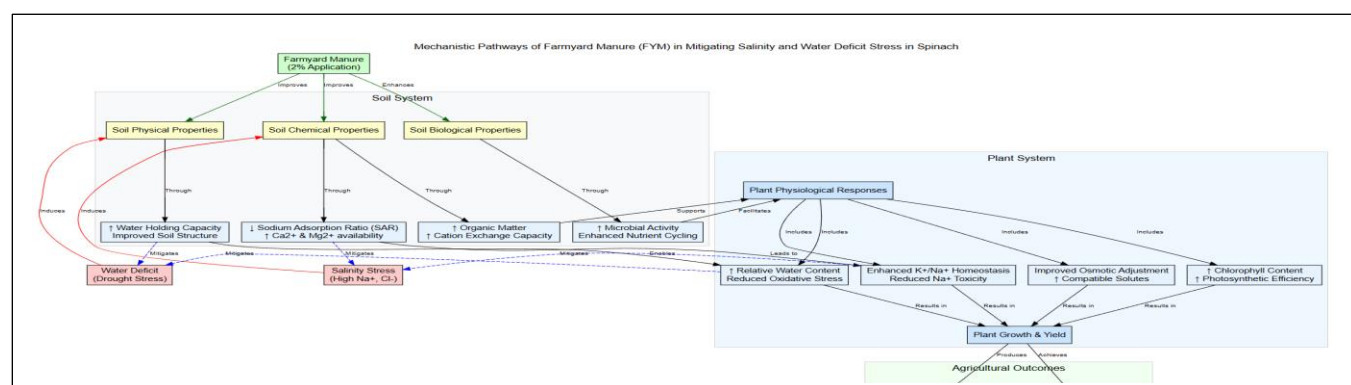
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Abstract

Soil salinity and water scarcity are critical constraints to global agriculture, threatening crop productivity. This study investigated the efficacy of farmyard manure (FYM) as an organic amendment to mitigate the combined effects of salinity ($EC_e \sim 4 \text{ dS m}^{-1}$) and water deficit on spinach (*Spinacia oleracea* L.). A pot experiment was conducted using a completely randomized design with three irrigation levels (100%, 75%, and 50% of water requirement) and two FYM rates (1% and 2% w/w). The results demonstrated that FYM application, particularly at 2%, significantly improved soil health by increasing organic matter content and reducing the sodium adsorption ratio (SAR) by up to 28% compared to the stressed control. These soil improvements translated into enhanced plant physiological performance: the 2% FYM treatment under full irrigation achieved the highest chlorophyll content (SPAD value of 62), relative water content (68.3%), and biomass yield. The amendment effectively buffered the impacts of water stress, with FYM-treated plants maintaining significantly better growth and water status even at 50% irrigation. The study concludes that FYM operates through dual mechanisms of soil reclamation—by improving nutrient availability and soil structure—and physiological enhancement—by promoting osmotic adjustment and ionic homeostasis. The application of 2% FYM is recommended as a sustainable strategy for cultivating spinach in salt-affected and water-deficient environments, enhancing resilience and productivity.



Graphical Abstract

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1. Introduction

Spinach (*Spinacia oleracea* L.) is a significant leafy vegetable belonging to the Chenopodiaceae family, renowned for its high concentration of bioactive compounds, vitamins (A, C, and folate), and essential minerals (iron, calcium) (Shahid et al., 2018). Its nutritional profile confers numerous human health benefits, including enhanced blood glucose management, improved bone health, and a reduced risk of degenerative diseases such as cardiovascular conditions, cataracts, and certain cancers. The global demand for spinach is rising, driven by its convenience as a pre-packaged, health-promoting food. However, its productivity and nutritional quality are highly susceptible to pre- and post-harvest factors, particularly abiotic stresses like soil salinity and water scarcity (Jafari et al., 2024).

Soil salinity is a critical environmental constraint to global agriculture, affecting over 20% of cultivated land worldwide. In Pakistan, approximately 20% of the total cultivable land is salt-affected, posing a severe threat to food security. Saline and saline-sodic soils are characterized by high levels of soluble salts and exchangeable sodium, which degrade soil structure, reduce hydraulic conductivity and aeration, and are typically low in organic matter. This leads to physiological drought, nutrient imbalances—particularly calcium deficiency—and oxidative stress in plants, ultimately suppressing growth and yield. Concurrently, water scarcity, exacerbated by climate change and inefficient irrigation practices, presents another major challenge. Deficit irrigation, while a strategy for water conservation, imposes significant water stress that disrupts biochemical and physiological processes in crops, further limiting productivity (Becker et al., 2017; Flowers & Colmer, 2008; Gorji, Tanik, & Sertel, 2015).

The reclamation of these problematic soils is imperative for sustainable agriculture. Traditional approaches involve chemical amendments to replace exchangeable sodium with calcium. However, the integration of organic amendments offers a sustainable strategy to improve soil health and enhance crop resilience. Amendments such as farmyard manure, compost, and biochar can ameliorate the adverse effects of salinity and drought by enhancing soil organic carbon, improving soil structure and water retention, increasing nutrient availability, and stimulating beneficial microbial activity. Specifically, biochar has shown promise in reducing the exchangeable sodium percentage and improving the soil's physicochemical environment. Similarly, vermicompost, a nutrient-rich bio-fertilizer produced through the bio-oxidation of organic waste by earthworms, can replenish soil organic matter and essential nutrients, which are critically low in most agricultural soils of Pakistan (Kafi & Rahimi, 2011; Li, Ge, Xie, Li, & Tan, 2022; Luján-Facundo et al., 2018; Qadeer, Wakeel, Cheema,

& Sanaullah, 2022; Singh, Hariprasanna, & Chaudhari, 2016).

Given the high susceptibility of spinach to abiotic stresses and the critical need to maintain its productivity and nutritional quality under challenging conditions, this study aims to investigate the efficacy of various organic amendments in mitigating the combined stresses of soil salinity and water deficit on spinach cultivation. The central hypothesis is that the application of organic amendments will improve soil health by increasing organic matter, enhancing nutrient availability, and improving soil physical properties, thereby alleviating the detrimental effects of salinity and water stress on spinach growth, yield, and physiological performance (Jafari et al., 2024; Qadeer et al., 2022).

