



Effects of Fenton-modified compost on photosynthetic pigments and growth indices of rosemary (*Rosmarinus officinalis* L.) under salinity stress

Sarah Hammadi^a, Siros Sadeghi^a, Esmaeil Karimi^a, Seyed Bahman Mousavi^a, Farzad Rasoli^b

^aUniversity of Maragheh, Faculty of Agriculture, Department of Soil Science and Engineering.

^bAssociate Professor, University of Maragheh, Faculty of Agriculture, Department of Horticultural Science and Engineering.

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ABSTRACT

Corresponding Author:
Marjan Nouri
sirossadeghi@gmail.com

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Soil salinity, through imposing osmotic stress and disturbing nutrient uptake, is one of the major constraints limiting agricultural productivity in arid and semi-arid regions. This study aimed to evaluate the effectiveness of compost enriched with Fenton-pretreated sawdust in alleviating salinity stress and improving photosynthetic capacity and growth performance of rosemary (*Rosmarinus officinalis* L.), a medicinal plant. It should be noted that the Fenton oxidation was applied exclusively to the sawdust fraction, not to the entire manure compost. A factorial experiment was conducted in a completely randomized design under greenhouse conditions, including three salinity levels (0, 4, and 8 dS m⁻¹) and four fertilization treatments (no fertilizer, conventional compost, sawdust-enriched compost, and 4% compost containing Fenton-pretreated sawdust), each with three replications. The results revealed that severe salinity (8 dS m⁻¹) significantly reduced leaf fresh and dry weights, total biomass, number of lateral branches, and plant height. However, application of the Fenton-pretreated sawdust compost markedly mitigated these adverse effects, leading to remarkable increases in leaf dry weight, total biomass, number of lateral branches, and plant height by 215%, 214%, 250%, and 116%, respectively, compared with the unfertilized control under severe salinity. Moreover, this treatment significantly enhanced chlorophyll a, chlorophyll b, and carotenoid contents. The improved photosynthetic performance explained the enhanced biomass accumulation and lateral branch development, indicating that reinforcement of photosynthetic capacity was the key driver of growth promotion. Notably, plant performance under severe salinity with the Fenton-pretreated sawdust compost even exceeded that of conventional and mixed composts under non-saline conditions, highlighting its superior qualitative efficiency. Therefore, compost enriched with Fenton-oxidized sawdust can be proposed as an innovative management strategy to enhance photosynthetic capacity and support the economic cultivation of medicinal plants in saline and low-fertility soils.

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1. Introduction

Soil salinity is one of the most important and devastating environmental stresses that seriously threatens global food security and the sustainability of agricultural production systems (FAO, 2023). More than 20% of the world's cultivated lands are affected by salinity, and this proportion is expected to increase due to climate change and improper water resource management (Singh, 2022). This issue is particularly critical in arid and semi-arid regions such as Iran, where water scarcity is already a major constraint. Estimates indicate that over 30% of Iran's agricultural lands are exposed to different levels of salinity, and this challenge is clearly evident in key

agricultural plains such as Maragheh, Qazvin, and Mashhad (Qureshi et al., 2008). In addition to reducing soil fertility, salinity leads to biodiversity loss, soil structural degradation, and substantial declines in crop productivity and economic returns (Machado & Serralheiro, 2017).

Furthermore, salinity constrains plant growth and productivity through several mechanisms, including the induction of osmotic stress, ion toxicity caused by excessive accumulation of sodium and chloride, disruption of nutrient uptake, and stimulation of oxidative stress (Munns & Tester, 2008). One of the major consequences of these processes is the reduction of



photosynthetic capacity due to decreased chlorophyll and carotenoid contents, which directly explains biomass reduction and poor growth performance (Walker et al., 2018). In Iran, the low quality of irrigation water and improper irrigation management further intensify these adverse effects (Ritzema et al., 2008). The continuous expansion of saline lands not only restricts crop cultivation but also poses serious challenges to the livelihoods of many farmers.

Similarly, previous studies reported that salinity stress reduces chlorophyll content, transpiration rate, relative water content, water-holding capacity, and K, Ca, and Mg concentrations in soybean leaves and stems. However, the application of water hyacinth compost and rice husk biochar alleviated the detrimental effects of salinity on soybean performance (Ferdous et al., 2018).

In response to this challenge, developing sustainable strategies for rehabilitating saline soils and enhancing plant photosynthetic capacity has become a research priority. In recent years, the application of organic amendments, particularly compost, has gained considerable attention due to their richness in organic matter and essential nutrients, thereby improving the physical, chemical, and biological properties of soil (Leogrande & Vitti, 2019). Compost improves plant growth by enhancing soil aggregation stability, increasing cation exchange capacity (CEC), and improving water-holding capacity (Diacono & Montemurro, 2010). The use of innovative composts as soil conditioners has been reported to significantly alleviate the adverse impacts of drought stress in sugar beet production, while the combination of deficit irrigation and compost application maximizes crop water productivity (Abd El-Mageed et al., 2019). Studies have also indicated that compost application can improve the hydraulic conductivity of saline soils by up to 35%, thereby increasing soil infiltration (Scotti et al., 2015).

The findings of Kamal et al. (2024) demonstrated that the application of compost derived from livestock manure combined with biochar and mineral fertilizers decreased H_2O_2 levels while increasing leaf relative water content (RWC), leaf proline, total soluble sugars, and ascorbic acid in tomato plants. Furthermore, it reduced membrane damage compared with untreated plants under salinity stress conditions.

