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RESEARCH ARTICLE

Reduced irrigation demand in maize cultivation through soil amendment with sheep wool: a natural water retention strategy

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Abstract

Background and aims Sheep wool (SW) is mostly underutilized and is treated as waste. This study investigates its ability to retain water in the soil.

Methods After determining the chemical composition of SW, it was mixed with soil at ratios of 97.5:2.5 and 95:5-(soil:SW) in the first experiment, and 99:1, 98:2, and 97:3 in the second experiment. Silage maize plants were then grown in these soil-SW mixtures.

Results Thermal camera imaging showed that SW treatments reduced canopy temperatures, indicating lower water and heat stress. Chlorophyll content increased with SW addition, peaking in the SW1 treatment (97.5:2.5 w/w) in the first experiment and in the SW2 treatment (98:2 w/w) in the second experiment. Stomatal resistance was generally higher in the first experiment but decreased with increasing SW levels in the second. Stomatal density increased across all SW treatments in both experiments. Pot weight confirmed that SW-treated pots retained more water. In the first experiment, maize dry weight increased with the SW1 treatment, while the highest dry weight was observed in SW2 treatment during the second experiment. Nutrient analysis showed significant increases in N and P concentrations with SW treatments. Potassium levels increased in the first experiment, while Ca and Mg showed variable

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responses across experiments. Manganese, Zn and Cu concentrations also increased with SW treatments.
Conclusions This study highlights the potential of SW as a soil conditioner for improving water retention, nutrient uptake, and plant growth. Further research is recommended to optimize SW application rates across crop species and environmental conditions.

Keywords Circular economy · Waste wool · Silage corn · Water retention

Introduction

Climate change and the growing global demand for food necessitate the adoption of sustainable strategies to improve the efficiency of water and soil resource use. Water scarcity is a major constraint to agricultural productivity, particularly in arid and semi-arid regions where irrigation-dependent cropping systems predominate. Rising temperatures accelerate crop development but simultaneously intensify water stress, especially under conditions of limited or inefficient irrigation (Oishy et al. 2025). Irrigated agriculture is the largest consumer of global freshwater resources, while climate-driven increases in temperature and precipitation variability are steadily reducing the availability and reliability of irrigation water (Grigorieva et al. 2023; Ingrao et al. 2023). Consequently, improving soil water use efficiency and reducing irrigation demand without substantial yield penalties have become central objectives of sustainable agriculture (Abbass et al. 2022; Tarolli et al. 2024). However, despite extensive research on irrigation management, there remains a limited understanding of how alternative organic amendments can be strategically used to directly reduce irrigation requirements under field-relevant conditions.

Silage maize is one of the most important fodder crops worldwide due to its high biomass production, nutritional value, and wide adaptability (Chaudhary et al. 2013; Karnatam et al. 2023). However, maize is characterized by relatively high-water demand, making it particularly sensitive to soil moisture deficits under irrigated systems (Farre and Faci 2006). Therefore, improving water use efficiency in maize cultivation is a key challenge for sustainable fodder production. Deficit irrigation has emerged as an effective strategy to conserve water by supplying less than full crop water requirements while maintaining acceptable yields. Nevertheless, the success of deficit irrigation depends not only on irrigation scheduling but also on soil properties that regulate water retention and plant-available water. There is a clear research gap regarding the integration of organic soil amendments with deficit irrigation strategies, particularly the lack of studies evaluating their capacity to reduce irrigation demand in maize systems.

In this context, increasing attention has been given to organic soil amendments that enhance soil physical structure and water-holding capacity. Materials such as compost, biochar, and agricultural by-products have demonstrated potential to improve soil moisture retention and crop resilience under limited water availability (Abedi-Koupai et al. 2008; Glab and Kulig 2008; Seyedsadr et al. 2022; Shyam et al. 2025). Among these materials, sheep wool (SW) has recently gained interest as a biodegradable, keratin-rich fiber with distinctive agronomic properties. Its slow decomposition rate allows progressive and prolonged regulation of soil moisture (Abdallah et al. 2019), while its nutrient content (C, N, S, Fe, Cu, and Zn) may contribute to plant nutrition during mineralization (Akca et al. 2023; Taskin 2024). These promising characteristics, the potential of SW to function not only as a soil conditioner but also as a tool to reduce irrigation inputs in water-demanding crops such as maize has not been systematically investigated. Despite these advantages, coarse and low-quality SW generated from dual-purpose or dairy sheep breeds has limited commercial value for the textile industry (Rajabinejad et al. 2019; Herfort et al. 2023; Taskin 2024). As a result, large quantities of SW are treated as waste and are often discarded or incinerated, creating environmental and management challenges (Parlato and Porto, 2020; Ozek 2024). The reuse of such agricultural residues offers an opportunity to reduce waste, lower environmental impacts, and enhance resource efficiency in agroecosystems within the framework of the circular economy (Zoccola et al. 2015; Yang et al. 2022).

Research has shown that SW amendments can increase soil water-holding capacity (Camilli et al. 2025), reduce bulk density, and improve soil aeration (Abdallah et al. 2019). However, a major limitation in the current body of knowledge is the insufficient understanding of SW decomposition

kinetics under different soil and moisture conditions. Specifically, there is a lack of quantitative information on the rate of keratin degradation, the temporal dynamics of nutrient mineralization, and the synchronization between nutrient release and crop demand. This gap is critical because the agronomic effectiveness of SW depends not only on its water retention capacity but also on whether its nutrient release pattern aligns with crop uptake dynamics. Furthermore, existing studies have largely focused on short-term soil physical improvements, with little emphasis on the role of SW in reducing irrigation demand while sustaining crop growth and nutrient uptake.