The objectives of this study are to evaluate the effects of different organic amendments on the growth, yield, and physiological parameters of spinach cultivated under salt-affected and water-deficient conditions, and to assess the subsequent changes in key soil physicochemical properties, including organic carbon, salinity, sodicity, and nutrient status. The hypothesis guiding this research is that the application of organic amendments will significantly improve soil health by increasing organic matter content and enhancing nutrient availability, which will in turn mitigate the adverse impacts of salinity and water deficit, leading to improved growth, yield, and physiological resilience in spinach.

2. Materials and Methods

2.1 Experimental Site and Plant Material

A pot experiment was conducted in a wire house at the Institute of Soil & Environmental Sciences (ISES), University of Agriculture Faisalabad (UAF). Spinach (*Spinacia oleracea* L.) seeds were procured from the Ayub Agriculture Research Institute, Faisalabad.

2.2 Soil Collection, Preparation, and Initial Characterization

Soil was collected from the soil science farm at UAF. It was air-dried, crushed, and passed through a 2-mm sieve. A representative sub-sample was analyzed for key physicochemical properties, which are presented in Table 1. The soil was classified as loam with slight salinity.

2.3 Experimental Design and Treatments

The experiment was laid out in a Completely Randomized Design (CRD) with three replications. Each pot was filled with 6 kg of processed soil. Soil salinity was artificially induced to a target level of 4 dS m⁻¹ EC and an SAR of 14 using a calculated amount of salts. After a 10-day incubation period, farmyard manure (FYM) was incorporated as an organic amendment.

Table 1. Pre-experiment physicochemical characteristics of the soil.

Characteristics	Units	Values
pH	-	7.45
Electrical Conductivity (EC)	dS m ⁻¹	1.98
Cation Exchange Capacity (CEC)	cmolc kg ⁻¹	14.2
Organic Matter	%	0.55
Texture	-	Loam
Saturation Percentage	%	30.1
Sodium Adsorption Ratio (SAR)	(mmol L ⁻¹) ^{0.5}	4.19

The treatments consisted of a factorial combination of three irrigation levels and two FYM rates, plus three control treatments: Full Irrigation (100% water requirement), Deficit Irrigation (¾ or 3/4 of water requirement), Severe Deficit Irrigation (½ or 1/2 of water requirement), Farmyard Manure (1% or 2% by soil weight). The nine treatments were: T1 (Full irrigation + 1% FYM), T2 (Full irrigation + 2% FYM), T3 (Severe deficit + 1% FYM), T4 (Severe deficit + 2% FYM), T5 (Deficit irrigation + 1% FYM), T6 (Deficit irrigation + 2% FYM), Control 1 (Full irrigation, no FYM), Control 2 (Severe deficit, no FYM), and Control 3 (Deficit irrigation, no FYM).

2.4 Crop Cultivation and Harvesting

Five to six spinach seeds were sown per pot in November 2021. The crop received two harvests: the first after 60 days of growth, and the second two months after the first harvest. Data were collected at various stages throughout the plant's development.

2.5 Data Collection

2.5.1 Soil Analysis

Post-harvest soil samples were analyzed for: pH of Saturated Paste was determined using a glass electrode pH meter. Electrical Conductivity (ECe) was Measured in the saturation extract using a conductivity meter. Organic Matter (OM) determined by the Walkley-Black chromic acid wet oxidation method. Sodium Adsorption Ratio (SAR) was Calculated from the concentrations of Na⁺, Ca²⁺, and Mg²⁺ in the saturation extract.

2.5.2 Plant Growth Parameters

At each harvest, the following were recorded: Plant height and root length (using a standard scale). Shoot and root fresh weight (immediately after harvesting). Shoot and root dry weight (after oven-drying at 60°C to constant weight).

2.5.3 Plant Physiological Parameters

Chlorophyll Content was measured in fresh leaves using a Minolta SPAD-502 meter. Relative Water Content (RWC) was determined using the formula: RWC (%) = [(Fresh Weight - Dry Weight) / (Turgid Weight - Dry Weight)] × 100.

2.6 Statistical Analysis

All collected 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 5% probability level. Variation in the data is presented as the standard error of the mean.

3. Results

3.1 Chlorophyll Content (SPAD Value) at First Harvest

The chlorophyll content of spinach, as indicated by SPAD meter readings, was significantly influenced by the interactive effects of irrigation regimes and farmyard manure (FYM) application under saline conditions (Figure 1a). The highest chlorophyll content (SPAD value of 62) was recorded in treatment T2, which received full irrigation and 2% FYM. This demonstrates that the synergistic effect of adequate water and a higher dose of organic amendment effectively