Despite these advantages, one of the major challenges associated with compost use is the variability in its quality and the relatively low content of biologically active humic compounds in conventional composts. This highlights the need to develop advanced technologies to enhance compost quality (Qu et al., 2025). In this regard, the Fenton process, as an advanced oxidation technology, has shown high potential in degrading complex organic compounds and accelerating humification processes (Wang et al., 2022). Collaborative mechanisms indicate

that Fenton-like factors contribute to bulk waste decomposition and stimulate microbial community evolution during composting (Cai et al., 2024). The generation of strong hydroxyl radicals ($\bullet OH$) in this process breaks down lignocellulosic structures and provides precursors for the formation of highly bioactive humic substances (Jiao et al., 2024). Preliminary studies have revealed that the incorporation of Fenton-pretreated sawdust into compost can increase humic acid content by up to 60% and shorten compost maturation time (Zhang et al., 2023). It should be emphasized that in these studies, the Fenton oxidation was applied specifically to the lignocellulosic fraction (e.g., sawdust) rather than to the entire compost matrix.

Humic acid, as the most active fraction of organic matter, enhances plant tolerance to salinity through chelation of toxic ions and stimulation of growth hormone synthesis (Canellas et al., 2015). It has also been reported that humic acid increases the activity of antioxidant enzymes such as catalase and peroxidase by up to 40% and enhances proline accumulation under salinity stress (Garcia et al., 2020). Moreover, humic substances can increase chlorophyll and carotenoid contents, thereby improving photosynthetic capacity and biomass production (Lichtenthaler, 1987).

Multiple studies have reported the positive effects of organic amendments on plants subjected to salinity stress. Norouzi et al. (2021) demonstrated that compost application in saline soils significantly increased dry weight and leaf area in medicinal plants. At the international level, Nadeem et al. (2019) also confirmed the beneficial effects of bio stimulants in improving yield and essential oil quality of medicinal plants under salinity conditions. Moreover, Guo et al. (2023) reported that the combined application of compost and humic acid can increase potassium uptake by up to 25% while reducing sodium uptake by up to 34%.

Although numerous studies have investigated the general effects of compost and humic acid, limited research has directly evaluated compost containing Fenton-pretreated sawdust and its influence on photosynthetic responses and growth performance of medicinal plants under salinity stress.

Rosemary, due to its high economic value, relative tolerance to drought and salinity, and sensitivity to photosynthetic reductions, serves as an appropriate model plant for such evaluation (Zingaretti et al., 2018). It is hypothesized that this type of compost (enriched with Fenton-oxidized sawdust) may enhance plant photosynthetic capacity by increasing chlorophyll and carotenoid contents, ultimately improving growth and biomass accumulation.

Accordingly, the main question of this study is whether compost containing Fenton-pretreated sawdust can more effectively improve growth indices and photosynthetic

capacity of rosemary under salinity stress compared with conventional composts. Therefore, the objective of this research was to investigate the effects of compost amended with Fenton-oxidized sawdust and compare its efficiency with commonly used composts in mitigating salinity stress and enhancing growth and photosynthetic traits of rosemary.

2. Materials and Methods

This experiment was conducted for 60 days in 2023 in the research greenhouses of the University of Maragheh, located in East Azerbaijan Province, Iran (46°16' E and 37°23' N). To ensure optimal growth conditions, greenhouse environmental parameters were continuously monitored and adjusted. Daytime and nighttime temperatures were maintained at 25 ± 2 °C and 18 ± 2 °C, respectively, while relative humidity was controlled between 60% and 70%.

The soil used in this study was collected from the 0–30 cm depth of the University of Maragheh research farm. Its physicochemical properties are presented in Table 1. After sampling, the soil was air-dried, passed through a 5-mm sieve, and subsequently used for preparing the experimental treatments.

Table 1. Physicochemical properties of the soil used in the study

Soil Texture	Sand (%)	Silt (%)	Clay (%)	EC (dS/m)	pH	OM (%)	T.N.V (%)
Clay Loam	42	34	24	0.8	7.3	0.9	12.5
N	P	K	Fe	Zn	Mn	Cu	
0.06	8.5	180	4.2	0.8	5.5	1.1	

The base organic material used for compost production consisted of a mixture of solid sheep manure (obtained from Varjovi village in Maragheh) and sawdust (collected from local carpentry workshops in Maragheh). Three types of organic compost with different compositions were prepared for use in the experiment: Conventional compost (C1): This treatment was considered the organic control and was produced solely from pure sheep manure without any additives. Mixed compost (C2): To provide a richer organic substrate, this treatment consisted of 75% (w/w) sheep manure and 25% (w/w) raw sawdust. Fenton-modified compost (C3): Representing the innovative component of this study, this treatment was produced through an advanced two-stage process. In the first stage, raw sawdust was subjected to the Fenton process to modify its lignocellulosic structure. For this purpose, sawdust was exposed to a solution containing hydrogen peroxide (H₂O₂) as the oxidizing agent and ferrous sulfate (FeSO₄) as the catalyst. The reaction was carried out under controlled acidic conditions (pH ≈ 3)

