Journal of Soil Science and Plant Nutrition
https://doi.org/10.1007/s42729-025-02431-x

ORIGINAL PAPER

# Harnessing Sheep Wool Fertilizer to Enhance *Lavandula officinalis* Mill. Resilience to Salt Stress

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Received: 31 October 2024 / Accepted: 8 April 2025

## Abstract

This study investigates the potential of sheep wool as an organic amendment to alleviate salinity stress and enhance the productivity of *Lavandula officinalis* in arid and semi-arid regions. A two-factor factorial design was employed under greenhouse conditions with five replications. The experiment tested varying levels of sheep wool fertilizer (SW) at concentrations of 0% (control), 0.5%, 1%, 2%, and 4%, alongside four salt concentrations: distilled water (control), 30 mM, 60 mM, and 90 mM NaCl. The study indicated that the application of sheep wool fertilizer significantly mitigated the adverse effects of NaCl on the growth, photosynthetic, and biochemical characteristics of L. officinalis. Increasing levels of sheep wool correlated with improved plant performance, while higher NaCl concentrations led to declines across all measured characteristics. Optimal performance was observed at the 2% SW treatment. Sheep wool fertilizer represents a promising strategy to enhance plant resilience in saline conditions. This study highlights the importance of optimizing sheep wool concentrations to maximize plant growth and stress tolerance. Future research should focus on investigating the long-term effects of different sheep wool doses and explore synergistic interactions with other organic amendments or bio-stimulants to improve agricultural sustainability in saline environments.

**Keywords** Salinity impact · Lavender · Photosynthetic · Biochemical · Organic amendment

## 1 Introduction

Salinity, which is one of the significant issues in plant production, negatively impacts agricultural productivity and success, particularly in arid and semi-arid regions (Korkmaz and Çiçek 2024). Türkiye, with two-thirds of its land in arid and semi-arid climate zones, faces severe drought and desertification risks, along with the Middle East and the Mediterranean basin (Ayan et al. 2021). According to FAO (2015), salinity issues effect on 1.5 million hectares of land in Türkiye. Of these areas, 60% are classified as saline, 19.6% as moderately saline, 0.4% as moderately alkaline, 12% as slightly saline-alkaline, and 8% as moderately saline-alkaline (Çiçek 2020). In this context, the salinity issue faced by Türkiye necessitates a reevaluation of agricultural production strategies. For this reason, improving the physical, chemical, and biological properties of the soil, alongside the selection and care of plant taxa, is crucial in any agricultural production program (Korkmaz and Çiçek 2024).

Salt stress negatively affects crop growth, development, and productivity, primarily due to ion toxicity (Rao et al. 2019). Slow growth, decreased branch growth, and decreased PH are all signs of salt stress in plants (Hao et al. 2021). Under salt stress conditions, plants usually restrict photosynthesis (Ahanger et al. 2017) and significantly slow down (- or entirely halt) their development (Rao et al. 2019; Szekely-Varga et al. 2020; Hao et al. 2021).

The growth and productivity of plant taxa can be significantly enhanced by improving the physical properties of the soil. In this context, some researchers (Demir and Doğan Demir 2019; Çiçek et al. 2021) have indicated that -incorporating organic materials into plant production can enhance soil physical properties. The application of organic material to the soil is one of the most common methods for improving soil quality (Çiçek and Yücedağ 2021). Organic matter is a

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vital component of soil, as it binds soil particles to protect against erosion, regulates water movement within the soil, increases the soil's water -absorption and aeration capacity, and provides organic nitrogen and other plant nutrients to boost soil fertility (Çiçek and Yücedağ 2021; Çiçek et al. 2022). Furthermore, organic materials -play a crucial role in reducing salinity effects and enhancing plant productivity.

Sheep wool (SW), a keratin-rich byproduct of sheep farming and the textile industry is highly resistant to decomposition due to the complex structure of keratin (Petek and Logar 2021). This waste is a natural raw material that can decompose in soil without harming the environment and contains no chemicals (Adi and Pacurar 2015). The application of wool waste significantly improves soil fertility, increasing organic carbon levels (30.8% increase), and nitrogen levels (32.6% increase). Moreover, this waste increases soil enzyme activities (Lal et al. 2020). Additionally, when used as a fertilizer in agricultural applications, sheep wool fertilizer serves as a water-conserving substrate (Zoccola et al. 2015), providing higher water use efficiency in plants with shorter cultivation times (Hill 2022) and alleviating oil salinity (Gorecki and Gorecki 2010). Additionally, the use of sheep wool offers a sustainable and effective alternative for advancing agricultural practices.

So far, several studies have investigated the use of sheep wool fertilizer in alleviating the effects of salinity on plant growth, biomass, and certain physiological characteristics in *Helianthus annuus* L. and *Zea mays* L. (Abdallah et al. 2019), plant growth and yield in *Capsicum annuum* L. (Çetin Karaca et al. 2022), and vegetative growth, root development, nutrient content, and sugar quality characteristics in *Beta vulgaris* L. cv."Terranova"(Taskin 2024).However, no research has yet explored the effects of sheep wool fertilizer on *L. officinalis* seedlings under salt stress. In this context, this study introduces an innovative methodological approach by focusing specifically on *L. officinalis*, a plant with unique physiological and biochemical characteristics, and evaluating its response to sheep wool fertilizer under controlled salinity stress conditions. What distinguishes this methodology is not only the novel application of sheep wool fertilizer to *L. officinalis* but also the integration of detailed soil salinity monitoring with comprehensive plant physiological assessments. This combined approach offers a deeper understanding of how this organic material impacts both soil and plant systems under salinity stress. By optimizing the application of sheep wool fertilizer, this study provides a more precise, effective, and sustainable strategy for mitigating salt stress in the cultivation of medicinal and aromatic plants.

The hypothesis in the current study is that the application of sheep wool fertilizer-supplement mitigates the detrimental effects of NaCl on the growth, quality, photosynthetic efficiency, and biochemical characteristics of *L. officinalis*. In order to test this hypothesis, this study aims to: determine (i) whether increasing salt stress negatively impacts the quality, growth, photosynthetic, and biochemical traits of *L. officinalis*, (ii) evaluate whether higher sheep wool fertilizer doses have positive effects on these traits in the absence of salt stress, (iii) assess whether sheep wool fertilizer has an alleviating effect on L. officinalis under salt stress, and (iv) identify whether there are correlations between the pairs of the examined characteristics. This study is the first of its kind in the world to demonstrate the restorative effects of sheep wool fertilizer on the growth and development of medicinal and aromatic plant species under salt stress. Furthermore, it provides novel insights to support sustainable agricultural practices and enhance plant productivity under salt stress.

## 2 Material and Methods

### 2.1 Experimental Design

The research was carried out in the Research and Application Greenhouse at Cankırı Karatekin University (40°37′32″ N, 33°36′30″ E; 884 m above sea level). During the study, light intensity fluctuated between 450 and 500 μmol $m^{-2}$ $s^{-1}$, temperatures ranged from 30 to 35 °C, and the average relative humidity was between 65 and 70%. Two-year-old *L. officinalis* seedlings, supplied by the Research and Application Greenhouse of Cankırı Karatekin University, were used as experimental plants. The lavender plant was chosen for this study because of its numerous uses and increasing popularity in Türkiye in recent years (Yücedağ et al. 2024). Additionally, autochthonous Mediterranean plants, including *Lavandula*, have gained popularity in landscaping in recent years due to their ability to withstand harsh environmental conditions, such as rising soil salinity (Alvarez et al. 2012). *L. officinalis* is relatively tolerant of salt stress (El-Sharnouby 2022).