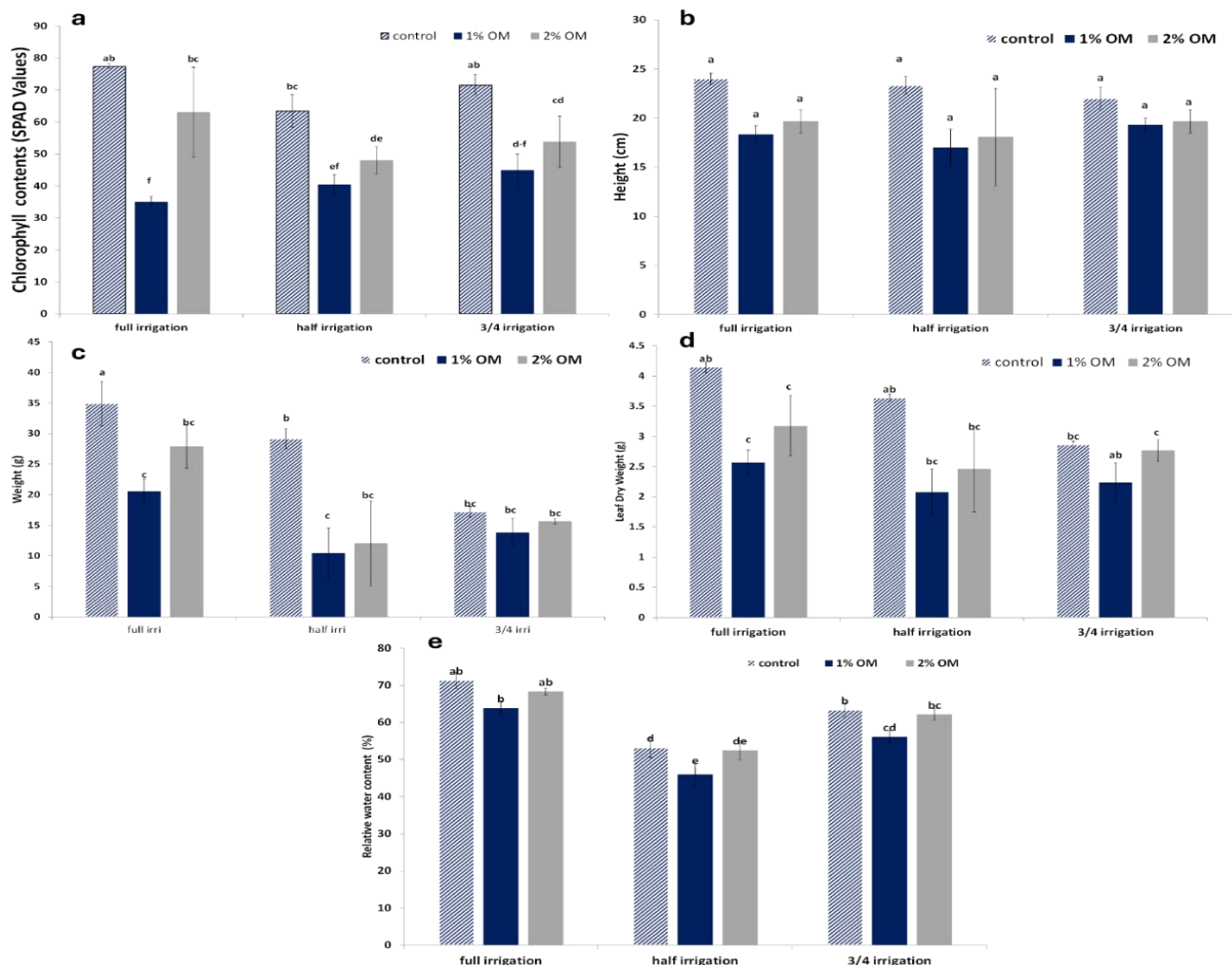


Figure 1: 1st harvest data recorded for chlorophyll contents, fresh and dry weight, height and relative water contents. (n=3) and different letters showed different levels of statistical significance.

mitigated salinity stress, promoting robust chlorophyll synthesis. In contrast, the combination of severe water deficit (half irrigation) and the lower FYM rate (1%) in treatment T3 resulted in the minimum SPAD value of 38. This represents a 39% reduction compared to T2, highlighting the severe physiological stress imposed by combined salinity and drought.

A clear dose-dependent response to FYM was observed. At every irrigation level, the application of 2% FYM resulted in significantly higher chlorophyll content compared to the 1% application. For instance, under full irrigation, the 2% FYM treatment (T2) maintained a SPAD value comparable to the non-saline, fully irrigated control (T7), whereas the 1% FYM treatment (T1) showed a notable decrease. This suggests that the higher organic matter input improved nutrient availability, particularly nitrogen, which is a fundamental building block of chlorophyll molecules, and potentially enhanced the plant's osmotic adjustment capacity.

Furthermore, chlorophyll content exhibited a progressive decline with increasing water stress across all FYM levels. The results indicate that while FYM amendment alleviated salt stress, its efficacy in preserving chlorophyll was constrained by the severity of water deficit. The superior performance of the 2% FYM treatment across all stress levels can be attributed to improved soil moisture retention and a more favorable rhizosphere environment, facilitating better photosynthetic performance.

3.2 Plant Growth Parameters at First Harvest

3.2.1 Plant Height and Biomass

The growth and biomass accumulation of spinach were profoundly affected by the main and interactive effects of water stress and FYM amendment (Figures 1b,c,d).

Consistent with the chlorophyll data, the maximum plant height (28 cm), fresh weight (28 g pot⁻¹), and dry weight (3.17 g pot⁻¹) were all recorded in treatment T2 (full irrigation

+ 2% FYM). This treatment combination created optimal conditions for cell expansion, division, and biomass partitioning. Conversely, the most stressed treatment, T3 (half irrigation + 1% FYM), exhibited the minimum values for plant height (16.9 cm), fresh weight (10.45 g pot⁻¹), and dry weight (2.07 g pot⁻¹). The fresh weight in T3 was 63% lower than in T2, underscoring the devastating impact of combined abiotic stresses.

The application of FYM, particularly at the 2% rate, consistently ameliorated the adverse effects of salinity and water stress on growth. Plants receiving 2% FYM demonstrated greater height and biomass than their 1% counterparts at equivalent irrigation levels. This growth promotion is likely due to multiple factors: FYM improves soil structure, enhancing root proliferation and water infiltration; it supplies essential macro and micronutrients; and it fosters beneficial microbial activity that can improve plant health and nutrient cycling.

The significant reduction in all growth parameters under water deficit conditions is a classic response to drought stress, which impairs turgor pressure, reduces photosynthetic rates, and accelerates senescence. The fact that FYM amendment partially offset these reductions, especially at the 2% rate, confirms its role in improving the plant's water relations and overall resilience.

3.2.2 Leaf Relative Water Content (RWC) at First Harvest

The relative water content (RWC) of spinach leaves, a key indicator of plant water status, was significantly impacted by the treatments (e). The highest RWC (68.3%) was observed in treatment T2 (full irrigation + 2% FYM), while the lowest value (46.0%) was found in T3 (half irrigation + 1% FYM). This 33% reduction in RWC under severe stress clearly illustrates the inability of plants in T3 to maintain tissue hydration.