Calcareous sandy loam soils are widespread in semi-arid regions and present specific challenges for sustainable water management due to low organic matter content, high calcium carbonate levels, rapid drainage, and limited plant-available water. Maize was selected as a model crop because of its economic importance, high biomass production, and sensitivity to both water and nutrient availability, making it particularly suitable for evaluating soil amendments with slow decomposition characteristics. To address the identified research gaps, this study specifically focuses on linking SW application with irrigation management by evaluating its dual role in water retention and nutrient supply. In this context, the present study investigates the potential of SW as a sustainable soil amendment to reduce irrigation requirements in silage maize cultivated on a calcareous sandy loam soil. The study specifically evaluates whether SW application can enhance soil water retention and regulate nutrient release sufficiently to reduce irrigation frequency and volume without adversely affecting plant growth or nutrient uptake. By explicitly addressing both the lack of studies on irrigation reduction and the uncertainty surrounding SW decomposition and nutrient release, this research provides a more mechanistic understanding of SW functionality in soil–plant systems. By integrating an underutilized agricultural residue into crop production systems, this study contributes to climate-smart agriculture and circular economy approaches, offering an eco-efficient strategy to mitigate water scarcity in fodder production systems.

Materials and methods

Functional and chemical characterization of sheep wool

For the experiment, pelletized SW was ground. During pelletization, the wool fibers were mechanically compressed and then processed through a pellet machine to form pellets. To determine whether the pelletization process caused any alteration in the structural composition of the wool, the functional groups of raw sheep wool (RSW) and pelletized SW were compared using Fourier Transform Infrared (FTIR) spectroscopy over the range of 400—4000 cm^{-1}, following the method described by Sahin et al. (2017) (Fig 1). The FTIR spectra were obtained using a Shimadzu Infinity FTIR-Spectrometer, with 20 scans obtained per sample. The SW sample was ground to pass through a 200 µm sieve. For elemental analysis, the sieved SW sample was pressed into thick pellets, 32 mm in diameter, using wax as a binder. For quality assurance, USGS Standards, GBW7109, and GBW-7309 sediment, as well as reference olive leaves standard materials, were similarly pressed into pellets. Elemental concentrations were determined using polarized energy dispersive X-ray fluorescence (PEDXRF; Spectro Xepos), as described by Gunes et al. (2014) (Table 1).

Experimental design and plant growth conditions

Experiment 1

Maize (*Zea mays* L. cv. Pioneer P2183) was selected as a test plant and cultivated under natural light conditions in a greenhouse at the Faculty of Agriculture, Ankara University. Plants were grown in polyethylene pots (20 cm deep, 22 cm top diameter, 15 cm bottom diameter), each containing 4 kg of soil. The properties of the experiment 1 soil are shown in Table 1. Twelve seeds were sown in each pot on June 24, 2024, thinned to six plants on July 5, 2024, and then harvested on July 27, 2024. Sheep wool was mixed with the soil at ratios of 97.5:2.5 w/w (soil:SW1) and 95:5 w/w (soil:SW2). Basal fertilization comprised 100 mg N kg^{-1} soil as NH_4NO_3 and 50 mg P kg^{-1} KH_2PO_4. Average day/night temperatures in June and July were 26.7 °C:13 °C and 30.3 °C:15.9 °C,

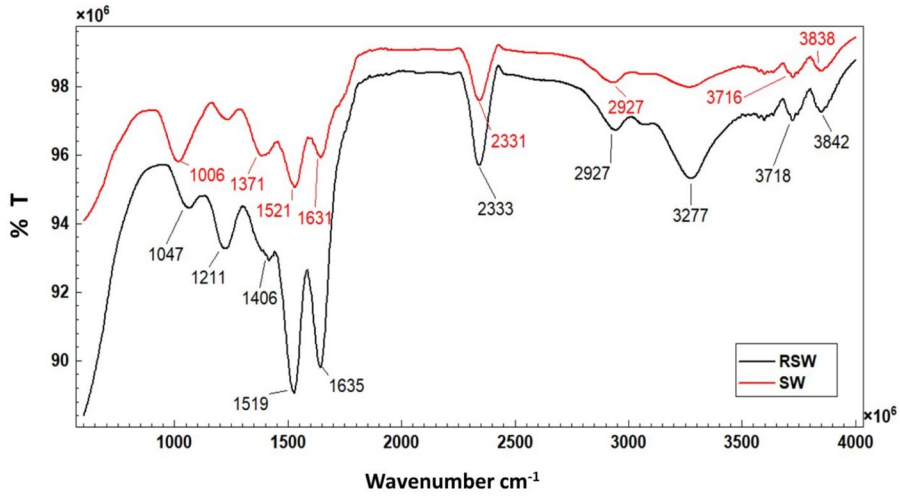


Fig. 1 Fourier transform infrared (FTIR) spectra of raw sheep wool (RSW) and pelletized sheep wool (SW). While the x axis shows wavenumber in per cm, y axis shows the percent transmittance

respectively, with relative humidity maintained at 50 ± 5% and 45 ± 5%.

Experiment 2

Twelve maize seeds (*Zea mays* L. cv. Pioneer P2183) were sown in each pot on July 7, 2024, and thinned to nine on July 24, 2024. Maize plants were grown in polyethylene pots containing 4 kg of soil. The properties of the experiment 2 soil are shown in Table 1. Sheep wool was mixed with the soil at three ratios of 99:1 w/w (SW1), 98:2 w/w (SW2), and 97:3 w/w (SW3). Basal fertilization comprised of 100 mg N kg^{-1} soil as NH_4NO_3 and 50 mg P kg^{-1} KH2PO4. The average day/night temperatures during June and July were maintained at 26.7 °C/13 °C and 30.5 °C/16.1 °C, respectively, with relative humidity maintained at 50 ± 5 and 43 ± 5%. After the completion of the maize vegetative period, plants were harvested on August 21, 2024.