for 2 hours with continuous stirring to maximize the generation of hydroxyl radicals (•OH). These radicals degraded the resistant lignin and hemicellulose bonds, breaking down the rigid structure of sawdust and preparing it for subsequent composting. At the end of the reaction, the modified sawdust was thoroughly washed and dried. In the second stage, it was mixed with 75% (w/w) pure sheep manure, similar to treatment C2, and the composting process was initiated. All compost piles (C1, C2, and C3) were maintained for three months under strictly controlled conditions in terms of temperature (maintained within the optimal range of 45–55 °C), moisture (50–60%), and aeration (regular turning every 10 days). These conditions ensured complete biological activity, resulting in mature and stabilized compost free from odor, pathogens, and weed seeds. The experiment was conducted in a factorial arrangement based on a completely randomized design (CRD) with three replicates. Experimental factors included salinity at three levels: 0, 4, and 8 dS m⁻¹, prepared using NaCl and CaCl₂ salts at a molar ratio of 1:1. Salinity treatments were imposed three weeks after plant establishment and gradually applied through irrigation water over a one-week period. Fertilizer treatments consisted of four levels: no fertilizer (control), C1, C2, and C3. The prepared composts were mixed with the main soil at a rate of 4% (w/w). Rosemary (*Rosmarinus officinalis* L.) seedlings (~15 cm height) were obtained from a commercial nursery in Urmia, Iran. Upon arrival, they were acclimatized to greenhouse conditions (25 ± 2 °C, 60–70% RH) for two weeks. After acclimatization, uniform seedlings were transplanted into 5-kg plastic pots containing the experimental substrates. At the end of the growth period, growth parameters including fresh and dry leaf weight, total biomass, number of lateral branches, and plant height were recorded. For determining dry weight, samples were dried in an oven at 70 °C for 48 hours. The number of lateral branches was measured by counting all secondary shoots, and plant height was recorded using a ruler. Photosynthetic pigments including chlorophyll a, chlorophyll b, and carotenoids were quantified using standard spectrophotometric procedures. For this purpose, 0.1 g of fully expanded young leaves from each treatment was homogenized using a porcelain mortar in the presence of 10 mL of 80% acetone and a small amount of quartz powder. Extraction was repeated until the leaf residues became completely colorless. The extract was transferred to centrifuge tubes and centrifuged for 10 minutes at 5000 rpm. The absorbance of the obtained supernatant was measured at 663, 645, and 470 nm using a UV–Vis spectrophotometer (UV-1800, Shimadzu, Japan). Pigment contents were

calculated using the standard Lichtenthaler equations and expressed as mg g⁻¹ leaf fresh weight.

- $Chlorophyll\ a_{(mg/g)} = [(12.7 \times A_{663}) - (2.69 \times A_{645})] \times (V / (1000 \times W))$
- $Chlorophyll\ b_{(mg/g)} = [(22.9 \times A_{645}) - (4.68 \times A_{663})] \times (V / (1000 \times W))$
- $Chlorophyll\ Total = Chlorophyll\ a + Chlorophyll\ b$
- $Carotenoids_{(mg/g)} = [(1000 \times A_{470}) - (1.82 \times Chl\ a) - (85.02 \times Chl\ b)] / 198$

In these equations, V represents the final volume of the extract (mL), W is the fresh weight of the leaf sample (g), and A denotes the absorbance at the specified wavelength.

The obtained data were subjected to analysis of variance (ANOVA) using MSTAT-C software (version 1.2), and mean comparisons were performed using Duncan's multiple range test at a 5% significance level. Graphical representations of the results were prepared using Microsoft Excel.

3. Results

Based on the analysis of variance (Table 2), all growth parameters of rosemary, including fresh leaf weight, dry leaf weight, total biomass, branch number, and plant height, were significantly affected by salinity treatments, compost application, and their interaction. Salinity exhibited a highly significant effect ($p \leq 0.01$) on all measured traits, indicating the considerable sensitivity of rosemary to salt stress. Similarly, compost treatments independently had a significant effect ($p \leq 0.01$) on all growth parameters, highlighting the mitigating role of compost in alleviating stress effects.

The data indicated that the interaction between salinity levels and compost type was highly significant ($p \leq 0.01$) for all measured growth parameters (Table 2).

Based on the results of this study, salinity stress had a pronounced inhibitory effect on rosemary growth. Increasing salinity from moderate (4 dS·m⁻¹) to high levels (8 dS·m⁻¹) intensified the percentage reduction in all growth parameters. For instance, fresh leaf weight decreased by 16.6% under moderate salinity and 31.8% under high salinity, while dry leaf weight decreased by 23.5% and 39.7%, respectively, compared to non-saline conditions (Figure 1).

Application of compost treatments significantly improved rosemary growth parameters under both non-saline and saline conditions. For fresh leaf weight, the addition of compost types C1, C2, and C3 increased growth by 46.2%, 73.1%, and 90.6% under non-saline conditions; 52.7%, 99.1%, and 114.0% under moderate salinity; and 62.5%, 107.2%, and 142.1% under high salinity, respectively. Regarding dry leaf weight, these

treatments resulted in increases of 58.8%, 100.0%, and 132.4% under non-saline conditions; 71.1%, 136.5%, and 178.8% under moderate salinity; and 78.0%, 146.3%, and 214.6% under high salinity, respectively (Figure 1). These results indicate that compost application effectively mitigates the adverse effects of salinity stress on rosemary growth, with higher levels of compost providing greater growth enhancement under increasing salinity conditions.