Using a two-factor factorial design, five replications of the experiment were conducted. They were moved to two-liter (16 × 14 cm) plastic pots within a soil + peat + pumice mixture (3:1:1) at varying NaCl applications, namely 0, 30, 60, and 90 mM, during the first week of May 2022. Subsequently, 100 pots received the addition of 0%, 0.5%, 1%, 2%, and 4% of sheep wool fertilizer per decare. The sheep wool fertilizer and pumice were purchased from Woolpell and Ayvalı Sera, two private companies. Table 1 displays the properties of the soil, peat and sheep wool fertilizer.

The values of pH, the organic matter, electrical conductivity (EC), $CaCO_3$, total nitrogen (N), phosphorous (P), potassium (K), sodium (Na), calcium (Ca), magnesium (Mg), iron (Fe), zinc (Zn), copper (Cu) and manganese (Mn) in the growing medium were determined by Çiçek et al. (2022) using a spectrophotometer and ICP-OES.

**Table 1** Some physical and chemical characteristics of soil, peat and sheep wool fertilizer

| Parameter | Soil | Peat | Sheep wool fertilizer |
|---|---|---|---|
| pH | 7.74 | 5.50 | 9.00–11.00 |
| EC (dS $m^{-1}$) | 2.40 | 0.40 | |
| Organic material (%) | 3.35 | 92.00 | 70.00–83.00 |
| $CaCO_3$ (%) | 27.95 | | |
| Total N (%) | 0.17 | 1.10 | 7.00–9.00 |
| Extractable P (mg $kg^{-1}$) | 13.38 | 0.35 | |
| Extractable K (mg $kg^{-1}$) | 320.00 | 15.00 | |
| Extractable Na (mg $kg^{-1}$) | 294.00 | | |
| Extractable Ca (mg $kg^{-1}$) | 9087.00 | 180.00 | 0.90 |
| Extractable Mg (mg $kg^{-1}$) | 802.00 | 17.00 | 0.40 |
| Water-soluble Fe (mg $kg^{-1}$) | 3.12 | 0.14 | 400.00 |
| Water-soluble Zn (mg $kg^{-1}$) | 0.23 | 0.41 | 90.00 |
| Water-soluble Cu (mg $kg^{-1}$) | 1.62 | 0.39 | |
| Water-soluble Mn (mg $kg^{-1}$) | 6.21 | 0.48 | |
| Water-soluble $K_2O$ (%) | - | | 5.00 |
| Water-soluble $P_2O_5$ (%) | | | 0.40 |
| Humic and fulvic acids (%) | - | | 42.00 |

*EC* Electrical conductivity

## 2.2 Growth Characteristics

The growth characteristics of *L. officinalis* seedlings, including plant height (PH, cm) and plant fresh and dry weights (PFW and PDW, g), were measured 40 days after the experiment was initiated. After harvesting, plants were washed with tap and deionized water to prevent soil-induced contamination. The prepared samples were dehydrated for 72 h at 65 ± 5 °C in order to determine their dry weights.

## 2.3 Quality Characteristics

Quality characteristics were identified as the number of flowers (NF), flower weight (g), aesthetic appearance score (AAS), and crown diameter (CD, cm). A five-person jury assessed each plant's condition, appearance, pot representation, vegetative component structure, vitality, and brightness before harvesting the plant material. They used a scale from 1 (poor) to 10 (excellent) to assign an aesthetic appearance to each plant. The width of each pot's crown was determined by taking two vertical measurements of the projection diameter of the plant crown (Çiçek and Yücedağ 2023).

## 2.4 Photosynthetic Characteristics

At the conclusion of the experiment, an analysis of photosynthetic characteristics was performed. Ten milliliters of 90% v/v acetone were used to homogenize 250 mg of fresh leaf samples. The absorbance of the photosynthetic pigments was measured at 645, 663, and 470 nm using a spectrophotometer (UV/VIS- 1201, Shimadzu Corp., Kyoto, Japan). the concentrations of carotenoids (car) and chlorophyll (chl) were determined based on the method described by Yücedağ et al. (2021).

## 2.5 Biochemical Characteristics

To measure the proline concentration, 250 mg of fresh leaves were homogenized in 10 mL of 3% sulphosalicylic acid and filtered through Whatman No. 2 filter paper. The extract produced by Yücedağ et al. (2021) was used to determine the proline.

After determining the fresh weights (FW) of the leaves immediately, the leaf samples were incubated in distilled water for four hours, subsequently turning turgor and determining the turgid weight (TW). After a full day of storage in the drying cabinet, the dry weight (DW) was determined. The relative water content (RWC) of the leaves was calculated using the following equation according to Dwivedi et al. (2018):

$$\mathrm{RWC}\ (\%) = \frac{\mathrm{FW} - \mathrm{DW}}{\mathrm{TW} - \mathrm{DW}}\ \mathrm{x}\ 100$$

Leaf samples of 0.1 g taken from the plant were soaked in 10 mL of distilled water at 40 °C for 30 min, and the electrical conductivity ($EC_1$) of the solution was measured. Then, the samples were heated in a water bath at 100 °C for 10 min, and the $EC_2$ was measured again. MSI was determined according to Dwivedi et al. (2018) using the following equation:

$$\mathrm{MSI}\ (\%) = \left(1 - \frac{\mathrm{EC}_1}{\mathrm{EC}_2}\right)\mathrm{x}\ 100$$

A 250 mg leaf sample representing the plant was homogenized in 10 mL of 0.1% trichloroacetic acid (TCA), and the homogenate was centrifuged at 15,000 g for 5 min. From the centrifuged sample, 1 mL of the clear supernatant was taken and mixed with 4 mL of 0.5% thiobarbituric acid (TBA) dissolved in 20% TCA. The mixture was incubated at 95 °C for 30 min, then rapidly cooled in an ice bath. After centrifuging at 10,000 g for 10 min, the absorbance of the clear supernatant was measured at wavelengths of 532 and 600 nm, and the malondialdehyde (MDA) content was determined using the following equation (Çiçek and Yücedağ 2023).

$$\mathrm{MDA}\ (\mathrm{nmol\ ml}^{-1}) = [\frac{(A_{532} - A_{600})}{155000}]\ \mathrm{x}106$$

One gram of titanium dioxide and ten grams of potassium sulfate were mixed with 150 mL of concentrated sulfuric acid and boiled on a hot plate for two hours. After cooling to room temperature, the mixture was diluted to 1.5 L with distilled water to prepare a titanium oxide solution. A 250 mg leaf sample was homogenized in 10 mL of cold acetone and filtered using Whatman No. 10 filter paper. To the extract, 4 mL of the titanium solution and 5 mL of concentrated ammonia solution were added to form a hydrogen peroxide-titanium complex. The mixture was centrifuged at 10,000 g for 5 min, and the clear supernatant was discarded, while the precipitate was dissolved in 10 mL of 1 M $H_2SO_4$. After another centrifugation at 10,000 g for 5 min to remove undissolved material, the absorbance was measured at 415 nm. The results were evaluated using a standard curve prepared with $H_2O_2$ (Çiçek and Yücedağ 2023).

### 2.6 Data Analysis

The Kolmogorov–Smirnov test was performed to assess the normality of data distributions. The homogeneity of the variance was controlled using the Levene test. A two-way analysis of variance was used in order to determine whether there was any interaction or difference between the means of the sheep wool fertilizer and NaCl treatments. One multiple comparison test, the Duncan test ($p < 0.05$), was employed to assess treatments that were homogeneous and significantly different. SPSS version 25 was used to perform these analyses (Corp IBM 2017). Principal Component Analysis was utilized to reduce the complexity of the dataset and preserve the important information expressed in terms of variable variance (Savy et al. 2022). R4.2.2 software was used to construct the correlation heat map, summarizing the associations between the pairs of quality, growth, photosynthetic, and biochemical characteristics of *L. officinalis* under varying concentrations of sheep wool fertilizer and NaCl.