Determination of field capacity and measurement of soil water content

For field capacity determination, soil samples were placed onto a pressure plate to exert a suction of −1/3

Table 1 Some of the physical and chemical properties of the experimental soils

Properties (Method)	Unit	Experiment 1	Experiment 2
Soil Texture (Hydrometer)	-	Clay Loam	Clay Loam
pH (1:2.5 ultra-pure water)	-	7.78	7.94
EC (1:2.5 ultra-pure water)	(dS m^{-1})	0.78	0.75
Organic Matter (WB)*	(g kg^{-1})	8.00	17.0
$CaCO_3$ (Scheibler)	(g kg^{-1})	175	83
Field capacity	(g kg^{-1})	208	288
Total Nitrogen (Kjeldahl)	(g kg^{-1})	0.69	0.81
Plant Available P ($NaHCO_3$)	(mg kg^{-1})	6.44	18.0
Exchangeable K (NH_4OAc)	(mg kg^{-1})	482	755
Exchangeable Ca (NH_4OAc)	(mg kg^{-1})	6888	5818
Exchangeable Mg (NH_4OAc)	(mg kg^{-1})	629	511
Extractable Fe (DTPA)	(mg kg^{-1})	9.05	35.0
Extractable Zn (DTPA)	(mg kg^{-1})	0.76	3.17
Extractable Cu (DTPA)	(mg kg^{-1})	1.43	0.58
Extractable Mn (DTPA)	(mg kg^{-1})	8.91	11.9

*Walkley–Black

atmosphere on a fully saturated soil sample. Once the soil no longer released water, its moisture content was assessed through gravimetric means and then equated to field capacity (Cassel and Nielsen 1986)

During the vegetative period, pot weights were periodically measured to estimate soil moisture by assessing water loss through evapotranspiration across treatments (Fig. 2). To isolate evaporation losses, a parallel incubation experiment without plants was conducted (Fig. 3). Both planted and unplanted pots were regularly weighed to monitor changes in soil water content. In the plant experiments, each pot contained 4 kg of soil, while the incubation setups used either 4 kg or 1 kg of soil. Throughout the experiment, pots were rotated regularly and irrigated to 80% of field capacity, with all measurements taken before irrigation.

Plant harvest and determination of element concentrations

After harvesting, maize samples were rinsed once with tap water, and then twice with deionized water. Further, they were dried in a thermo-ventilated oven at 65 °C until a constant dry weight was achieved to determine dry weight and subsequently ground for elemental analysis. Later, the ground material was passed through a 200 µm sieve, and total N concentrations were measured using the Kjeldahl method (Walinga et al. 1989). For other elemental analysis such as P, K, Ca, Mg, Fe, Zn, Cu, Mn and B, 0.2 g subsample of milled material were digested in a microwave system (Cem MARSX press 6 One Touch model, USA) under high temperature (210 °C) and pressure (200 PSI) using 5 mL concentrated HNO_3 and 2 mL H_2O_2. Using distilled water, the digested samples were diluted to a final volume of 20 mL and mineral element concentrations of plants were determined using inductively coupled plasma optical emission spectrometry (ICP-OES: PerkinElmer Optima 2100 DV, Waltham, MA) (Tošic et al. 2015). Analytical accuracy was verified using NIST SRM 1547 (peach leaf) certified reference material provided by the National Institute of Standards and Technology (USA).

Stomatal resistance measurements

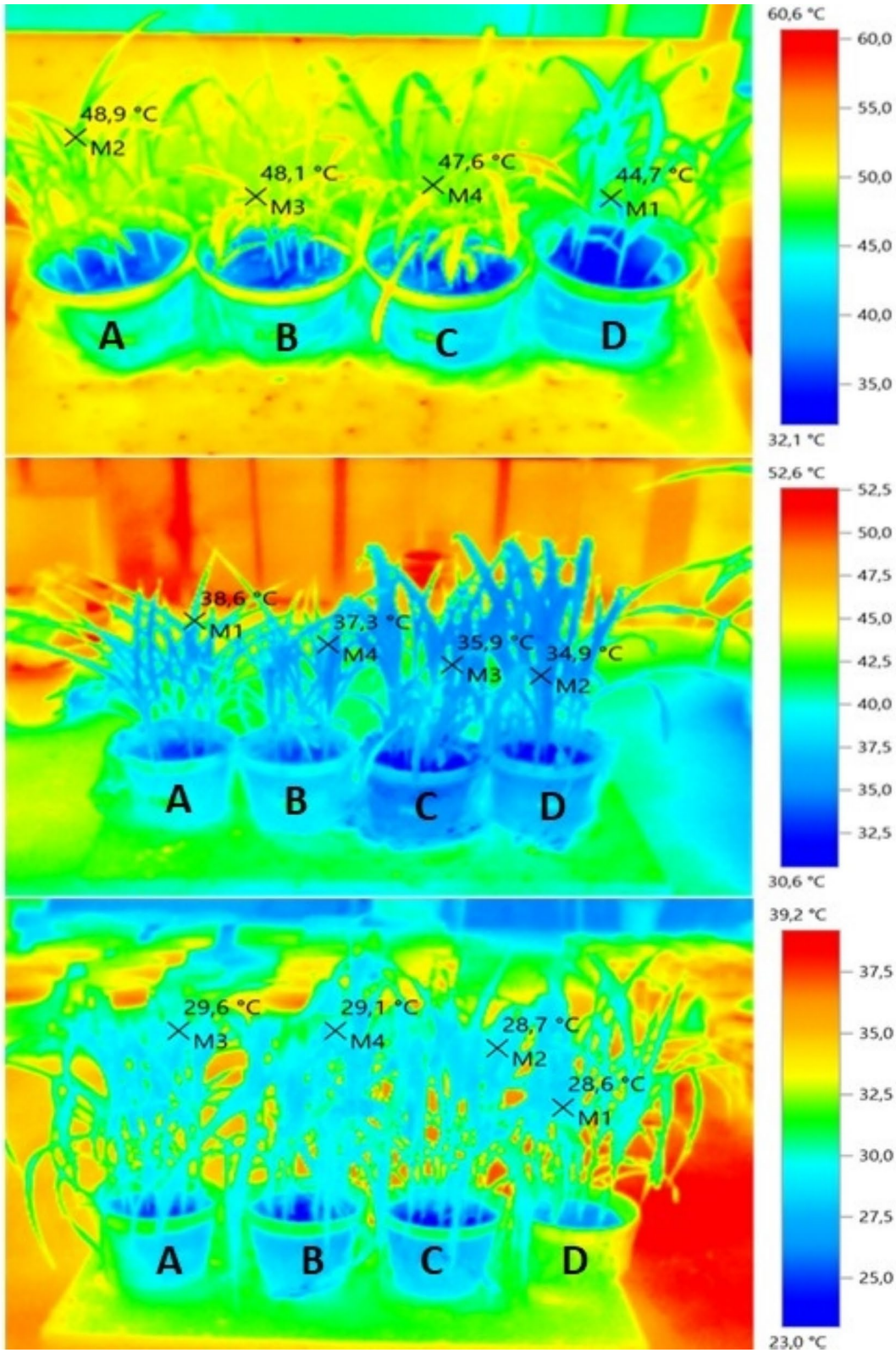
Stomatal resistance was measured using a steady-state porometer (ΔT Porometer AP4, Delta-T Devices, UK). Measurements were conducted at the end of the experiment on three randomly selected plants in each pot. Readings were taken from fully expanded, healthy leaves, and the porometer sensor head was placed on the abaxial surface of the leaf, avoiding major veins. To minimize diurnal and environmental variability, measurements were performed in the morning between 09:30 and 11:30 under steady photosynthetically active radiation (>400 µmol m^{-2} s^{-1}). During measurements, leaf temperature ranged between 28 ± 3 °C. For each plant, multiple readings were recorded from the same leaf and averaged to obtain a representative stomatal resistance value. Subsequently, mean stomatal resistance values were calculated for each pot by averaging measurements from the three plants. The instrument was calibrated and operated according to the manufacturer's guidelines, and measurements were conducted under stable environmental conditions to ensure consistency across treatments.