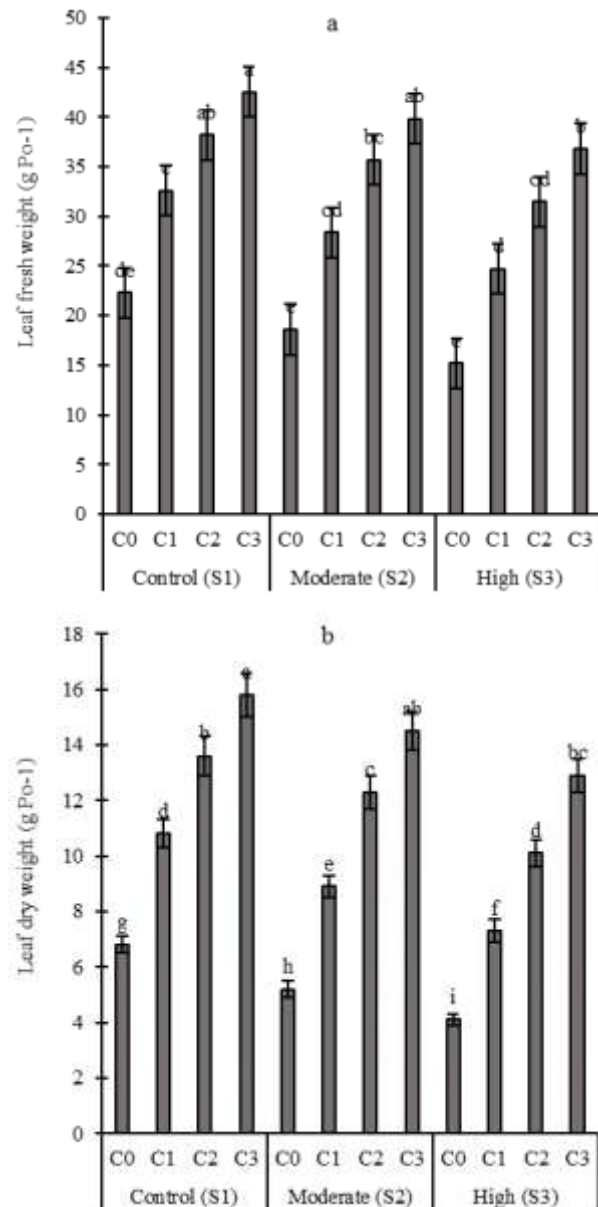


Fig 1. Mean values ($\pm$ SE) of leaf fresh (a) and dry (b) weight of *Rosmarinus officinalis* L. as affected by salinity levels and compost treatments. Different lowercase letters indicate significant differences among treatments according to Duncan's multiple range test ($p < 0.05$). Abbreviations: S1, S2, S3 = salinity levels (0, 4, 8 dS·m⁻¹); C0= Unamended soil (0% compost) C1, C2, C3=compost formulations (C1: 100% sheep manure compost, C2: Compost blend of 75% sheep manure+25% sawdust, C3: Compost blend of 72% sheep manure+25% Fenton-processed sawdust).

Total fresh plant weight decreased by 16.3% under moderate salinity and 31.5% under high salinity, while

total dry plant weight decreased by 23.0% and 39.5%, respectively, compared to non-saline conditions. Conversely, application of compost treatments significantly improved rosemary growth parameters under both non-saline and saline conditions.

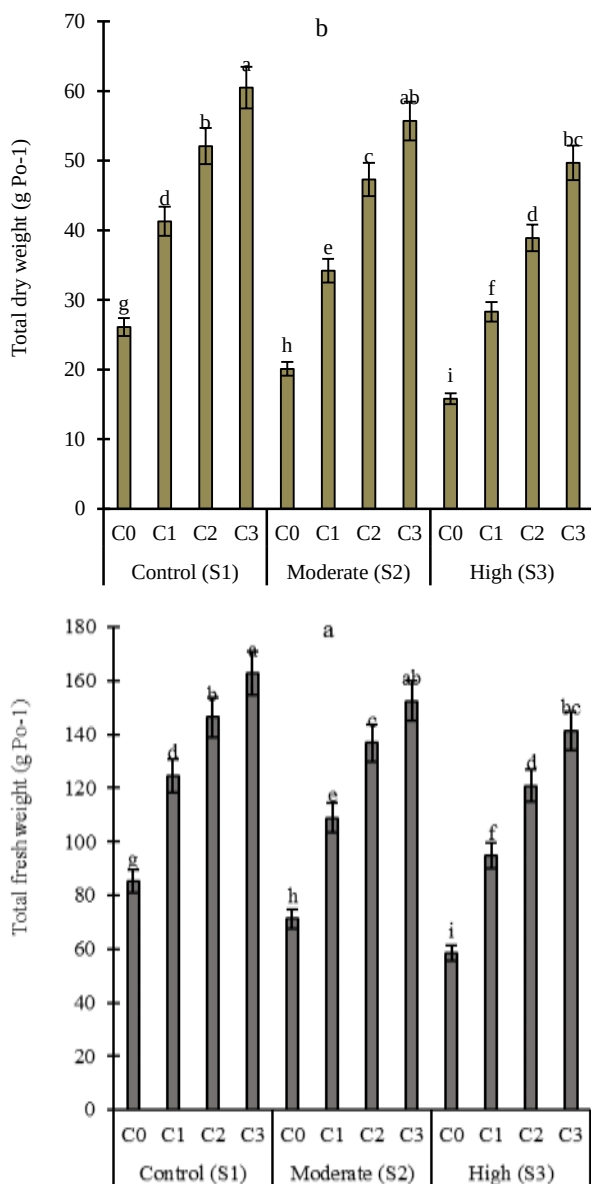


Fig 2. Mean values (±SE) of total fresh (a) and dry (b) weight of *Rosmarinus officinalis* L. as affected by salinity levels and compost treatments. Different lowercase letters indicate significant differences among treatments according to Duncan's multiple range test ($p < 0.05$). Abbreviations: S1, S2, S3=salinity levels (0, 4, 8 dS/m); C0=Unamended soil (0% compost) C1, C2, C3=compost treatments (C1: 100% sheep manure compost, C2: Compost blend of 75% sheep manure+25% sawdust, C3: Compost blend of 72% sheep manure+25% Fenton-processed sawdust).