The results demonstrate a positive correlation between FYM application and leaf RWC. At each level of water stress, the plots amended with 2% FYM maintained a higher RWC than those with 1% FYM or no amendment. This can be directly linked to the soil-amending properties of FYM. By increasing the soil's organic matter content, FYM enhances its water-holding capacity, allowing more water to be retained in the root zone and available for plant uptake during periods of deficit irrigation. Consequently, plants in FYM-amended soils experienced less severe water stress, as reflected in their higher tissue water content. This improved water status is fundamental to maintaining physiological processes such as photosynthesis and growth, as confirmed by the parallel trends in chlorophyll content and biomass data.

3.3 Plant Physiological and Growth Parameters (2nd Harvest)

The mitigating effect of farmyard manure (FYM) on spinach under combined salinity and water deficit stress remained pronounced at the second harvest, though a general decline in plant vigor was observed compared to the first harvest. Chlorophyll content (SPAD value) continued to be significantly influenced by the treatments. The maximum value (31.3) was maintained in the T2 treatment (full irrigation + 2% FYM), while the minimum (23.46) was again recorded in T3 (half irrigation + 1% FYM) (Figure 2).

This represents a 25% reduction in the most stressed treatment, confirming the sustained role of FYM in supporting photosynthetic machinery under prolonged stress. The overall lower SPAD values across all treatments at the second harvest suggest a cumulative stress effect or natural leaf aging. A similar trend was observed for shoot biomass. The highest leaf fresh weight (20.36 g pot⁻¹) and dry weight (6.18 g pot⁻¹) were recorded in T2. In contrast, the most stressed treatment (T3) showed the lowest values, with a fresh weight of 14.0 g pot⁻¹ and a dry weight of 1.65 g pot⁻¹. Notably, plant height was not significantly affected at the second harvest, with a maximum mean value of 19.22 cm in T2. This indicates that while biomass accumulation was sensitive to the treatments, the vertical growth had largely stabilized after the first harvest. The application of FYM significantly improved root architecture under stress conditions. The maximum root length (33.3 cm), fresh weight (14.5 g), and dry weight (4.1 g) were all observed in the T2 treatment. The 2% FYM application consistently promoted better root growth than the 1% rate across all irrigation levels. This enhanced root system is critical for exploiting a larger soil volume for water and nutrient uptake, which is a key mechanism for coping with salinity and drought. The poorest root development was found in T3, with values of 20 cm, 9.8 g, and 1.7 g for length, fresh, and dry weight, respectively. The plant's water status, as indicated by RWC, mirrored the trends from the first harvest. Treatment T2 maintained the highest RWC (68.3%), while T3 showed the lowest (49.6%). This demonstrates that the improved soil moisture retention from the 2% FYM amendment continued to benefit the plant's hydration status over time, even under deficit irrigation. The results from both harvests consistently demonstrate that the co-application of FYM, particularly at a 2% rate, effectively mitigates the adverse effects of combined salinity and water stress on spinach. The enhancement in chlorophyll content, biomass, root development, and tissue water status can be attributed to the multifaceted benefits of FYM. These include improved soil physical structure, enhanced water and nutrient retention, and a gradual release of essential nutrients. The superior performance of the 2%