Thermal infrared image

Canopy temperature of maize plants was compared among treatments using an infrared thermal camera (Testo™ 875—1i, Germany). The thermal images were acquired from a fixed distance of approximately 1.0 m above the plant canopy, with the camera oriented perpendicular to the canopy surface to minimize angular distortion. The Testo infrared camera had a resolution of 160×120 pixels, a thermal sensitivity of <50 mK at 30 °C, and a temperature measurement range of −20 °C to 350 °C. All measurements were conducted under similar environmental conditions to ensure reliable comparison among treatments.

Determination of relative chlorophyll

Relative chlorophyll content was determined using a portable chlorophyll meter (CM 100, Spectrum Technologies Inc., USA). Measurements were conducted on fully expanded, healthy leaves of all plants in each pot immediately prior to harvest. To minimize diurnal variation, readings were taken during the morning hours between 10:30 and 12:30. For each plant, multiple readings were taken from the central portion of the leaf blade, avoiding the midrib, and the values were averaged to obtain a representative chlorophyll index per plant. Subsequently, mean chlorophyll


48,9 °C
M2
48,1 °C
M3
47,6 °C
M4
44,7 °C
M1
A
B
C
D
60,6 °C
60,0
55,0
50,0
45,0
40,0
35,0
32,1 °C
38,6 °C
M1
37,3 °C
M4
35,9 °C
M3
34,9 °C
M2
A
B
C
D
52,6 °C
52,5
50,0
47,5
45,0
42,5
40,0
37,5
35,0
32,5
30,6 °C
29,6 °C
M3
29,1 °C
M4
28,7 °C
M2
28,6 °C
M1
A
B
C
D
39,2 °C
37,5
35,0
32,5
30,0
27,5
25,0
23,0 °C

◂**Fig. 2** A: Thermal camera images of the second experiment, captured on August 2, 9, and 16, 2024. Panel **A** shows the control, while panels **B**, **C**, and **D** represent SW1, SW2, and SW3 treatments, respectively

values were calculated for each pot by averaging measurements from all plants within the pot. The chlorophyll meter was used according to the manufacturer's instructions, and measurements were performed under similar ambient light and temperature conditions to ensure consistency and comparability across treatments.

Number of stomata

Leaf samples were collected from the plants and stomatal measurements were done employing the nail varnish technique, which is widely used in scientific studies (Brewer 1992). Leaf imprints were taken from both abaxial and adaxial surfaces of the leaves. A thin layer of nail varnish was applied, and the samples were then allowed to dry at room temperature. Clear adhesive tape was then properly pressed onto the dried varnish and peeled off, capturing the epidermal imprint. These imprints were transferred to microscopic slides and photographed using a light microscope (LEICADM 1000, Leica Microsystems, Wetzlar, Germany) at 40 × magnification. Stomatal density (stomata mm^{-2}) was determined from microphotographs, covering an area of 0.055 mm^2.

Statistical analyses

The experiment was performed following a factorial design arranged in a completely randomized manner with four replications. Analysis of variance (ANOVA) was performed using Minitab software (version 17), and mean comparisons were conducted using Duncan's Multiple Range Test (Johnson and Bhattacharyya 2019).

Results

Chemical and functional properties of sheep wool

According to the analyses, SW composition was 82.2 g kg^{-1} N, 1.14 g kg^{-1} P, 102 g kg^{-1} K, 11 g kg^{-1} Ca, 1.12 g kg^{-1} Mg, 64 g kg^{-1} S, 380 mg kg^{-1} Fe, 133 mg kg^{-1} Zn, 9.8 mg kg^{-1} Cu, and 200 mg kg^{-1} Mn (Table 2).

Pelletized sheep wool was ground and applied to the soil. Therefore, to determine whether the structural integrity of SW was altered by the pelletizing process, the FTIR spectra of the pelletized SW used in the experiment were compared with those of RSW. The results showed that the peaks observed at 1047, 1211, 1519, and 1635 cm^{-1} in the RSW spectrum were slightly shifted to lower wavenumbers in the SW spectrum. Additionally, the FTIR peaks observed after 2000 cm^{-1} at 2333, 2927, 3277, 3718, and 3842 cm^{-1} were found to be similar between RSW and SW (Fig. 1).

Thermal camera imaging

Thermal camera images were taken only during the second experiment. As clearly observed in these images, the canopy temperatures of the plants were lower in the SW treatments, indicating reduced heat and water stress (Fig. 4).