For total fresh plant weight, the addition of compost types C1, C2, and C3 increased growth by 46.4%, 71.7%, and 91.1% under non-saline conditions; 52.7%, 91.9%, and 113.9% under moderate salinity; and 62.2%, 106.8%, and 142.0% under high salinity, respectively. Regarding total dry plant weight, these treatments resulted in increases of

58.2%, 99.6%, and 131.8% under non-saline conditions; 70.1%, 135.3%, and 177.1% under moderate salinity; and 79.1%, 146.2%, and 214.6% under high salinity, respectively (Figure 2).

These findings indicate that compost application effectively enhances rosemary growth across all salinity levels, with higher compost doses providing greater mitigation of salinity-induced growth reductions.

According to Figure 3, in the unfertilized control treatment (C0), increasing salinity from 0 to 4 and 8 dS m^{-1} resulted in a numerical decrease in lateral branch number from 1.0 to 0.83 and 0.67 (equivalent to 16.7% and 33.3% reductions, respectively), although these differences were not statistically significant as indicated by the shared letter (f) among the S0C0, S1C0, and S2C0 bars. In contrast, plant height in the same C0 treatment showed significant reductions from 25 cm (S0C0) to 22 cm (S1C0) and 20 cm (S2C0), corresponding to 12.5% and 21.9% decreases, respectively, and these differences were statistically significant based on the distinct letters (i, h, and g) in Figure 3.

Conversely, compost application significantly enhanced these traits across all salinity levels. For lateral branch number, the addition of compost types C1, C2, and C3 increased growth by 100.0%, 166.7%, and 200.0% under non-saline conditions; 100.0%, 180.0%, and 220.0% under moderate salinity; and 100.0%, 200.0%, and 250.0% under high salinity, respectively. Regarding plant height, these treatments resulted in increases of 50.0%, 81.3%, and 103.1% under non-saline conditions; 50.0%, 85.7%, and 114.3% under moderate salinity; and 52.0%, 84.0%, and 116.0% under high salinity, respectively.

This improvement pattern clearly demonstrates the mitigating role of compost in reducing the negative effects of salinity stress. Notably, the application of compost C3 under high salinity increased lateral branch number and plant height to 14 branches and 54 cm, respectively, surpassing even the non-saline, non-compost control (Figure 3).

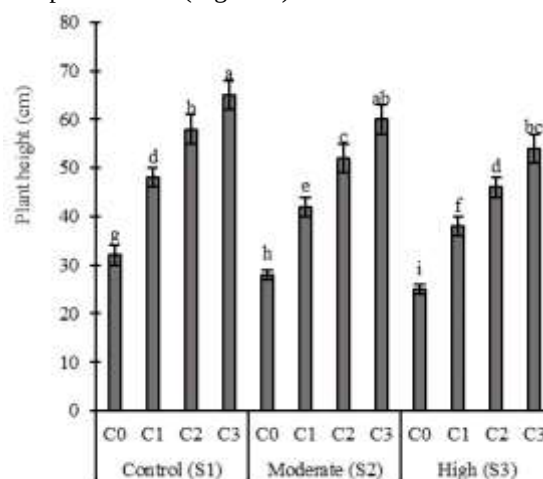


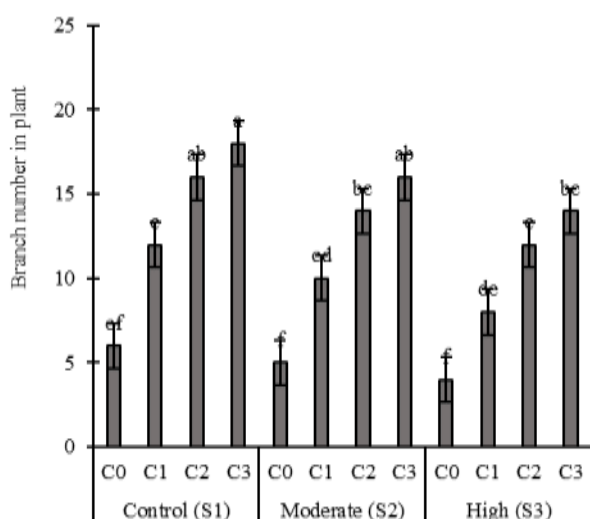
Table 2. Analysis of variance (ANOVA) for the main and interaction effects of salinity and compost treatments on rosemary growth parameters

Source of variation	Degrees of Freedom (df)	Mean Squares (MS)				
		Fresh leaf weight	Dry leaf weight	Total biomass	Number of branches	Plant height
Salinity	2	2.185**	4.62**	7.842**	3.48**	8.364**
Compost	3	7.98**	1.35**	6.521**	6.32**	3.245**
Salinity × Compost	6	4.12*	8.4*	3.68*	2.5*	7.42*
Error	24	1.2	7.0	5.9	9.0	2.7
(CV)(%)		7.85	2.98	9.71	4.11	6.12

* and ** indicate significance at the 5% and 1% probability levels, respectively.

Table 3. Analysis of variance (ANOVA) for the main and interaction effects of salinity and compost treatments on the photosynthetic pigments of rosemary

Source of variation	Degrees of Freedom (df)	Mean Squares (MS)			
		كلروفيل كل Chlorophyll Total	كلروفيل a Chlorophyll a	كلروفيل b Chlorophyll b	كاروتينويدها Carotenoids
Salinity	2	1,250,000 **	1,000,000 **	400,000 **	75,000 **
Compost	3	400,000 **	500,000 **	200,000 **	33,333 **
Salinity × Compost	6	100,000 **	100,000 **	40,000 **	10,000 *
Error	24	14,583	12,500	8,000	2,500
(CV)(%)		7.6	7.1	10	11.2