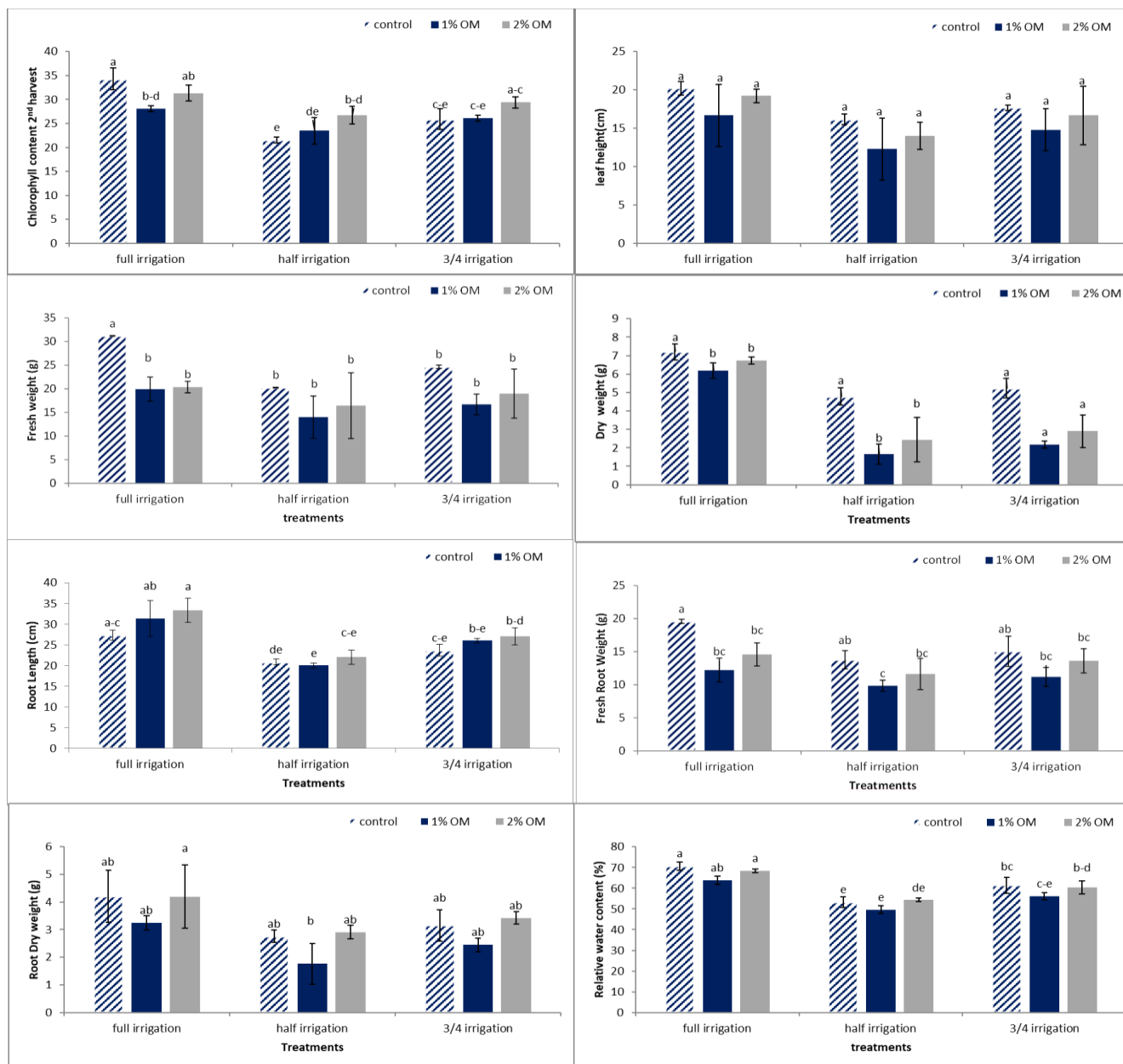


Figure 2: 1st harvest data recorded for chlorophyll contents, fresh and dry weight, root length, fresh weight and dry weight and relative water contents. (n=3) and different letters showed different levels of statistical significance.

FYM dose highlights a clear dose-response relationship, suggesting that a higher input of organic matter is necessary to significantly counter the severe osmotic and ionic stresses. The progressive decline in some metrics at the second harvest underscores the cumulative nature of these abiotic stresses, yet the FYM-amended plants consistently outperformed the non-amended controls, affirming the value of this management practice for sustainable crop production in degraded soils.

3.4 Comparative Analysis of First and Second Harvests and Underlying Causes

A comparative analysis of the two harvests reveals a clear trend of declining plant vigor and productivity over time, underscoring the cumulative nature of combined salinity and water deficit stress. However, the efficacy of farmyard manure (FYM) as a mitigating amendment remained consistent throughout the growing period.

3.4.1 Observed Differences Between Harvests

The most pronounced difference was a general reduction in measured parameters from the first to the second harvest, particularly in above-ground biomass and chlorophyll content. For instance, the maximum chlorophyll content

(SPAD value) dropped from 62 in the first harvest to 31.3 in the second, representing a nearly 50% decrease in the highest-performing treatment (T2). Similarly, the maximum leaf fresh weight declined from 28 g pot⁻¹ to 20.36 g pot⁻¹. In contrast, the maximum leaf *dry* weight in the best treatment (T2) increased from 3.17 g pot⁻¹ in the first harvest to 6.18 g pot⁻¹ in the second. Furthermore, root development metrics (length, fresh, and dry weight) were notably strong in the second harvest, indicating a shift in resource allocation within the plant.

3.4.2 Probable Reasons for the Observed Differences

a larger and deeper root system is a survival strategy to explore a greater soil volume for water and scarce nutrients. This explains the robust root development recorded in the second harvest. The increase in leaf *dry* weight, despite a decrease in fresh weight, indicates a higher accumulation of structural carbohydrates and possibly osmolytes, further supporting the idea of a shift towards stress tolerance rather than rapid expansion. Spinach is a short-duration crop. The period between the first and second harvest coincides with the plant's natural progression towards maturity and senescence. Abiotic stresses significantly accelerate this process. The sharp decline in chlorophyll content is a classic

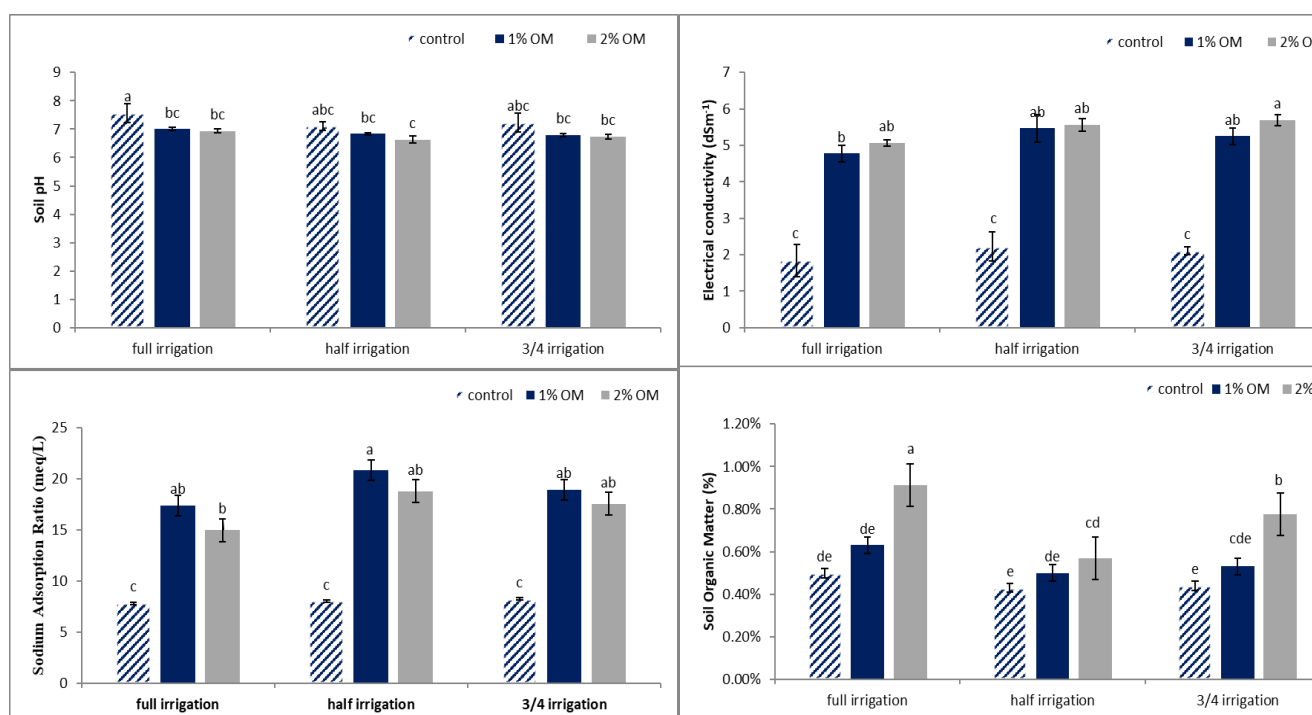


Figure 3: Soil physicochemical attributes recorded after the experiment.