Relative chlorophyll, stomatal resistance, and stomata number of plants

The relative chlorophyll content of the plants increased in response to SW applications. In the first experiment, the highest chlorophyll concentration was observed in the SW1 treatment (97.5:2.5 w/w), while in the second experiment, the maximum value was recorded in the SW2 treatment (98:2 w/w). In the first experiment, stomatal resistance increased, particularly in the treatment with the highest SW dosage. In contrast, in the second experiment, stomatal resistance significantly decreased with increasing levels of SW application. Moreover, higher levels of SW application resulted in a significant increase in stomatal density in both experiments (Table 3 and Figs. 5 and 6).

Pot weights measured at regular intervals

The pots, both with and without plants, were weighed before each irrigation to determine the amount of water retained in each treatment. In both experiments, throughout the measurement period, the pots treated with SW were consistently heavier than the control pots. This clearly indicated that the SW treated pots retained more water, whether under conditions of evapotranspiration or evaporation alone (Figs. 2 and 3).

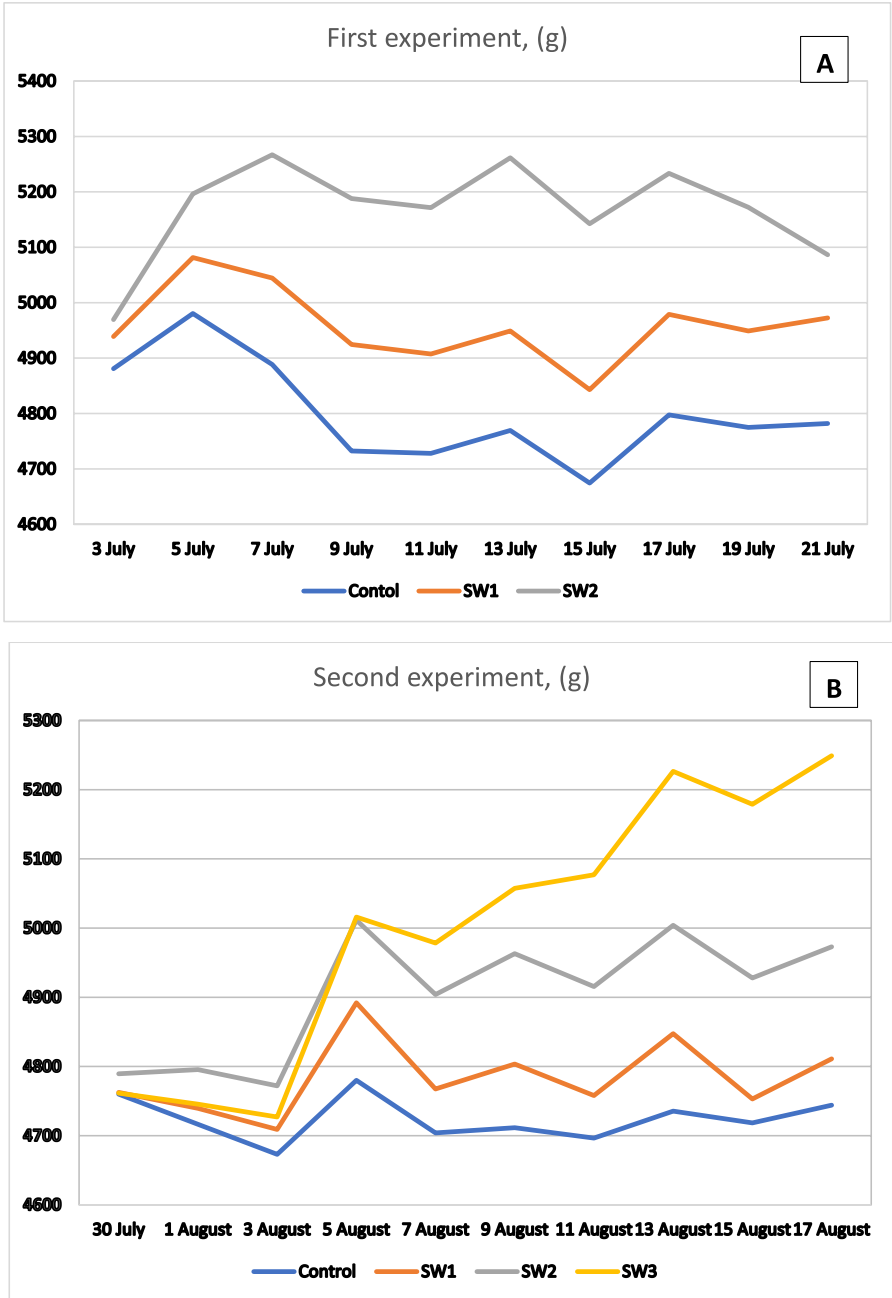


Fig. 3 Pot weights measured at specific intervals in the first (**A**) and second (**B**) experiments during the vegetation

Dry weights of plants

In the first experiment, the dry weight of maize plants increased significantly under the SW1 treatment (97.5:2.5 w/w, soil/SW) compared to the control. In contrast, the SW2 treatment (97.5:2.5 w/w, soil/SW) resulted in plant dry weights similar to those of the control group. Due to the negative effects of high SW doses on plant growth observed in the first experiment, the application rates were adjusted in the second trial. In the second experiment, maize dry weight increased significantly under the SW2 treatment (98:2