## 3 Results

The concentrations of NaCl and SW affected all quality characteristics with the exception of NF ($p < 0.05$) but their interaction had no significant effect. Without sheep wool fertilizer, the increase in salt concentration resulted in significant decreases in all quality characteristics, with the highest effect (696%) on the NF. Under salt-free conditions, FW showed the highest increase (13%) in SW- 0.5, AAS (16%) in SW- 1, and CD (9%) and NF (32%) in SW- 2. The increase in the sheep wool fertilizer dose under NaCl- 90 caused an increase in quality characteristics, which is evidence of its alleviating effect. SW- 2_NaCl- 0 showed the highest AAS (9.96), FW (5.52 g) and CD (24.74 cm) while the highest NF was obtained from SW- 1_NaCl- 30 (Table 2).

All growth traits were impacted by the amounts of NaCl and SW ($p < 0.01$) but their interaction had no effect. The increase in salt concentration without sheep wool fertilizer led to decreases in all growth characteristics, with the plant dry weight showing the largest effect (29%). SW- 0.5 resulted in the highest increase (8%) in PH while SW- 4 caused the highest increase (14%) in PFW and PDW under salt-free conditions. Under NaCl- 90, even if the dosage of sheep wool fertilizer led to constant increases in PH and plant dry weight, a substantial increasing tendency (277%) in PFW resulted from SW- 2 and SW- 4. SW- 1_NaCl- 0 showed the highest PH (57.18 cm) while the highest PFW and PDW (47.09 g and 22.38 g) were obtained from SW- 4_NaCl- 0 (Table 3).

NaCl concentration had effects on all photosynthetic characteristics ($p < 0.05$) but sheep wool fertilizer influenced only chl *a*, chl $a+b$ and car. Significant reductions in the measured photosynthetic characteristics, ranging from 45% (chl *a*) to 58% (chl *b*), were caused by the increase in salt concentration in the absence of sheep wool fertilizer. In the absence of salt, the greatest increases were observed in chl *a*, chl *b*, and chl $a+b$ (45%, 58%, and 67%) in SW- 2, and in car (51%) in SW- 1. The increase in the sheep wool fertilizer dose under NaCl- 90 caused the increase in photosynthetic characteristics as an indicator of its alleviating effect. The highest chl *a* (0.77 mg $g^{-1}$ FW), chl *b* (0.26 mg $g^{-1}$ FW), chl $a+b$ (1.03 mg $g^{-1}$ FW) and car (0.30 mg $g^{-1}$ FW) resulted from SW- 2_NaCl- 0 (Table 4).

NaCl and sheep wool fertilizer concentrations affected all biochemical characteristics ($p < 0.05$). Significant decreases in the proline, MDA and $H_2O_2$ and increases in MSI and RWC resulted from the increase in salt concentration in the absence of sheep wool fertilizer. In the absence of salt, the greatest decrease and increase were observed in proline (10%) and in RWC (6%) with the effect of SW- 4. The increase in the sheep wool fertilizer dose under NaCl- 90 caused the decrease in proline, MDA and $H_2O_2$ and the increase in MSI and RWC. The highest proline (2.47 mmol $kg^{-1}$ FW), MDA (8.54 nmol $ml^{-1}$) and $H_2O_2$ (37.55 nmol $g^{-1}$ FW) were obtained from SW- 0_NaCl- 90 while SW- 4_NaCl- 0 showed the highest MSI (77.08%) and RWC (85.85%) (Table 5).

Correlation analysis showed significant associations between the pairs of quality, growth, photosynthetic and biochemical characteristics without chl *a/b* and car/chl $a+b$ under various sheep wool fertilizer and NaCl treatments (Fig. 1). Notably, there were significant correlations between the pairs of photosynthetic characteristics. CD, AAS, FW, RWC and MSI had positive correlations with chl *a*, chl *b*, car and chl $a+b$ ($R > 0.50$). On the contrary, proline and $H_2O_2$ had negative correlations with AAS, FW, CD, PH, chl *a*, chl *b*, chl $a+b$, and car ($R > 0.50$).

The first two factors (PC1 and PC2) of principal component analysis accounted for 88.75% of the variation in the entire sample. The PC1 had strong positive correlations with proline, MDA and $H_2O_2$ but strong negative

**Table 2** Effects of NaCl and sheep wool fertilizer on quality traits of *L. officinalis*

| Source of variation | AAS (1–10) | NF | FW (g) | CD (cm) |
|---|---|---|---|---|
| SW | *** | NS | * | *** |
| NaCl | *** | *** | *** | *** |
| SW x NaCl | NS | NS | NS | NS |
| SW- 0 | 6.33 ±0.12$^{c}$ | 20.65 ±0.75 | 2.61 ±0.22$^{b}$ | 20.55 ±0.31$^{b}$ |
| SW- 0.5 | 6.52 ±0.13$^{c}$ | 22.70 ±0.71 | 3.49 ±0.24$^{a}$ | 22.62 ±0.30$^{a}$ |
| SW- 1 | 7.74 ±0.10$^{b}$ | 22.95 ±0.69 | 3.37 ±0.21$^{a}$ | 22.58 ±0.31$^{a}$ |
| SW- 2 | 8.25 ±0.12$^{a}$ | 23.05 ±0.74 | 3.64 ±0.20$^{a}$ | 22.40 ±0.33$^{a}$ |
| SW- 4 | 8.37 ±0.12$^{a}$ | 22.40 ±0.75 | 3.44 ±0.24$^{a}$ | 22.18 ±0.30$^{a}$ |
| NaCl- 0 | 9.36 ±0.11$^{a}$ | 24.00 ±0.67$^{a}$ | 5.20 ±0.20$^{a}$ | 23.91 ±0.28$^{a}$ |
| NaCl- 30 | 8.56 ±0.10$^{b}$ | 24.24 ±0.69$^{a}$ | 4.88 ±0.21$^{a}$ | 23.12 ±0.26$^{b}$ |
| NaCl- 60 | 6.94 ±0.13$^{c}$ | 21.44 ±0.69$^{b}$ | 2.23 ±0.20$^{b}$ | 20.91 ±0.26$^{c}$ |
| NaCl- 90 | 4.91 ±0.11$^{d}$ | 19.72 ±0.64$^{b}$ | 0.93 ±0.19$^{c}$ | 20.33 ±0.27$^{c}$ |
| SW- 0_NaCl- 0 | 8.50 ±0.24 | 21.80 ±1.51 | 4.30 ±0.44 | 22.60 ±0.62 |
| SW- 0_NaCl- 30 | 7.46 ±0.25 | 22.20 ±1.49 | 3.94 ±0.43 | 20.83 ±0.60 |
| SW- 0_NaCl- 60 | 6.40 ±0.21 | 20.00 ±1.51 | 1.66 ±0.40 | 19.84 ±0.64 |
| SW- 0_NaCl- 90 | 2.96 ±0.24 | 18.60 ±1.52 | 0.54 ±0.43 | 18.93 ±0.62 |
| SW- 0.5_NaCl- 0 | 8.60 ±0.23 | 23.80 ±1.50 | 5.66 ±0.43 | 24.48 ±0.60 |
| SW- 0.5_NaCl- 30 | 7.60 ±0.24 | 26.20 ±1.51 | 5.14 ±0.44 | 24.07 ±0.59 |
| SW- 0.5_NaCl- 60 | 6.28 ±0.23 | 21.40 ±1.53 | 2.25 ±0.44 | 21.02 ±0.56 |
| SW- 0.5_NaCl- 90 | 3.60 ±0.20 | 19.40 ±1.51 | 0.89 ±0.40 | 20.89 ±0.59 |
| SW- 1_NaCl- 0 | 9.88 ±0.24 | 23.60 ±1.48 | 5.14 ±0.44 | 24.60 ±0.62 |
| SW- 1_NaCl- 30 | 8.56 ±0.23 | 26.40 ±1.51 | 5.03 ±0.41 | 24.29 ±0.61 |
| SW- 1_NaCl- 60 | 7.04 ±0.25 | 21.80 ±1.49 | 2.36 ±0.39 | 21.31 ±0.65 |
| SW- 1_NaCl- 90 | 5.48 ±0.24 | 20.00 ±1.52 | 0.93 ±0.42 | 20.12 ±0.61 |
| SW- 2_NaCl- 0 | 9.96 ±0.21 | 25.80 ±1.52 | 5.52 ±0.41 | 24.74 ±0.62 |
| SW- 2_NaCl- 30 | 9.36 ±0.23 | 23.60 ±1.54 | 5.21 ±0.44 | 22.73 ±0.59 |
| SW- 2_NaCl- 60 | 7.44 ±0.21 | 22.60 ±1.51 | 2.66 ±0.44 | 21.15 ±0.61 |
| SW- 2_NaCl- 90 | 6.24 ±0.24 | 20.20 ±1.52 | 1.16 ±0.39 | 20.99 ±0.62 |
| SW- 4_NaCl- 0 | 9.86 ±0.22 | 25.00 ±1.54 | 5.37 ±0.42 | 23.13 ±0.62 |
| SW- 4_NaCl- 30 | 9.84 ±0.24 | 22.80 ±1.53 | 5.08 ±0.41 | 23.69 ±0.64 |
| SW- 4_NaCl- 60 | 7.52 ±0.24 | 21.40 ±1.51 | 2.21 ±0.44 | 21.22 ±0.61 |
| SW- 4_NaCl- 90 | 6.26 ±0.21 | 20.40 ±1.53 | 1.11 ±0.42 | 20.70 ±0.63 |