The decline in chlorophyll and fresh biomass, coupled with an increase in root investment and leaf dry matter, can be attributed to the following interconnected factors: salinity and water deficit impose both osmotic and ionic stress. Over time, the continuous struggle to maintain osmotic balance and exclude or compartmentalize toxic ions (like Na⁺ and Cl⁻) consumes a significant amount of the plant's energy. This chronic energy drain reduces the resources available for new growth, leading to the observed decline in fresh yield and chlorophyll, which is often degraded under stress. The data suggest a strategic shift in the plant's resource allocation, known as assimilate partitioning. Faced with persistent stress from the soil environment (salinity and limited water), the plant prioritizes root growth over shoot growth. Investing in

symptom of stress-induced senescence, where nutrients are remobilized from older leaves to younger tissues or storage organs. In a pot culture under deficit irrigation, there is a high likelihood of secondary salinization. Evaporation and insufficient leaching can cause salts to accumulate in the rooting zone over time. The stress from this increasing salt concentration would be more acute during the second growth cycle, further suppressing growth and accelerating physiological decline.

The differences between the harvests highlight a transition from a growth-oriented phase (first harvest) to a resilience-oriented phase (second harvest). While FYM amendment consistently alleviated stress, evidenced by treated plants outperforming controls at every stage, it could

not fully override the cumulative physiological costs of prolonged exposure to salinity and drought. The plant's response—reduced shoot growth, chlorophyll degradation, and enhanced root investment—is a coherent adaptive strategy to a deteriorating soil environment.

3.5 Post-Harvest Soil Chemical Properties

The application of farmyard manure (FYM) and varying irrigation levels significantly influenced the chemical properties of the soil after the cultivation period, revealing important trends in soil reclamation and stress dynamics (Figure 3).

3.5.1 Soil pH and Electrical Conductivity (EC)

While statistical analysis indicated that treatments did not induce drastic, overall significant changes in soil pH, a clear and consistent trend of acidification was observed in amended pots. The soil pH decreased from its initial level of 7.45, with the most pronounced effect found in the T2 treatment (full irrigation + 2% FYM), which recorded a pH of 6.93. A further slight reduction to pH 6.8 was observed under the most severe stress combination (T3: half irrigation + 1% FYM). This subtle acidification can be attributed to the release of organic acids and carbon dioxide during the decomposition of FYM, which helps in mobilizing essential nutrients in alkaline-saline soils.

In contrast, soil EC exhibited a concerning trend of increase. The highest EC value (5.4 dS m^{-1}) was recorded in the T3 treatment (half irrigation + 1% FYM), surpassing the initial artificial salinity level. This was closely followed by the T2 treatment (5.0 dS m^{-1}). This increase is directly linked to the deficit irrigation regimes, which provided insufficient water to leach salts below the root zone. Consequently, evaporation and plant water uptake concentrated salts in the soil profile. The non-saline control treatments (T7, T8, T9) maintained a low EC, ranging from 1.8 to 2.1 dS m^{-1} , confirming that the observed high EC in other pots was a result of the induced salinity and irrigation management.

3.5.2 Sodium Adsorption Ratio (SAR) and Organic Matter

The Sodium Adsorption Ratio (SAR), a critical indicator of sodicity, was significantly affected by the treatments. The application of FYM was effective in reducing SAR, with a clear dose-response effect. The lowest SAR value (14.9) was achieved with the 2% FYM application under full irrigation (T2). In contrast, the combination of severe water deficit and the lower FYM rate (T3) resulted in the highest SAR value of 20.8. The reduction in SAR with FYM amendment is likely due to the provision of calcium and magnesium, which compete with sodium for exchange sites on soil colloids, and the enhanced leaching of sodium in the presence of organic matter, though this was limited by water deficit.

As expected, soil organic matter (OM) content was significantly increased by the addition of FYM. The maximum OM content (0.91%) was found in the T2

treatment (full irrigation + 2% FYM), a substantial increase from the initial value of 0.55%. The minimum value (0.50%) was observed in the most stressed treatment (T3), indicating that the beneficial effect of the amendment was constrained under severe water deficit, potentially due to reduced microbial activity. Control pots without amendments showed the lowest OM levels, confirming FYM as the primary source of the increase.

3.5.3 Integrated Discussion of Soil and Plant Responses

The post-harvest soil data provide a mechanistic explanation for the observed plant growth patterns. The combination of full irrigation and 2% FYM (T2) created the most favorable soil environment by moderately lowering pH, significantly increasing organic matter, and most importantly, effectively reducing the sodicity hazard (SAR) despite a higher EC. This improved soil physical and chemical environment facilitated better plant growth, as seen in T2's superior performance in chlorophyll content, biomass, and water status.

Conversely, the poor plant performance in the T3 treatment (half irrigation + 1% FYM) is directly linked to the severely degraded soil conditions: the highest EC and SAR, and the lowest OM content among amended soils. This created a dual stress of high osmotic pressure and poor soil structure, severely restricting root function and nutrient uptake. The data conclusively show that while FYM is beneficial, its ability to reclaim saline-sodic soil and support crop growth is highly dependent on adequate irrigation water to facilitate the leaching of displaced sodium salts.

4. Discussion

The results of this study demonstrate that the application of farmyard manure (FYM) is an effective strategy for mitigating the adverse effects of combined salinity and water deficit stress on spinach, primarily by improving key soil chemical properties and enhancing plant physiological resilience. Our findings align with and are strongly supported by a body of existing research.