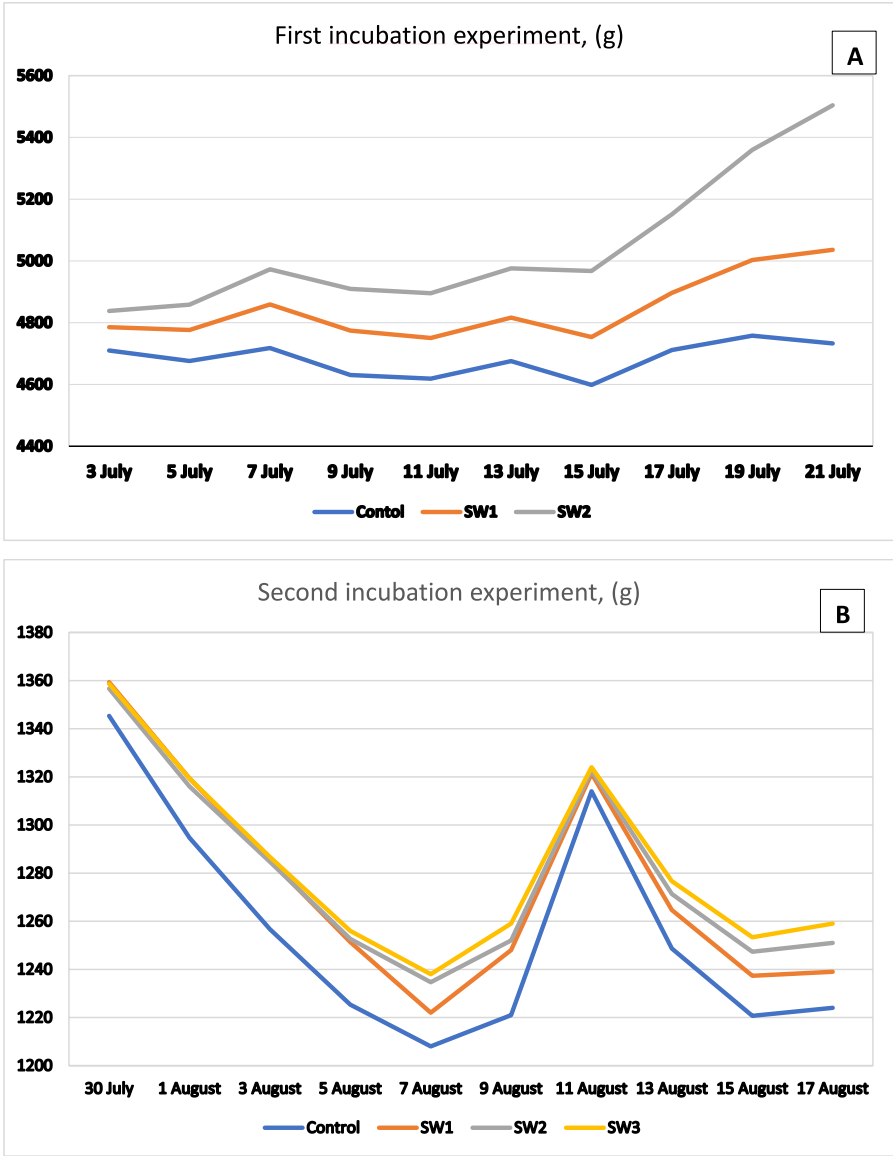


Fig. 4 Pot weights measured at specific intervals in the first (**A**) and second (**B**) incubation experiments without plants

w/w) compared to the control, whereas in the SW3 treatment (97:3 w/w), although still higher than the control, a reduction in plant dry weight was observed (Table 4).

Total-N, phosphorus, potassium, calcium, and magnesium concentrations of plants

In both experiments, the N and P concentrations in the plants increased significantly compared to the control group. In the first experiment, K concentration in plants increased from 52.5 g kg^{-1} in the control to 69.3 g kg^{-1} under the SW2 treatment. However, in the second experiment, the SW treatments had no significant effect on plant K concentration (Table 4).

The SW treatments had a notable effect on Ca concentration in the second experiment. While the Ca concentration in control plants was 3.14 g kg^{-1}, it increased to 6.08 g kg^{-1} under the SW3 treatment (Table 4).

In the first experiment, plant Mg concentrations decreased with SW applications, whereas in the second experiment, Mg concentrations increased, particularly under the SW1 and SW2 treatments (Table 4).

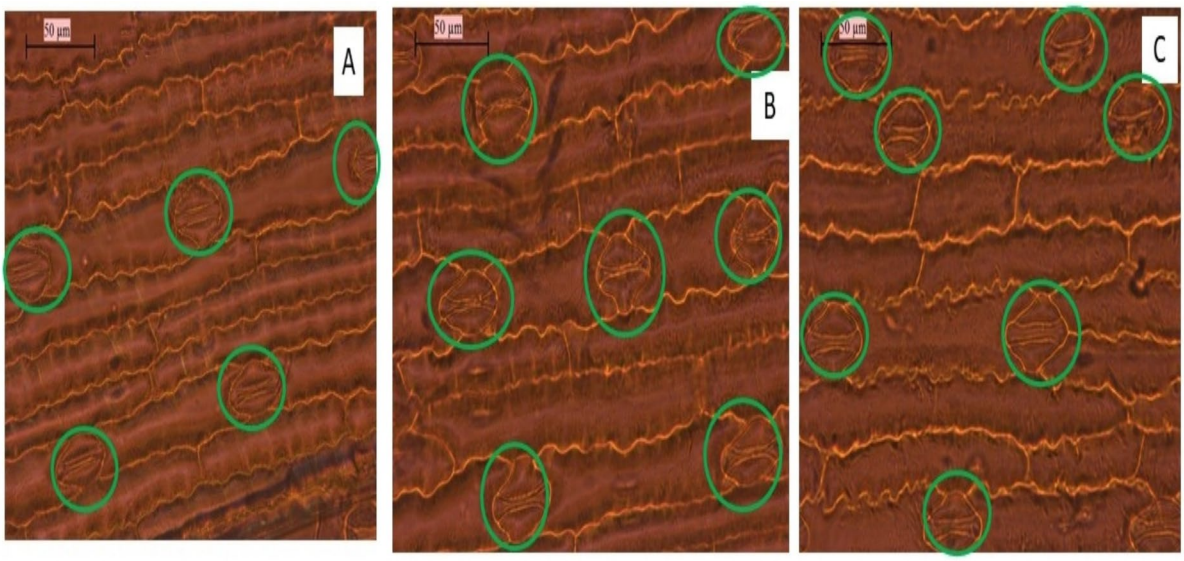


Fig. 5 Images showing the number of stomata on maize leaves in the first experiment: **A**) Control, **B**) SW1, and **C**) SW2 treatments

Iron, manganese, zinc, copper and boron concentrations of plants

Although SW treatments generally had a positive effect on plant Fe concentrations, the increases were not statistically significant. In contrast, SW treatments significantly affected Mn and Zn concentrations in both experiments. Similarly, Cu concentrations in the plants increased in the second experiment as a result of SW treatments. While SW treatments also appeared to positively influence B concentrations in both experiments, these increases were not statistically significant (Table 5).