* $p < 0.05$; *** $p < 0.001$; NS, not significant. Mean values with the same letter in each column were not different according to Duncan's test

*SW* Sheep wool, *AAS* Aesthetic appearance score, *NF* Number of flowers, *FW* Flower weight, *CD* Crown diameter. The data represents means ± standard error

correlations with other examined characteristics without chl *a/b* and chl *a* + *b*/car while PC2 showed positive correlation with chl *a/b* and negative correlations with chl *a* + *b*/car. Except for proline, MDA, $H_2O_2$, chl *a/b* and chl *a* + *b*/car, all other traits showed positive relationships among themselves and centered by SL concentrations with NaCl-0 and NaCl- 30 while proline, MDA and $H_20_2$ had positive correlations among themselves and centered by most SL concentrations with NaCl- 60 and NaCl- 90. Three significant groups were revealed by principal component analysis among different NaCl concentrations (Fig. 2).

## 4 Discussion

Sheep wool fertilizer supplement mitigated the detrimental effects of NaCl on *L. officinalis* quality, growth, photosynthetic, and biochemical characteristics. Increases in sheep wool fertilizer resulted in higher values for all examined characteristics, while increases in NaCl concentration resulted in lower values.

The study demonstrated that while higher NaCl concentrations negatively impacted quality characteristics,

**Table 3** Effects of NaCl and sheep wool fertilizer on growth traits of *L. officinalis*

| Source of variation | PH (cm) | PFW (g) | PDW (g) |
|---|---|---|---|
| SW | *** | ** | *** |
| NaCl | *** | *** | ** |
| SW x NaCl | NS | NS | NS |
| SW- 0 | 49.53 ±0.75$^{b}$ | 37.57 ±1.17$^{b}$ | 17.20 ±0.54$^{b}$ |
| SW- 0.5 | 54.13 ±0.74$^{a}$ | 41.26 ±1.15$^{a}$ | 19.42 ±0.50$^{a}$ |
| SW- 1 | 54.11 ±0.75$^{a}$ | 42.71 ±1.20$^{a}$ | 20.31 ±0.51$^{a}$ |
| SW- 2 | 54.26 ±0.70$^{a}$ | 43.90 ±1.15$^{a}$ | 20.90 ±0.48$^{a}$ |
| SW- 4 | 54.31 ±0.75$^{a}$ | 44.03 ±1.18$^{a}$ | 20.99 ±0.51$^{a}$ |
| NaCl- 0 | 55.87 ±0.67$^{a}$ | 45.21 ±1.05$^{a}$ | 21.14 ±0.48$^{a}$ |
| NaCl- 30 | 53.97 ±0.65$^{ab}$ | 43.74 ±1.03$^{ab}$ | 20.07 ±0.45$^{ab}$ |
| NaCl- 60 | 52.75 ±0.65$^{b}$ | 41.17 ±1.00$^{b}$ | 19.51 ±0.46$^{bc}$ |
| NaCl- 90 | 50.47 ±0.60$^{c}$ | 37.46 ±1.08$^{c}$ | 18.33 ±0.48$^{c}$ |
| SW- 0_NaCl- 0 | 52.94 ±1.51 | 40.63 ±2.34 | 19.43 ±1.08 |
| SW- 0_NaCl- 30 | 50.76 ±1.48 | 37.79 ±2.30 | 18.09 ±1.05 |
| SW- 0_NaCl- 60 | 49.52 ±1.50 | 37.47 ±2.33 | 16.18 ±1.07 |
| SW- 0_NaCl- 90 | 44.88 ±1.51 | 34.40 ±2.29 | 15.11 ±1.05 |
| SW- 0.5_NaCl- 0 | 57.06 ±1.50 | 45.69 ±2.33 | 20.53 ±1.05 |
| SW- 0.5_NaCl- 30 | 56.08 ±1.52 | 44.84 ±2.34 | 20.22 ±1.08 |
| SW- 0.5_NaCl- 60 | 53.00 ±1.51 | 38.83 ±2.31 | 20.18 ±1.09 |
| SW- 0.5_NaCl- 90 | 50.36 ±1.49 | 35.66 ±2.30 | 0.16.75 ±1.08 |
| SW- 1_NaCl- 0 | 57.18 ±1.50 | 46.89 ±2.35 | 21.55 ±1.05 |
| SW- 1_NaCl- 30 | 54.48 ±1.51 | 46.96 ±2.34 | 20.17 ±1.06 |
| SW- 1_NaCl- 60 | 53.46 ±1.54 | 40.92 ±2.31 | 20.09 ±1.08 |
| SW- 1_NaCl- 90 | 51.30 ±1.49 | 36.06 ±2.29 | 19.41 ±1.06 |
| SW- 2_NaCl- 0 | 56.20 ±1.51 | 45.73 ±2.33 | 21.81 ±1.08 |
| SW- 2_NaCl- 30 | 54.60 ±1.48 | 44.85 ±2.31 | 20.98 ±1.09 |
| SW- 2_NaCl- 60 | 54.00 ±1.50 | 44.29 ±2.28 | 20.76 ±1.07 |
| SW- 2_NaCl- 90 | 52.24 ±1.51 | 40.72 ±2.34 | 20.03 ±1.08 |
| SW- 4_NaCl- 0 | 55.96 ±1.51 | 47.09 ±2.33 | 22.38 ±1.08 |
| SW- 4_NaCl- 30 | 53.94 ±1.54 | 44.25 ±2.29 | 20.88 ±1.04 |
| SW- 4_NaCl- 60 | 53.78 ±1.50 | 44.33 ±2.34 | 20.34 ±1.05 |
| SW- 4_NaCl- 90 | 53.56 ±1.51 | 40.44 ±2.30 | 20.36 ±1.08 |

** $p<0.01$; *** $p<0.001$; NS, not significant. Mean values with the same letter in each column were not different according to Duncan's test

*SW* Sheep wool, *PH* Plant height, *PFW* and *PDW* Plant fresh and dry weights. The data represents means ± standard error

the application of sheep wool fertilizer can mitigate these effects, enhancing AAS, NF, FW, and CD. Similarly, the NF, FW, and CD of *L. officinalis* (Korkmaz and Çiçek 2024) as well as the flower dry weight of *L. stoechas* L. (Valizadeh-Kamran et al. 2019) were reduced with the increasing of NaCl concentration. Paraskevopoulou et al. (2020) also discovered that *L. angustifolia, L. dentata* var. *dentata*, *L. d.* var. *candicans*, and *L. stoechas* all suffered from the deleterious effects of salinity stress at greater NaCl concentrations than 50 mM. Notably, SW- 2_NaCl- 0 produced the best overall quality in the present study, highlighting the potential for optimizing growth conditions through targeted fertilization strategies.