The significant improvement in plant growth parameters—including chlorophyll content, biomass, and relative water content—in FYM-amended treatments, particularly at the 2% rate, can be directly linked to the amendment's role in improving soil health. The observed increase in soil organic matter (OM) is a cornerstone of this improvement. As noted by Laxminarayana (2022), organic amendments serve as a substrate for soil microbes, enhancing microbial activity that is typically suppressed in saline soils also supported by Yadav et al. (2025). This revitalized biological activity is crucial for nutrient cycling. Furthermore, the addition of FYM directly introduced essential nutrients, consistent with the findings of (Abou El-Magd, Zaki, & Abou-Hussein, 2008), who reported that organic manure improved the uptake of N, P, and K and enhanced the K/Na ratio in plants under stress, a critical factor for maintaining ionic homeostasis.

A key finding of this study was the significant reduction in the Sodium Adsorption Ratio (SAR) in FYM-amended soils. This reclamation effect is well-documented. Similar to the results of (Muhammad & Hussain, 2010), the FYM likely provided soluble calcium (Ca^{2+}) and magnesium (Mg^{2+}), which displaced exchangeable sodium (Na^+) from soil colloids. The subsequent leaching of this displaced Na^+ , though limited by water deficit, was facilitated by the improved soil physical structure. This process is vital for reducing the specific ion toxicity and soil dispersion associated with high sodicity (Ondrasek et al., 2022). The more pronounced effect of the 2% FYM rate underscores a clear dose-dependent response in soil reclamation efficiency. The mitigation of water stress by FYM, as evidenced by higher leaf relative water content (RWC) in amended pots, can be attributed to the amendment's profound impact on soil physical properties. Organic matter enhances soil aggregation, pore space, and water-holding capacity (WHC) (Rehana & Kini, 2008). This creates a reservoir of plant-available water, buffering the effects of deficit irrigation. Our results corroborate with Ejaz et al. (2022), who found that drought stress significantly reduced RWC, but amendments can help prevent wilting. The superior performance of the 2% FYM treatment confirms that a higher organic input leads to greater water retention, directly translating to improved plant water status and sustained growth under drought conditions.

4.1 Underlying Mechanisms of Stress Mitigation

The synergistic mitigation of salinity and drought stress by FYM can be explained through several interconnected physiological and soil-mediated mechanisms: FYM decomposition releases organic acids and facilitates the production of compatible solutes (e.g., proline, glycine betaine) in plants. These solutes lower the osmotic potential within plant cells, helping to maintain turgor pressure and water uptake from the soil despite the low external water potential caused by salinity and drought (Hichem et al., 2009). A critical mechanism for salt tolerance is the maintenance of a high K^+/Na^+ ratio in the cytoplasm. FYM improves the availability of potassium (K^+) in the soil. Plants can then selectively uptake K^+ over the toxic Na^+ , a process facilitated by membrane transporters. The improved K^+ nutrition, as reported by (Zaki and Radwan, 2011), is essential for enzyme activation, stomatal regulation, and overall cellular function, counteracting the disruptive effects of Na^+ . The addition of FYM alters the rhizosphere environment, boosting the population and activity of beneficial microorganisms. These microbes can produce exopolysaccharides that bind soil particles, improving aggregation and stability. Furthermore, certain rhizobacteria can produce plant growth-promoting hormones (e.g., auxins, cytokinins) and ACC-deaminase, an enzyme that reduces

ethylene levels in plants under stress, thereby preventing stress-induced senescence (Etesami & Noori, 2019). As supported by (Tejada et al., 2008), the increase in OM reduces soil bulk density and enhances porosity. This improved soil aeration is crucial for root respiration, especially in waterlogged saline soils, and allows for better root penetration, enabling the plant to explore a larger soil volume for water and nutrients.

The integration of FYM, particularly at a 2% application rate, serves as a sustainable soil management practice. It addresses the core limitations of saline-sodic and water-deficient soils by simultaneously lowering SAR, increasing OM and nutrient availability, enhancing soil water retention, and triggering key plant defense mechanisms. This multi-faceted approach makes it a highly effective strategy for securing spinach productivity in marginal environments.

5. Conclusion and Future Perspectives

This study conclusively demonstrates that the application of farmyard manure (FYM) is a highly effective strategy for mitigating the combined detrimental effects of salinity and water deficit stress on spinach cultivation. The integration of FYM, particularly at a 2% rate, significantly improved soil health by increasing organic matter content, reducing the sodium adsorption ratio (SAR), and moderately acidifying the soil, thereby enhancing nutrient availability. These soil amendments translated directly into superior plant performance, as evidenced by increased chlorophyll synthesis, greater biomass production (in both shoots and roots), and improved leaf relative water content.

The research clearly establishes a dose-dependent response, with the 2% FYM application consistently outperforming the 1% rate across all measured parameters. Furthermore, while deficit irrigation inevitably constrained plant growth and led to salt accumulation in the soil, the co-application of FYM substantially buffered these negative impacts. The most favorable outcomes were achieved under full irrigation with 2% FYM, but even under water-scarce conditions, FYM proved vital in maintaining plant physiological functions and yield. Therefore, the use of organic amendments like FYM presents a sustainable and accessible approach for reclaiming salt-affected soils and enhancing crop resilience, ensuring productivity in increasingly challenging agricultural environments.