Table 2 Some of the element concentrations of sheep wool (SW)

Properties	SW
N, g kg^{-1}	82.2
P, g kg^{-1}	1.14
K, g kg^{-1}	102
Ca, g kg^{-1}	11.0
Mg, g kg^{-1}	1.12
S, g kg^{-1}	64.0
Fe, mg kg^{-1}	380
Zn, mg kg^{-1}	133
Cu, mg kg^{-1}	9.8
Mn, mg kg^{-1}	200

Discussion

FTIR analysis was conducted to evaluate whether the pelletizing process induced structural changes in SW. A comparison of spectra from raw sheep wool (RSW) and pelletized SW showed minor shifts in characteristic peaks at 1047, 1211, 1519, and 1635 cm^{-1} associated with the functional groups of keratin toward lower wavenumbers in the pelletized sample. The peak around 1047 cm^{-1} is often assigned to C-O or C-N stretching vibrations. The 1211 cm^{-1} band may be linked to amide III, while the peak at 1519 cm^{-1} represents amide II. The band at 1635 cm^{-1} is characteristic of amide I. These FTIR peaks of SW were consistent with those reported in previous studies (Urdanpilleta et al. 2022; Oussadi et al. 2025; Sahin et al. 2025). These slight shifts suggest minor alterations in protein conformation, likely due to heat or pressure applied during pelletization. In contrast, peaks above 2000 cm^{-1} remained unchanged, indicating the preservation of key functional groups. Overall, while pelletization may cause minor structural modifications, the molecular integrity of sheep wool is largely retained, supporting its continued

Table 3 Effect of sheep wool (SW) treatments on relative chlorophyll content, stomatal resistance and stomatal density measured in abaxial surface of the leaves in maize plants

Treatments	Relative chlorophyll	Stomata resistance s cm^{-1}	Stomata number mm^{-2}
Experiment 1			
Control	277 ± 7.58 b	9.26 ± 1.07 b	5.66 ± 0.30 b
SW1	356 ± 14.8 a	7.04 ± 0.72 b	6.66 ± 0.41 a
SW2	265 ± 10.6 b	14.9 ± 0.34 a	7.07 ± 0.28 a
F	18.9**	27.4**	4.58**
LSD	36.5	2.47	0.96
Experiment 2			
Control	166 ± 9.50 c	11.2 ± 0.90 a	6.33 ± 0.25 b
SW1	207 ± 8.39 b	7.61 ± 0.27 b	7.00 ± 0.14 ab
SW2	245 ± 9.14 a	5.15 ± 0.82 c	7.68 ± 0.29 a
SW3	225 ± 8.70 ab	4.05 ± 0.34 c	7.60 ± 0.29 a
F	14.2**	23.9**	6.21**
LSD	27.6	2.00	0.71

The values are means of four replicates ± standard errors. Different letters in each column represent significant difference at $p < 0.05$ level based on Duncan's multiple range test. ** $p < 0.01$

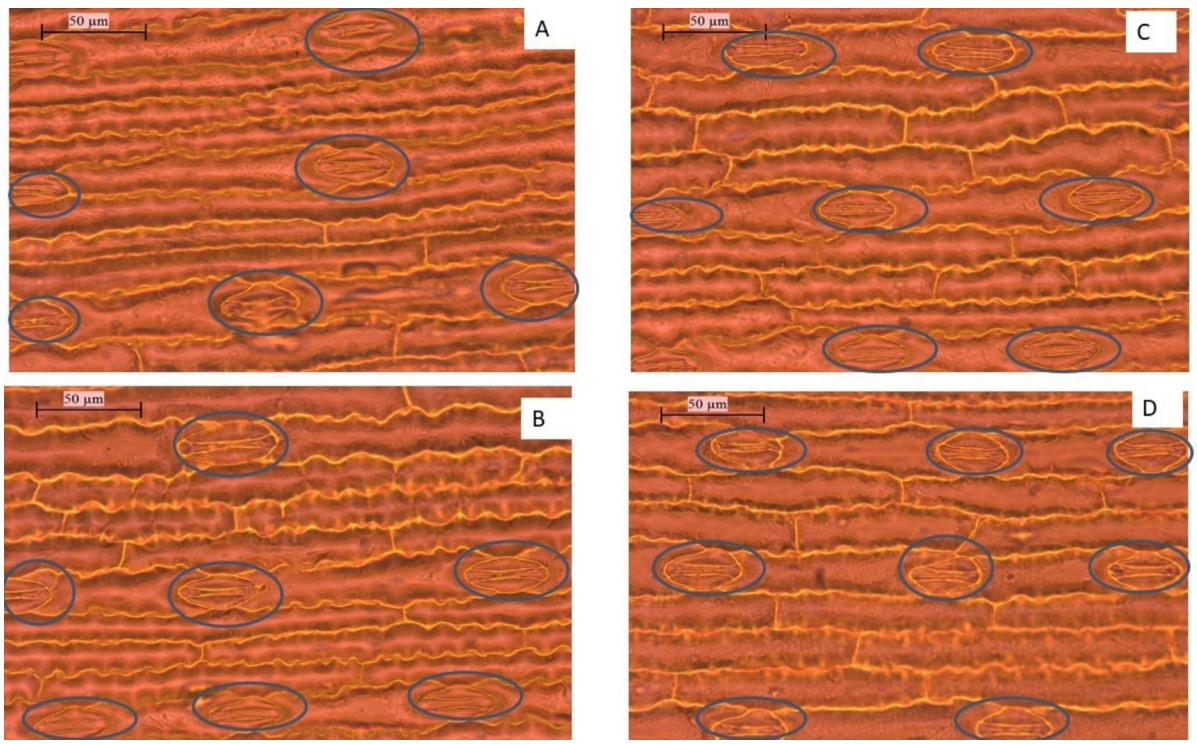


Fig. 6 Images showing the number of stomata on maize leaves in the second experiment: **A**) Control, **B**) SW1, **C**) SW2 and **D**) SW3 treatments

efficacy as an organic soil amendment. This preservation of keratin structure is particularly important because it governs the resistance of SW to rapid biodegradation, thereby influencing both its water retention behavior and its delayed nutrient release in soil systems.