The application of sheep wool fertilizer significantly improved the performance of *L. officinalis*, even though increasing NaCl concentrations have a detrimental effect on its growth characteristics. Salt stress caused the most significant decrease (29%) in plant dry weight among the growth characteristics. Similarly, Szekely-Varga et al. (2020) reported that the growth of *L. angustifolia* vars."Codreanca,"which originated in Romania, and"Sevtopolis,"which originated in Bulgaria, was considerably suppressed by salt stress. According to the study of El-Khadir et al. (2024a), the PFW of *L. dentata* decreased the most (162%) as the concentration of salt increased. Previous studies (Chrysargyris et al. 2018; Abdo et al. 2020; Hammam and AwadAlla 2020; Paraskevopoulou et al. 2020; Abdelsadek et al. 2022; Ahmad Khatami et al. 2022; Samet et al. 2023; Korkmaz and Çiçek 2024; Shala et al. 2024) reported the negative effects of salt stress on plant growth characteristics in various *Lavandula* species. Moreover, during the early growth phase, *L. stoechas* was found to be tolerant to moderate salty stress (< 50 mM) (Dadach et al. 2021).

The substantial increase in PFW of *L. officinalis* under NaCl- 90 with SW- 2 and SW- 4 suggests that these doses can mitigate salt stress, promoting improved growth outcomes. Previous studies showed similar benefits of sheep wool fertilizer, with the greatest PH achieved in *Capsicum annuum* (Çetin Karaca et al. 2022), *Helianthus annuus* L. (Abdallah et al. 2019), *Rubus fructicosus* L. (Adi and Pacurar 2016), and *Chlorophytum comosum* (Gabrys and Fryczkowska 2022). In this regard, Haque and Naebe (2022) emphasized the importance of maintaining an optimal amount of sheep wool fertilizer to sustain appropriate moisture levels and promote plant growth. Furthermore, El-Khadir et al. (2024b) stressed that the growth of *L. dentata* is better preserved in the presence of the halophyte *Atriplex prostrata*, even at high NaCl concentrations. In the presence of this halophyte, PFW of *L. dentata* increased by 35% (El-Khadir et al. 2024a).

The increase in NaCl level significantly caused substantial reductions (45%– 58%) in photosynthetic characteristics in the absence of sheep wool fertilizer. Previous research highlighted the detrimental effects of salt stress on the contents of chl in different *Lavandula* species (Chrysargyris et al. 2018; Ahmad Khatami et al. 2022; Samet et al. 2023; Korkmaz and Çiçek 2024; Shala et al. 2024). Similarly, El-Khadir et al. (2024a) reported that salt stress reduced chl content of *L. dentata* by 156%. However, the application of sheep wool fertilizer, particularly at the SW- 2 dosage, not only mitigates these negative effects but also enhances the overall photosynthetic performance, as evidenced by the highest values recorded for the contents of chl and car. In line with these findings, Abdallah et al. (2019) found that

**Table 4** Effects of NaCl and sheep wool fertilizer on photosynthetic characteristics of *L. officinalis*

| Source of variation | chl *a* (mg g$^{-1}$ FW) | chl *b* (mg g$^{-1}$ FW) | chl *a/b* | chl *a* + *b* (mg g$^{-1}$ FW) | car (mg g$^{-1}$ FW) | chl *a* + *b*/car |
|---|---|---|---|---|---|---|
| SW | *** | NS | NS | ** | * | NS |
| NaCl | *** | *** | * | *** | *** | * |
| SW x NaCl | NS | NS | NS | NS | NS | NS |
| SW- 0 | 0.49 ±0.02$^{c}$ | 0.18 ±0.01 | 2.85 ±0.09 | 0.66 ±0.02$^{c}$ | 0.18 ±0.01$^{b}$ | 0.28 ±0.01 |
| SW- 0.5 | 0.53 ±0.01$^{bc}$ | 0.18 ±0.01 | 2.95 ±0.08 | 0.71 ±0.01$^{bc}$ | 0.19 ±0.02$^{ab}$ | 0.27 ±0.02 |
| SW- 1 | 0.55 ±0.02$^{ab}$ | 0.19 ±0.02 | 2.93 ±0.08 | 0.74 ±0.02$^{ab}$ | 0.20 ±0.02$^{ab}$ | 0.27 ±0.01 |
| SW- 2 | 0.59 ±0.03$^{a}$ | 0.19 ±0.01 | 3.12 ±0.09 | 0.78 ±0.03$^{a}$ | 0.21 ±0.01$^{a}$ | 0.27 ±0.01 |
| SW- 4 | 0.58 ±0.01$^{a}$ | 0.19 ±0.01 | 3.09 ±0.08 | 0.77 ±0.01$^{ab}$ | 0.21 ±0.01$^{a}$ | 0.27 ±0.02 |
| NaCl- 0 | 0.68 ±0.01$^{a}$ | 0.25 ±0.01$^{a}$ | 2.79 ±0.08$^{b}$ | 0.93 ±0.02a | 0.27 ±0.01a | 0.29 ±0.01$^{a}$ |
| NaCl- 30 | 0.57 ±0.02$^{b}$ | 0.18 ±0.01$^{b}$ | 3.12 ±0.07$^{a}$ | 0.75 ±0.03$^{b}$ | 0.20 ±0.02$^{b}$ | 0.27 ±0.02$^{b}$ |
| NaCl- 60 | 0.48 ±0.01$^{c}$ | 0.16 ±0.02$^{c}$ | 3.06 ±0.08$^{a}$ | 0.64 ±0.02$^{c}$ | 0.16 ±0.02$^{c}$ | 0.26 ±0.01$^{b}$ |
| NaCl- 90 | 0.45 ±0.01$^{c}$ | 0.15 ±0.01$^{c}$ | 2.98 ±0.08$^{ab}$ | 0.61 ±0.02$^{c}$ | 0.16 ±0.02$^{c}$ | 0.26 ±0.01$^{b}$ |
| SW- 0_NaCl- 0 | 0.59 ±0.03 | 0.24 ±0.02 | 2.54 ±0.18 | 0.83 ±0.04 | 0.23 ±0.02 | 0.28 ±0.02 |
| SW- 0_NaCl- 30 | 0.51 ±0.04 | 0.17 ±0.01 | 2.94 ±0.17 | 0.68 ±0.03 | 0.19 ±0.02 | 0.29 ±0.02 |
| SW- 0_NaCl- 60 | 0.44 ±0.04 | 0.15 ±0.01 | 3.16 ±0.18 | 0.59 ±0.04 | 0.16 ±0.01 | 0.27 ±0.01 |
| SW- 0_NaCl- 90 | 0.41 ±0.02 | 0.15 ±0.03 | 2.78 ±0.19 | 0.55 ±0.02 | 0.15 ±0.03 | 0.28 ±0.02 |
| SW- 0.5_NaCl- 0 | 0.63 ±0.03 | 0.24 ±0.02 | 2.65 ±0.18 | 0.87 ±0.03 | 0.25 ±0.02 | 0.28 ±0.02 |
| SW- 0.5_NaCl- 30 | 0.57 ±0.04 | 0.18 ±0.02 | 3.18 ±0.19 | 0.75 ±0.04 | 0.19 ±0.01 | 0.26 ±0.03 |
| SW- 0.5_NaCl- 60 | 0.46 ±0.02 | 0.16 ±0.01 | 2.96 ±0.18 | 0.62 ±0.02 | 0.16 ±0.03 | 0.26 ±0.02 |
| SW- 0.5_NaCl- 90 | 0.45 ±0.02 | 0.15 ±0.02 | 3.01 ±0.17 | 0.61 ±0.04 | 0.16 ±0.02 | 0.26 ±0.02 |
| SW- 1_NaCl- 0 | 0.70 ±0.03 | 0.25 ±0.02 | 2.86 ±0.18 | 0.95 ±0.04 | 0.29 ±0.02 | 0.31 ±0.03 |
| SW- 1_NaCl- 30 | 0.57 ±0.01 | 0.19 ±0.01 | 3.10 ±0.18 | 0.76 ±0.03 | 0.20 ±0.01 | 0.26 ±0.02 |
| SW- 1_NaCl- 60 | 0.46 ±0.03 | 0.17 ±0.01 | 2.81 ±0.19 | 0.63 ±0.02 | 0.16 ±0.03 | 0.26 ±0.02 |
| SW- 1_NaCl- 90 | 0.46 ±0.02 | 0.16 ±0.02 | 2.94 ±0.17 | 0.61 ±0.04 | 0.16 ±0.02 | 0.26 ±0.01 |
| SW- 2_NaCl- 0 | 0.77 ±0.04 | 0.26 ±0.01 | 2.98 ±0.16 | 1.03 ±0.02 | 0.30 ±0.02 | 0.29 ±0.02 |
| SW- 2_NaCl- 30 | 0.61 ±0.04 | 0.19 ±0.02 | 3.27 ±0.19 | 0.80 ±0.02 | 0.23 ±0.03 | 0.28 ±0.03 |
| SW- 2_NaCl- 60 | 0.51 ±0.03 | 0.16 ±0.01 | 3.13 ±0.18 | 0.67 ±0.04 | 0.16 ±0.04 | 0.25 ±0.01 |
| SW- 2_NaCl- 90 | 0.47 ±0.02 | 0.15 ±0.02 | 3.10 ±0.18 | 0.62 ±0.03 | 0.16 ±0.03 | 0.26 ±0.02 |
| SW- 4_NaCl- 0 | 0.74 ±0.04 | 0.25 ±0.03 | 2.91 ±0.18 | 0.99 ±0.02 | 0.30 ±0.02 | 0.30 ±0.02 |
| SW- 4_NaCl- 30 | 0.59 ±0.02 | 0.19 ±0.02 | 3.10 ±0.19 | 0.78 ±0.04 | 0.20 ±0.03 | 0.26 ±0.03 |
| SW- 4_NaCl- 60 | 0.51 ±0.03 | 0.16 ±0.01 | 3.25 ±0.17 | 0.67 ±0.03 | 0.17 ±0.02 | 0.26 ±0.03 |
| SW- 4_NaCl- 90 | 0.49 ±0.04 | 0.16 ±0.01 | 3.08 ±0.18 | 0.64 ±0.04 | 0.17 ±0.02 | 0.26 ±0.02 |

* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$; NS, not significant. Mean values with the same letter in each column were not different according to Duncan's test

*SW* Sheep wool, *chl* Chlorophyll, *car* Carotenoids. The data represents means ± standard error

even without nitrogen fertilization, soil containing 1% sheep wool waste improved the physiological behavior of *Zea mays* L. Furthermore, the chl content of *L. dentata* rose by 20% in the presence of *A. prostrata* (El-Khadir et al. 2024a).

Both NaCl and sheep wool fertilizer concentrations significantly influenced various biochemical characteristics. In the absence of sheep wool fertilizer, significant decreases in proline, MDA, and $H_2O_2$ levels were observed under salt stress. In parallel with these results, previous studies (Ahmad Khatami et al. 2022; Mehrabani 2023; El-Khadir et al. 2024a; Korkmaz and Çiçek 2024; Shala et al. 2024) reported that proline level in various *Lavandula* species increased in response to salt stress. For instance, El-Khadir et al. (2024a) found that salt stress caused a 43% reduction in RWC and a 60% increase in proline levels in *L. dentata*. Conversely, the present study revealed that the application of sheep wool fertilizer under high salt conditions (NaCl- 90) effectively reduced stress markers while enhancing membrane stability index and relative water content, which suggests the significant role of sheep wool fertilizer in mitigating salt stress.

Interestingly, contrasting effects were observed with SW- 4 under salt-free conditions, highlighting the potential of sheep wool fertilizer to optimize plant physiological

**Table 5** Effects of NaCl and sheep wool fertilizer on biochemical traits of *L. officinalis*

| Source of variation | Proline (mmol kg$^{-1}$ FW) | MSI (%) | RWC (%) | MDA (nmol ml$^{-1)}$ | $H_2O_2$ (nmol g$^{-1}$ FW) |
|---|---|---|---|---|---|
| SW | *** | *** | *** | * | ** |
| NaCl | *** | *** | *** | *** | *** |
| SW x NaCl | NS | NS | NS | NS | NS |
| SW- 0 | 1.45 ±0.08$^{a}$ | 64,40 ±0,61$^{c}$ | 74,42 ±0,73$^{d}$ | 7,37 ±0,21$^{a}$ | 30,46 ±0,65$^{a}$ |
| SW- 0.5 | 1,24 ±0,07$^{ab}$ | 66,32 ±0,62$^{b}$ | 77,30 ±0,70$^{c}$ | 7,07 ±0,23$^{ab}$ | 29,18 ±0,62$^{ab}$ |
| SW- 1 | 1,09 ±0,08$^{bc}$ | 69,38 ±0,63$^{a}$ | 79,48 ±0,72$^{b}$ | 6,61 ±0,19$^{b}$ | 28,46 ±0,65$^{bc}$ |
| SW- 2 | 1,02 ±0,08$^{bc}$ | 69,29 ±0,61$^{a}$ | 80,73 ±0,72$^{ab}$ | 6,54 ±0,23$^{b}$ | 28,10 ±0,63$^{bc}$ |
| SW- 4 | 0,97 ±0,06$^{c}$ | 70,43 ±0,62$^{a}$ | 81,66 ±0,75$^{a}$ | 6,49 ±0,21$^{b}$ | 26,98 ±0,63$^{c}$ |
| NaCl- 0 | 0,54 ±0,07$^{d}$ | 76,27 ±0,54$^{a}$ | 83,51 ±0,65$^{a}$ | 6,08 ±0,19$^{b}$ | 22,41 ±0,58$^{d}$ |
| NaCl- 30 | 0,77 ±0,08$^{c}$ | 69,08 ±0,55$^{b}$ | 80,75 ±0,64$^{b}$ | 6,37 ±0,18$^{b}$ | 27,27 ±0,59$^{c}$ |
| NaCl- 60 | 1,51 ±0,07$^{b}$ | 64,64 ±0,54$^{c}$ | 77,49 ±0,65$^{c}$ | 7,16 ±0,21$^{a}$ | 30,92 ±0,56$^{b}$ |
| NaCl- 90 | 1,80 ±0,07$^{a}$ | 61,87 ±0,56$^{d}$ | 73,11 ±0,60$^{d}$ | 7,65 ±0,21$^{a}$ | 33,95 ±0,58$^{a}$ |
| SW- 0_NaCl- 0 | 0,58 ±0,16 | 74,85 ±1,21 | 80,92 ±1,45 | 6,13 ±0,43 | 22,81 ±1,30 |
| SW- 0_NaCl- 30 | 0,85 ±0,15 | 67,09 ±1,22 | 77,91 ±1,40 | 6,79 ±0,45 | 28,84 ±1,32 |
| SW- 0_NaCl- 60 | 1,91 ±0,15 | 58,93 ±1,21 | 72,11 ±1,46 | 8,04 ±0,39 | 32,64 ±1,33 |
| SW- 0_NaCl- 90 | 2,47 ±0,17 | 56,71 ±1,21 | 66,75 ±1,48 | 8,54 ±0,43 | 37,55 ±1,30 |
| SW- 0.5_NaCl- 0 | 0,53 ±0,15 | 77,03 ±1,23 | 83,18 ±1,45 | 6,10 ±0,43 | 22,69 ±1,35 |
| SW- 0.5_NaCl- 30 | 0,81 ±0,16 | 67,29 ±1,22 | 79,81 ±1,42 | 6,64 ±0,45 | 27,86 ±1,36 |
| SW- 0.5_NaCl- 60 | 1,65 ±0,14 | 61,95 ±1,21 | 74,58 ±1,45 | 7,30 ±0,45 | 31,00 ±1,33 |
| SW- 0.5_NaCl- 90 | 1,99 ±0,16 | 58,99 ±1,21 | 71,60 ±1,45 | 8,24 ±0,43 | 35,19 ±1,30 |
| SW- 1_NaCl- 0 | 0,53 ±0,15 | 76,23 ±1,22 | 83,00 ±1,42 | 6,07 ±0,43 | 22,50 ±1,31 |
| SW- 1_NaCl- 30 | 0,73 ±0,15 | 70,93 ±1,22 | 81,82 ±1,39 | 6,11 ±0,43 | 27,12 ±1,33 |
| SW- 1_NaCl- 60 | 1,42 ±0,16 | 66,63 ±1,21 | 79,58 ±1,42 | 6,99 ±0,45 | 30,91 ±1,30 |
| SW- 1_NaCl- 90 | 1,66 ±0,15 | 63,74 ±1,23 | 73,53 ±1,45 | 7,27 ±0,47 | 33,32 ±1,34 |
| SW- 2_NaCl- 0 | 0,54 ±0,15 | 76,14 ±1,21 | 84,60 ±1,46 | 6,10 ±0,43 | 22,63 ±1,35 |
| SW- 2_NaCl- 30 | 0,73 ±0,16 | 69,87 ±1,24 | 81,12 ±1,45 | 6,15 ±0,41 | 26,67 ±1,30 |
| SW- 2_NaCl- 60 | 1,32 ±0,17 | 67,03 ±1,22 | 80,76 ±1,45 | 6,75 ±0,43 | 30,58 ±1,30 |
| SW- 2_NaCl- 90 | 1,48 ±0,16 | 64,11 ±1,21 | 76,43 ±1,42 | 7,15 ±0,43 | 32,53 ±1,32 |
| SW- 4_NaCl- 0 | 0,53 ±0,16 | 77,08 ±1,22 | 85,85 ±1,41 | 6,02 ±0,41 | 21,40 ±1,30 |
| SW- 4_NaCl- 30 | 0,72 ±0,15 | 70,19 ±1,22 | 83,11 ±1,41 | 6,16 ±0,43 | 25,88 ±1,34 |
| SW- 4_NaCl- 60 | 1,24 ±0,15 | 68,67 ±1,21 | 80,44 ±1,45 | 6,73 ±0,43 | 29,48 ±1,30 |
| SW- 4_NaCl- 90 | 1,40 ±0,16 | 65,77 ±1,21 | 77,24 ±1,45 | 7,05 ±0,41 | 31,15 ±1,33 |

* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$; NS, not significant. Mean values with the same letter in each column were not different according to Duncan's test

*SW* Sheep wool, *MSI* Membrane stability index, *RWC* Relative water content, *MDA* Malondialdehyde; $H_2O_2$: Hydrogen peroxide. The data represents means ± standard error

responses across varying environmental stresses. Ahmad Khatami et al. (2022) also stated that the treatments with plant growth-promoting bacteria, compost, and compost with biodynamic preparations had the opposite effect on the proline of *L. officinalis* compared to salt stress. Besides, El-Khadir et al. (2024a) indicated that the presence of *A. prostrata*, proline content in *L. dentata* decreased by 10%, while increasing leaf water content by 15%.

The significant positive correlations observed between photosynthetic characteristics and growth parameters, coupled with the negative correlations of proline and $H_2O_2$ with these characteristics under various sheep wool fertilizer and NaCl treatments, suggest that effective management of sheep wool fertilizer and NaCl treatments can enhance plant resilience and productivity. This can be achieved by optimizing chl content and reducing oxidative stress. Similarly, El-Khadir et al. (2024a) found that RWC showed high positive association with chl concentration and negative correlation with proline, indicating the intricate connections between leaf hydration and cellular physiology. Their study also showed the strong negative correlation between proline and PFW under salt stress.

In the current study, the principal component analysis highlighted distinct physiological responses of *L.*

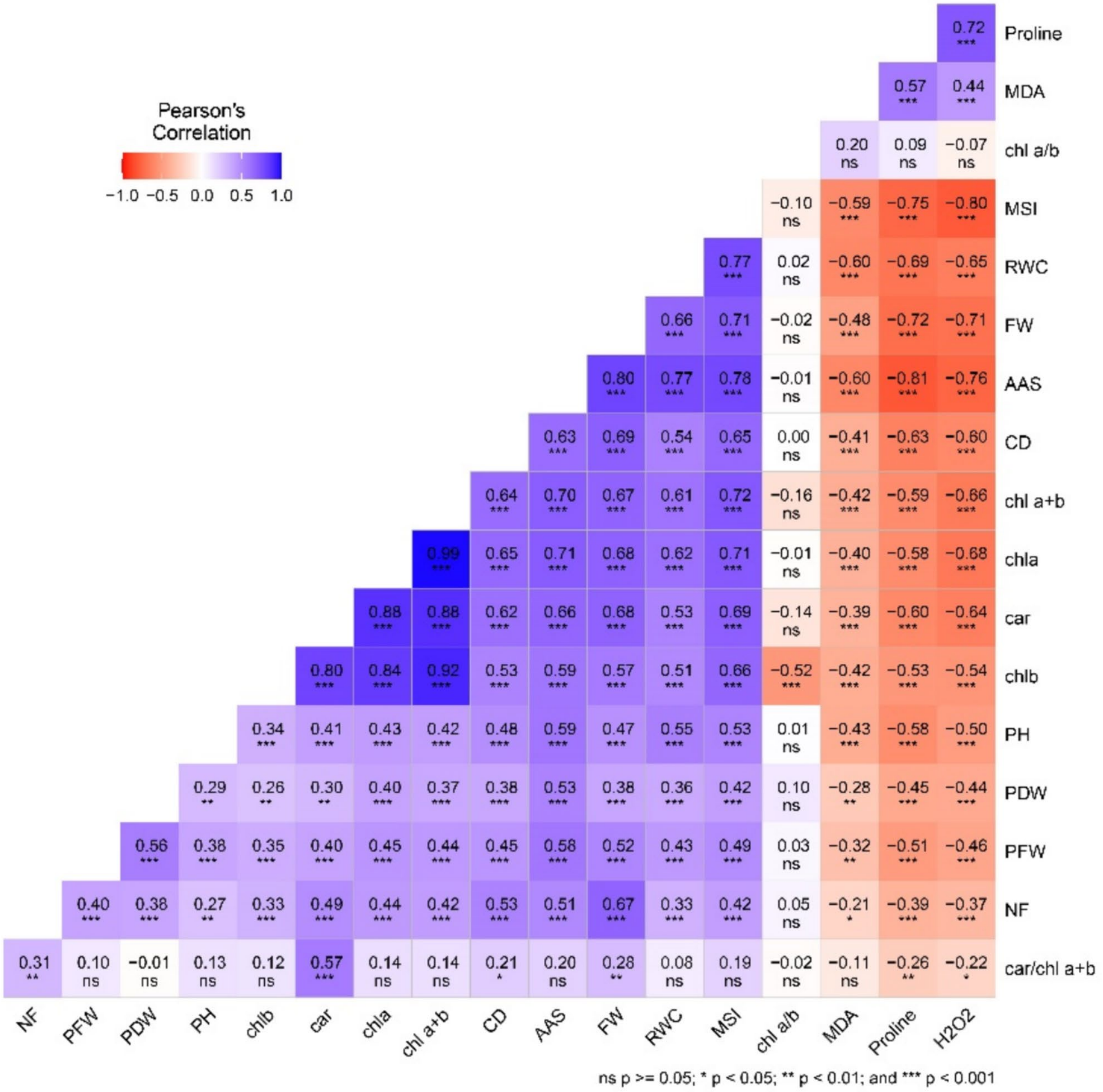

**Fig. 1** Correlation heat map between the pairs of the examined characteristics of *L. officinalis* under various sheep wool fertilizer and NaCl treatments. AAS: Aesthetic appearance score; NF: Number of flowers; FW: Flower weight; CD: Crown diameter; PH: Plant height; PFW and PDW: Plant fresh and dry weights; chl: Chlorophyll; car: Carotenoids; MSI: Membrane stability index; RWC: Relative water content; MDA: malondialdehyde; $H_2O_2$: Hydrogen peroxide