While this study provides strong evidence for the benefits of FYM, several avenues for future research can build upon these findings to optimize and scale this practice: Pot experiments provide controlled insights, but long-term field trials are crucial to validate these results under real-world conditions. Research should focus on the multi-seasonal impact of FYM on soil carbon sequestration, the evolution of soil microbial communities, and the potential for

reducing the need for inorganic fertilizers. Future work should compare the efficacy of FYM with other organic and inorganic amendments, such as biochar, compost, gypsum, and their integrated combinations. Understanding the synergistic effects of these materials could lead to more potent and cost-effective reclamation strategies. Deeper investigation into the physiological and molecular mechanisms is warranted. This includes profiling the expression of stress-responsive genes (e.g., those involved in ion transport, such as NHX and SOS1, and osmolyte biosynthesis), antioxidant enzyme activity, and hormonal regulation in plants grown in FYM-amended, stressed soils. Given the critical role of irrigation, future studies should focus on developing precise deficit irrigation schedules (e.g., regulated deficit irrigation or partial root-zone drying) specifically tailored for use with organic amendments. This will help in creating water-saving protocols that minimize yield penalties. A comprehensive socioeconomic analysis is needed to evaluate the cost-benefit ratio and scalability of using high rates of FYM for smallholder farmers. Additionally, a lifecycle assessment would be valuable to understand the environmental footprint of sourcing and applying organic amendments on a large scale. By exploring these future perspectives, the scientific community can develop more robust, precise, and sustainable agronomic packages to ensure food security in the face of expanding soil salinity and water scarcity.

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8. Authors Contribution:

Noor Fatima: Investigations, Data Curation and Visualization, Writing Original Draft; Muhammad Tahir Shehzad, Amina Rashid: Revisions and Supervision; Hamna Bashir: Writing reviews and corrections.

9. Conflict of Interest:

Authors declare no conflict of interest.

10. Sustainable Development Goals

This study supports SDG 2 (Zero Hunger) and SDG 12 (Responsible Consumption and Production).

10. References:

Abou El-Magd, M., Zaki, M., & Abou-Hussein, S. (2008). Effect of organic manure and different levels of saline irrigation water on growth, green yield and chemical content of sweet fennel. *Australian Journal of basic and applied sciences*, 2(1), 90-98.

Becker, V. I., Goessling, J. W., Duarte, B., Caçador, I., Liu, F., Rosenqvist, E., & Jacobsen, S.-E. (2017).

Combined effects of soil salinity and high temperature on photosynthesis and growth of quinoa plants (*Chenopodium quinoa*). *Functional Plant Biology*, 44(7), 665-678.

- Ejaz, M. K., Aurangzaib, M., Iqbal, R., Shahzaman, M., Habib-ur-Rahman, M., El-Sharnouby, M., . . . Ogbaga, C. C. (2022). The use of soil conditioners to ensure a sustainable wheat yield under water deficit conditions by enhancing the physiological and antioxidant potentials. *Land*, 11(3), 368.
- Flowers, T. J., & Colmer, T. D. (2008). Salinity tolerance in halophytes. *New Phytologist*, 945-963.
- Gorji, T., Tanik, A., & Sertel, E. (2015). Soil salinity prediction, monitoring and mapping using modern technologies. *Procedia Earth and Planetary Science*, 15, 507-512.
- Jafari, A., rasoli, f., Behtash, F., Mosavi, S. B. M., Ferdowsi Qebchaq, P., & Asadi, M. (2024). Evaluation of different concentrations of Fe and Zn in nutrient solution on yield, biochemical, and nutrient content of spinach in soilless conditions. *Journal of Vegetables Sciences*, 8(15), 183-200. doi:10.22034/iuvs.2023.2010676.1316
- Kafi, M., & Rahimi, Z. (2011). Effect of salinity and silicon on root characteristics, growth, water status, proline content and ion accumulation of purslane (*Portulaca oleracea* L.). *Soil Science and Plant Nutrition*, 57(2), 341-347.
- Laxminarayana, K. (2022). Effect of Organic and Inorganic Fertilization on Soil Enzyme Activities in Relation to Yield and Proximate Composition of Colocasia (*Colocasia esculenta* L) in Alfisols of Eastern India. *Communications in Soil Science and Plant Analysis*, 53(19), 2635-2651.
- Li, Y.-L., Ge, Z.-M., Xie, L.-N., Li, S.-H., & Tan, L.-S. (2022). Effects of waterlogging and salinity increase on CO₂ efflux in soil from coastal marshes. *Applied Soil Ecology*, 170, 104268.
- Luján-Facundo, M. J., Fernández-Navarro, J., Alonso-Molina, J. L., Amorós-Muñoz, I., Moreno, Y., Mendoza-Roca, J. A., & Pastor-Alcañiz, L. (2018). The role of salinity on the changes of the biomass characteristics and on the performance of an OMBR treating tannery wastewater. *Water Research*, 142, 129-137. doi:<https://doi.org/10.1016/j.watres.2018.05.046>
- Muhammad, Z., & Hussain, F. (2010). Effect of NaCl salinity on the germination and seedling growth of some medicinal plants. *Pak. J. Bot*, 42(2), 889-897.
- Ondrasek, G., Rathod, S., Manohara, K. K., Gireesh, C., Anantha, M. S., Sakhare, A. S., . . . Raihan, F. (2022). Salt stress in plants and mitigation approaches. *Plants*, 11(6), 717.
- Qadeer, A., Wakeel, A., Cheema, S. A., & Sanaullah, M. (2022). Interactive effects of salinity and drought stresses on soil respiration and microbial activities.

- Pakistan Journal of Agricultural Sciences*, 59(1), 35-42.
- Rehana, S., & Kini, R. M. (2008). Complement C3 isoforms in *Austrelaps superbus*. *Toxicon*, 51(5), 864-881.
- Shahid, M., Dumat, C., Khalid, S., Rabbani, F., Farooq, A. B. U., Amjad, M., . . . Niazi, N. K. (2018). Foliar uptake of arsenic nanoparticles by spinach: an assessment of physiological and human health risk implications. *Environmental Science and Pollution Research*, 1-11.
- Singh, A., Hariprasanna, K., & Chaudhari, V. (2016). Differential nutrients absorption an important tool for screening and identification of soil salinity tolerant peanut genotypes. *Indian Journal of Plant Physiology*, 21(1), 83-92.
- Yadav, A. P., Gudadhe, S., Kumari, S., Shukla, R., Tripathi, M., & Shukla, A. K. (2025). Impact of heavy metals assessments on the physiological aspects of spinach plant (*Spinacia oleracea* L.).

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