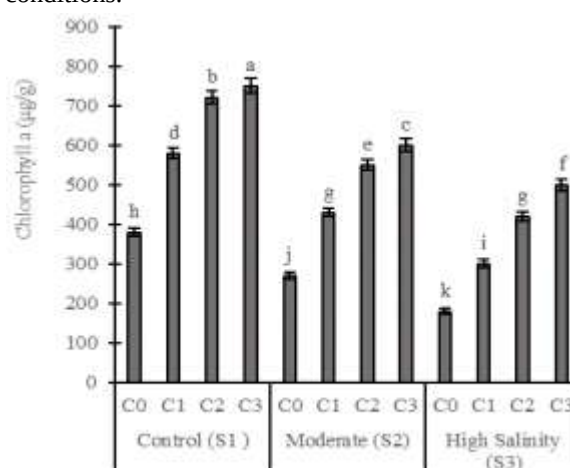
**Figure 3.** Mean values ($\pm$ SE) of branch number in plant and plant height of *Rosmarinus officinalis* L. as affected by salinity levels and compost treatments. Different lowercase letters indicate significant differences among treatments according to Duncan's multiple range test ($p < 0.05$). Abbreviations: S0, S1, S2=salinity levels (0, 4, 8 dS/m); C0= Unamended soil (0% compost) C1, C2, C3=compost formulations (C1: 100% sheep manure compost, C2: Compost blend: 75% sheep manure+25% sawdust, C3: Compost blend: 72% sheep manure+25% Fenton-processed sawdust).

Based on the results presented in Table 3, salinity stress had a significant inhibitory effect on the photosynthetic pigment content of rosemary leaves. Increasing salinity from the control to moderate and high levels resulted in a significant reduction in all pigments. Total chlorophyll decreased by 28.8% and 51.5%, chlorophyll a by 28.9% and 52.6%, chlorophyll b by 33.3% and 58.3%, and

carotenoids by 33.3% and 55.5% under moderate and high salinity, respectively, compared to the control.

In contrast, compost application significantly improved pigment content across all salinity levels. For total chlorophyll, the addition of compost levels C1, C2, and C3 increased content by 51.1%, 82.2%, and 88.9% under non-saline conditions; 62.5%, 103.1%, and 118.8% under moderate salinity; and 72.7%, 127.3%, and 172.7% under high salinity, respectively. A similar pattern was observed for other pigments, such that under high salinity, treatment C3 increased chlorophyll a, chlorophyll b, and carotenoid content by 177.7%, 260.0%, and 425.0%, respectively, compared to the control (Figure 4).

These results indicate that compost application effectively mitigates the adverse effects of salinity stress on photosynthetic pigments, with higher compost levels providing greater enhancement under elevated salinity conditions.



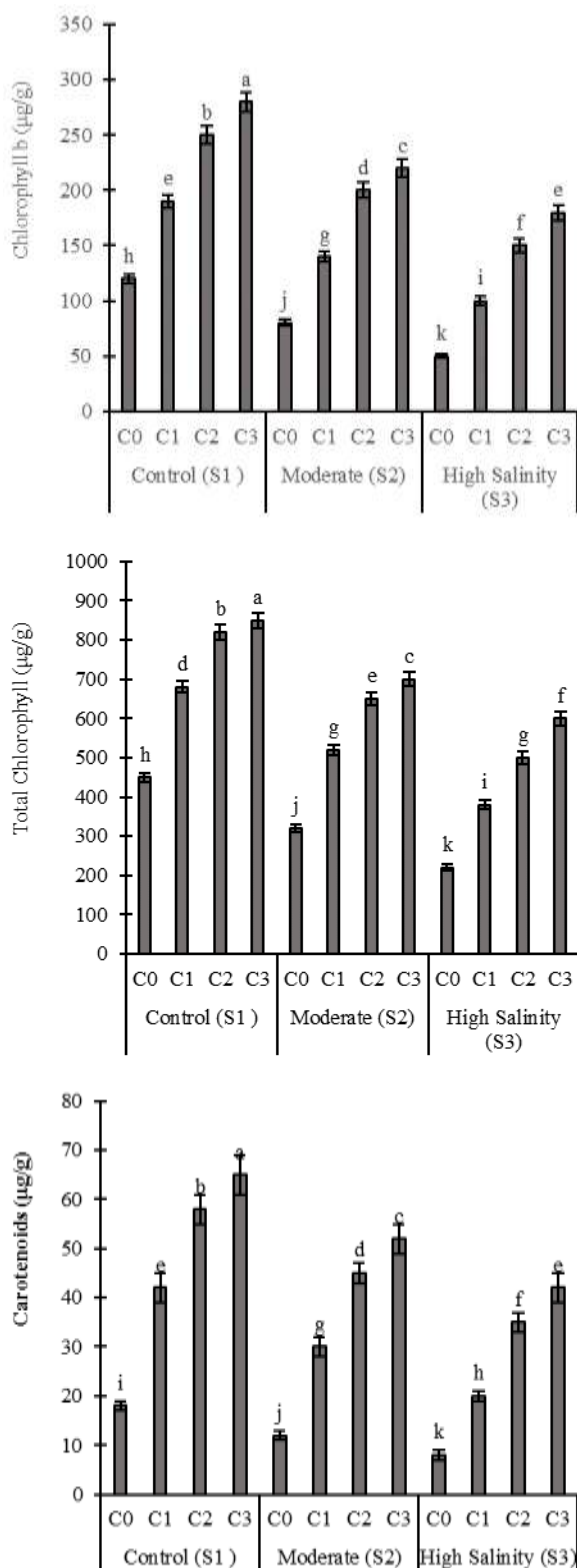
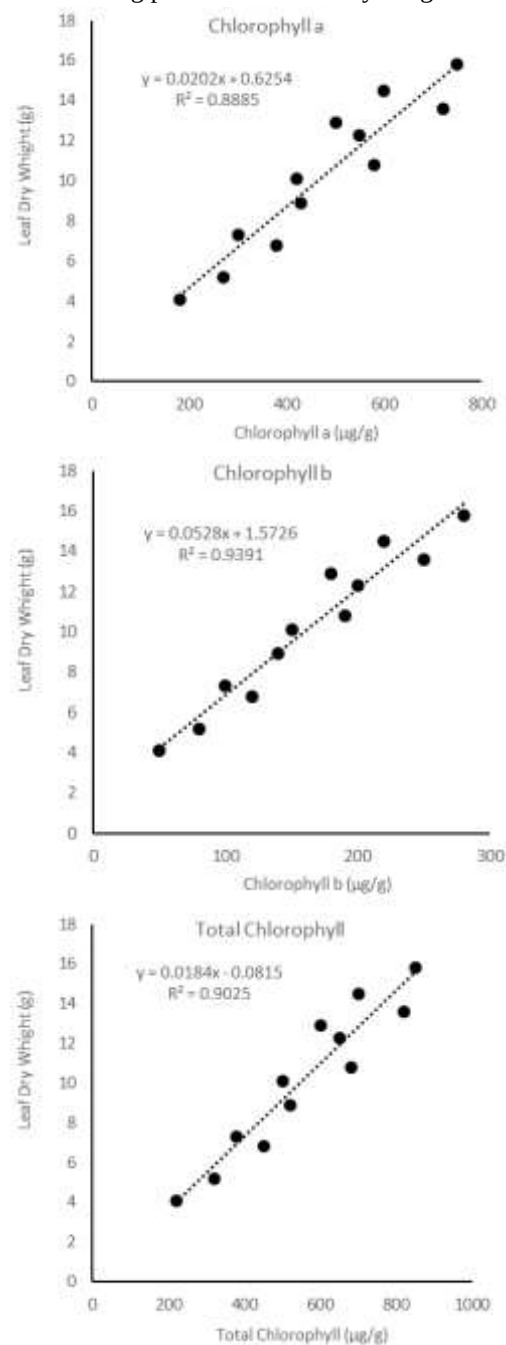