*officinalis* to varying NaCl concentrations, with the first two factors illustrating a clear separation between stress indicators (proline, MDA, and $H_2O_2$) and beneficial photosynthetic traits (chl *a/b*), underscoring the complex interplay between salt stress and plant resilience mechanisms. According to this multivariate analysis, SW- 2 typically resulted in the highest values for all examined characteristics. In order to maximize plant resistance in saline conditions, this analysis provides valuable insights into the interactions and adaptations of *L. officinalis* in response to salt stress. Taskin (2024) suggested that adding sheep wool to organo-mineral fertilizers could improve sugar beet cultivation by reducing fertilizer overuse and enhancing efficiency. Moreover, Gillespie et al. (2022) emphasized that hydrolyzed sheep wool might economically supply up to 15.8% of the nitrogen required for Ireland's cereal crops

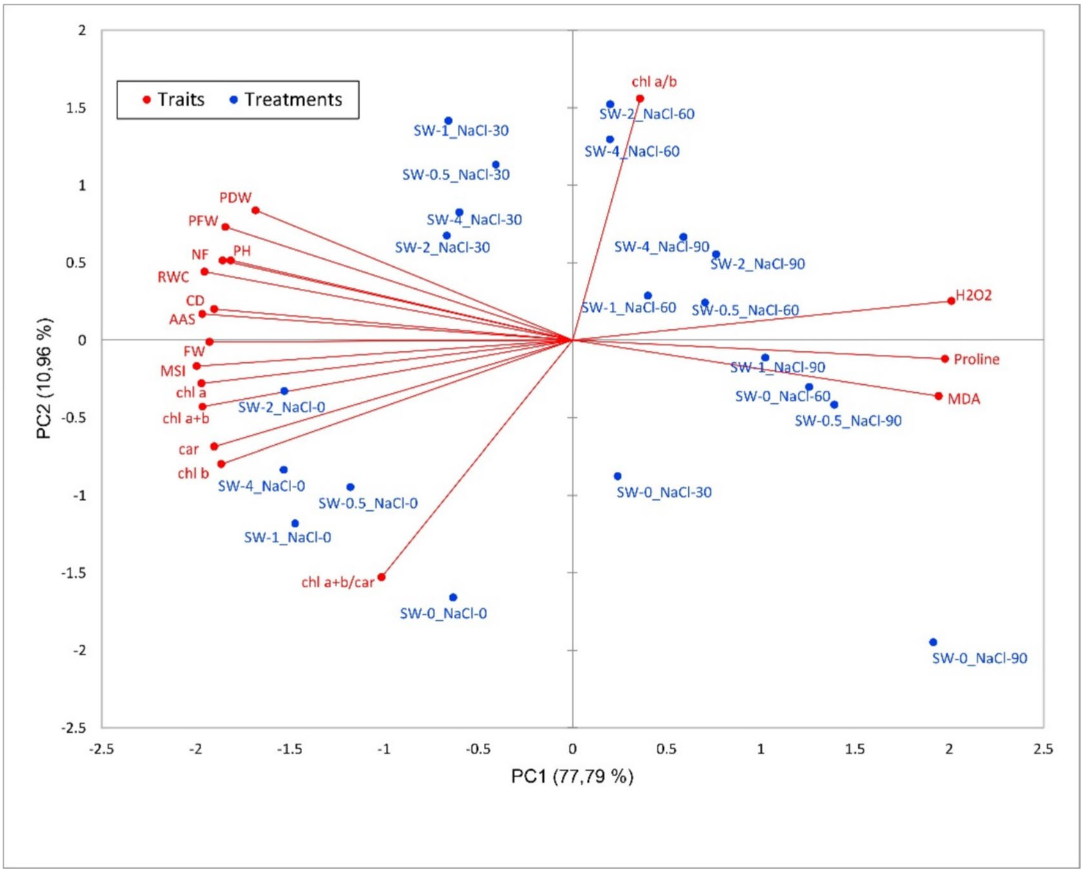

**Fig. 2** Principal component analysis using all examined characteristics in *L. officinalis.* SW- 0_NaCl- 0: No sheep wool fertilizer and no salt; SW- 0.5_NaCl- 30: The interaction of 0.5 L sheep wool fertilizer and 30 mM salt; AAS: Aesthetic appearance score; NF: Number of flowers; FW: Flower weight; CD: Crown diameter; PH: Plant height; PFW and PDW: Plant fresh and dry weights; chl: Chlorophyll; car: Carotenoids; MSI: Membrane stability index; RWC: Relative water content; MDA: malondialdehyde; $H_2O_2$: Hydrogen peroxide

annually, along with significant amounts of copper, zinc, and sulfur.

## 5 Conclusions

The application of sheep wool fertilizer significantly mitigated the adverse effects of NaCl on the growth, quality, and physiological characteristics of *L. officinalis*, promoting higher chl content and reducing stress markers such as proline and $H_2O_2$. This study highlights the potential of sheep wool fertilizer as an effective strategy for enhancing plant resilience in saline environments, particularly at optimal concentrations such as SW- 2. Given the observed correlations between photosynthetic traits and growth parameters, tailored fertilization strategies can be key to improving plant performance under salt stress.

Future research should explore the long-term effects of varying sheep wool fertilizer doses across different saline conditions. Investigating the synergistic effects of sheep wool fertilizer combined with other organic amendments or bio-stimulants could further enhance plant growth and stress tolerance. Additionally, field trials are essential to validate these findings in real-world agricultural settings. Understanding the mechanisms by which sheep wool fertilizer influences biochemical pathways can provide deeper insights into improving crop yields and sustainability, particularly in arid and saline-prone regions. Ultimately, integrating organic fertilizers like sheep wool into conventional practices could promote environmental sustainability while optimizing resource use in agriculture. By using less chemical fertilizer, sheep wool—a waste product of the textile industry—in agricultural production could improve soil nutrient content, fights erosion, and reduce pollution in the environment, while mitigating the impact of various stressors.

**Authors Contributions** Original idea: CY. Experiment design and measurement: GO and NC. Data analysis: CY. Manuscript preparation and revisions: CY, NC and GO.

**Funding** Open access funding provided by the Scientific and Technological Research Council of Türkiye (TÜBİTAK). This study, produced from the master thesis of Gizem Öztürk, was supported by the Scientific Research Projects Coordination Unit at Burdur Mehmet Akif Ersoy University [Project Nr. 0857-YL- 22].

**Data Availability** The datasets used and/or analyzed during the current study are available from the corresponding author upon reasonable request.

**Code availability** Not applicable.

## Declarations

**Ethics Approval and Consent to Participate** Not applicable.

**Consent for Publication** Not applicable.

**Conflict of Interest** All authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript.

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