Fig 4. Mean values ($\pm$ SE) of total chlorophyll, chlorophyll a, b and carotenoids of *Rosmarinus officinalis* L. as affected by salinity levels and compost treatments. Different lowercase letters indicate significant differences among treatments according to Duncan's multiple range test ($p < 0.05$). Abbreviations: S0, S1, S2=salinity levels (0, 4, 8 dS/m); C0=Unamended soil (0% compost) C1, C2, C3=compost formulations (C1: 100% sheep manure compost, C2: Compost blend: 75% sheep manure+25% sawdust, C3: Compost blend: 72% sheep manure+25% Fenton-processed sawdust).

Establishing regression relationships between photosynthetic pigments and leaf dry weight yielded significant results (Figure 5). The analysis revealed a positive and significant correlation between total chlorophyll, chlorophyll a, chlorophyll b, and leaf carotenoids with rosemary leaf dry weight, with all models being significant at the 5% probability level. The high regression coefficients indicate that variations in photosynthetic pigment content have a direct effect on leaf dry weight, and increases in these pigments lead to higher leaf biomass. Therefore, photosynthetic pigments serve as key indicators of photosynthetic capacity and act as strong predictors of leaf dry weight in rosemary.



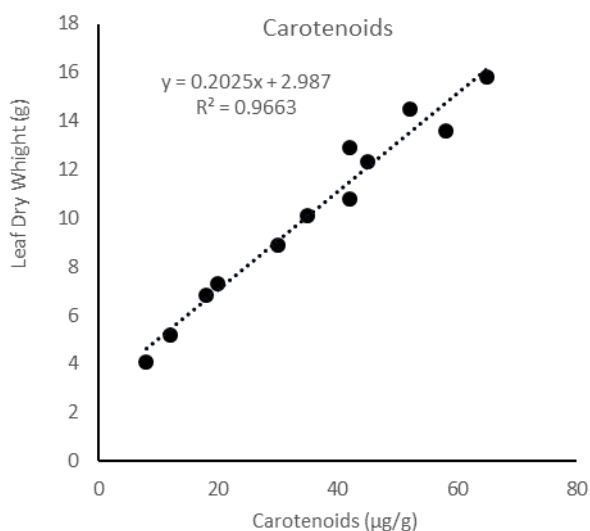


Fig 5. Regression relationships between total chlorophyll, chlorophyll a, chlorophyll b, and carotenoids with rosemary leaf dry weight, all models being significant at the 5% probability level.

4. Discussion

Soil salinity, as one of the most critical environmental constraints, adversely affects plant growth and productivity through three main mechanisms: osmotic stress, ionic toxicity, and oxidative damage (Munns & Tester, 2008; Machado & Serralheiro, 2017).

In the present study, the significant reductions observed in all measured traits under saline conditions (8 dS m⁻¹) can be directly attributed to these mechanisms. The decrease in chlorophyll a, chlorophyll b, total chlorophyll, and carotenoid contents by 52.6%, 58.3%, 51.5%, and 55.5%, respectively (Figure 4), is primarily due to the disruption of chlorophyll biosynthesis and the accelerated degradation of photosynthetic pigments under salt stress. This is because salinity-induced ionic imbalances, particularly the accumulation of Na⁺ and Cl⁻ ions, interfere with the uptake of essential nutrients such as Mg²⁺, Fe²⁺, and K⁺, which are critical for the synthesis and stabilization of chlorophyll molecules (Munns & Tester, 2008; Machado & Serralheiro, 2017). Furthermore, salinity promotes the overproduction of reactive oxygen species (ROS), which attack the chloroplast membrane and degrade chlorophyll and carotenoid pigments (Lichtenthaler, 1987). The substantial decline in carotenoids (55.5%), which play a protective role against photo-oxidative damage, confirms the occurrence of oxidative stress in the salt-treated plants. Consequently, the decrease in photosynthetic pigments directly reduces the photosynthetic capacity, limiting carbon assimilation and carbohydrate production.

This reduction in photosynthetic efficiency is the primary reason for the decreased leaf dry weight (39.7%), total biomass (39.5%), plant height (21.9%),

and lateral branch number (33.3%) under severe salinity (Figures 1, 2, and 3). In other words, the lower supply of photosynthates restricts cell division, elongation, and meristematic activity, ultimately suppressing overall vegetative growth.

The strong positive regression relationships obtained between chlorophyll a, chlorophyll b, total chlorophyll, and carotenoids with leaf dry weight (Figure 5) provide robust evidence that variations in photosynthetic pigment content have a direct and significant impact on biomass accumulation. This confirms that photosynthetic capacity is the key determinant of growth performance in rosemary under saline conditions.

In contrast to salinity, the application of compost treatments, particularly the Fenton-modified compost (C3), markedly alleviated the deleterious effects of salt stress on all measured growth and physiological traits.

The most striking finding was the considerable increase in chlorophyll a (177.7%), chlorophyll b (260.0%), total chlorophyll (172.7%), and carotenoids (425.0%) under the C3 treatment at 8 dS m⁻¹ salinity compared to the unfertilized control (Figure 4).

This substantial improvement in pigment content can be attributed to the high-quality humic substances produced during the Fenton process (Jiao et al., 2024; Zhang et al., 2023). These bioactive humic compounds enhance chloroplast membrane permeability, stimulate the enzymes involved in chlorophyll biosynthesis (such as aminolevulinic acid dehydratase), and increase the uptake of essential cations like Mg²⁺ and Fe²⁺ via chelation (Canellas et al., 2015).

Moreover, the remarkable increase in carotenoids suggests that Fenton compost effectively protects the photosynthetic apparatus from oxidative damage, likely due to the antioxidant properties of humic substances (Garcia et al., 2020).

As a direct consequence of improved photosynthetic pigment content, the photosynthetic capacity of rosemary was significantly enhanced, which is clearly reflected in the strong regression coefficients between pigments and leaf dry weight (Figure 5). This improved photosynthesis, in turn, provided sufficient assimilates to support vigorous vegetative growth, as evidenced by the increases in leaf dry weight (214.6%), total biomass (214.6%), plant height (116.0%), and lateral branch number (250.0%) under C3 treatment at 8 dS m⁻¹ (Figures 1, 2, and 3).

The superiority of Fenton-modified compost (C3) over conventional compost (C1) and mixed compost (C2) can be explained by the qualitative enhancement of organic matter rather than the total quantity of added compost.

The Fenton process, by generating hydroxyl radicals (•OH), breaks down the resistant lignocellulosic structures of sawdust, producing low-molecular-weight,

highly bioactive humic compounds that are more effective in stimulating plant physiological processes (Jiao et al., 2024). These compounds not only enhance photosynthetic pigment synthesis but also improve nutrient bioavailability and promote root growth, leading to better water and nutrient uptake under saline conditions (Canellas et al., 2015; Guo et al., 2023). Interestingly, the performance of rosemary under severe salinity with the Fenton-modified compost (C3) even exceeded that of conventional and mixed composts under non-saline conditions, highlighting the superior qualitative efficiency of this innovative organic amendment.

Overall, the results of this study clearly demonstrate a causal chain linking the application of Fenton-modified compost to improved growth performance under salinity stress:

Fenton-modified compost → increased humic substances → enhanced chlorophyll and carotenoid contents (Figure 4) → improved photosynthetic capacity (as confirmed by regression analysis in Figure 5) → increased biomass production and vegetative growth (Figures 1, 2, and 3).

Therefore, the primary mechanism by which Fenton-modified compost alleviates salinity stress in rosemary is through the protection and enhancement of the photosynthetic apparatus, which subsequently fuels growth and biomass accumulation.

This finding is consistent with previous studies that have demonstrated the role of humic substances in improving plant tolerance to salinity by protecting chloroplast structure, enhancing antioxidant defense, and improving nutrient balance (Canellas et al., 2015; Garcia et al., 2020; Guo et al., 2023).

In conclusion, compost enriched with Fenton-oxidized sawdust can be introduced as a novel and sustainable strategy for improving the photosynthetic capacity and supporting the economic cultivation of medicinal plants such as rosemary in saline and low-fertility soils, particularly in arid and semi-arid regions like Iran. Further research is recommended to investigate the long-term effects of this compost on soil properties and the performance of other salt-sensitive crops.

5. Conclusion

The present study demonstrated that salinity stress negatively affected rosemary growth and photosynthetic performance through pigment degradation, while application of Fenton-modified compost effectively mitigated these adverse effects by enhancing photosynthetic capacity and biomass accumulation. The superiority of Fenton-modified compost over conventional and mixed composts was attributed to the qualitative improvement of organic matter through the Fenton process rather than the quantity of compost

applied, as the generation of highly bioactive humic substances improved nutrient availability and protected the photosynthetic apparatus under saline conditions. Therefore, compost enriched with Fenton-oxidized sawdust can be proposed as a novel and sustainable strategy for improving plant performance in saline and low-fertility soils, particularly in arid and semi-arid regions such as Iran. Further research is recommended to evaluate the long-term effects of this compost on soil properties and its effectiveness for other salt-sensitive crops.

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