There are only a limited number of scientific studies reporting that the application of SW to soil

Table 4 Effect of sheep wool treatments on dry weight, and the concentrations of nitrogen (N), phosphorus (P), potassium (K), calcium (Ca) and magnesium (Mg)

Treatments	Dry weight g	N g kg^{-1}	P g kg^{-1}	K g kg^{-1}	Ca g kg^{-1}	Mg g kg^{-1}
Experiment 1						
Control	24.2 ± 2.35 b	25.8 ± 0.88 b	2.60 ± 0.11 b	52.5 ± 3.58 b	4.70 ± 0.11	4.46 ± 0.14 a
SW1	29.8 ± 0.21 a	37.6 ± 0.57 a	3.44 ± 0.14 a	55.9 ± 1.58 b	5.26 ± 0.40	3.17 ± 0.04 b
SW2	23.7 ± 1.62 b	39.8 ± 0.66 a	3.16 ± 0.29 ab	69.7 ± 3.93 a	4.22 ± 0.66	2.74 ± 0.14 c
F	4.19*	110**	4.80*	8.07**	1.32^{ns}	57.9**
LSD	5.29	2.30	0.62	10.3	-	0.38
Experiment 2						
Control	16.8 ± 0.50 c	19.9 ± 0.27 c	1.52 ± 0.03 d	52.5 ± 1.32	3.14 ± 0.09 c	2.82 ± 0.08 c
SW1	17.9 ± 1.39 BC	40.9 ± 1.03 a	2.72 ± 0.06 c	44.8 ± 0.47	4.49 ± 0.21 b	4.17 ± 0.09 a
SW2	20.5 ± 0.54 a	36.9 ± 0.97 b	2.59 ± 0.17 b	47.5 ± 3.99	5.06 ± 0.52 b	3.66 ± 0.34 ab
SW3	19.9 ± 0.54 ab	36.9 ± 0.77 b	2.59 ± 0.09 a	53.1 ± 1.95	6.08 ± 0.34 a	3.20 ± 0.22 BC
F	4.11**	130**	30.5**	2.96^{ns}	13.7**	7.53**
LSD	2.57	2.52	0.31	-	1.02	0.66

The values are means of four replicates ± standard errors. Different letters in each column represent significant difference at $p < 0.05$ level based on Duncan's multiple range test. ns: non-significant; * $p < 0.05$; ** $p < 0.01$

Table 5 Effect of sheep wool treatments on iron (Fe), manganese (Mn), zinc (Zn), copper (Cu) and boron (B) concentrations in maize plants

Treatments	Fe mg kg^{-1}	Mn mg kg^{-1}	Zn mg kg^{-1}	Cu mg kg^{-1}	B mg kg^{-1}
Experiment 1					
Control	92.6 ± 5.12	71.2 ± 1.60 b	19.6 ± 0.20 b	7.56 ± 0.21	30.7 ± 6.68
SW1	102 ± 20.5	84.9 ± 3.25 ab	24.1 ± 1.66 ab	8.13 ± 0.22	42.0 ± 3.08
SW2	78.4 ± 9.09	99:3 ± 7.02 a	28.2 ± 2.57 a	8.24 ± 0.19	45.1 ± 5.68
F	0.83^{ns}	9.48**	6.03*	3.43^{ns}	2.01^{ns}
LSD	-	14.6	5.67	-	-
Experiment 2					
Control	83.1 ± 12.9	43.5 ± 1.23 c	18.7 ± 0.83 b	4.56 ± 0.22 c	36.0 ± 4.49
SW1	119 ± 23.8	69.5 ± 2.05 b	26.1 ± 1.17 a	7.23 ± 0.21 ab	34.3 ± 2.42
SW2	141 ± 26.6	74.5 ± 6.81 ab	26.8 ± 1.19 a	7.68 ± 0.38 a	37.3 ± 5.21
SW3	130 ± 37.0	84.2 ± 5.08 a	27.5 ± 2.47 a	6.64 ± 0.21 b	40.0 ± 2.11
F	0.90^{ns}	15.5**	6.83**	27.0**	0.39^{ns}
LSD	-	13.6	4.77	0.82	-

The values are means of four replicates ± standard errors. Different letters in each column represent significant difference at $p < 0.05$ level based on Duncan's multiple range test. ns: non-significant; * $p < 0.05$; ** $p < 0.01$

positively influences agricultural productivity by enhancing water retention capacity. These studies have demonstrated that sheep wool has a remarkable ability to absorb and retain water in the soil. Sheep wool fibers can absorb up to 400 times their own weight in water and gradually release this moisture during periods of plant water demand (Gitea et al. 2024). Furthermore, SW contributes to improving the physical structure of the soil, helping to retain water for longer periods. This characteristic is particularly beneficial in sandy and permeable soils, where it reduces rapid drainage and allows plants prolonged access to water. SW has also been reported to increase the organic matter content of the soil.

In line with previous findings, our study demonstrated that SW applications significantly improved water-holding capacity of the soil in both experimental setups. Thermal imaging revealed lower canopy temperatures in SW-treated plants, while pot weight measurements confirmed higher moisture retention. Mechanistically, these effects can be attributed to the fibrous structure of SW, which increases soil porosity while simultaneously enhancing capillary water retention, leading to a more favorable balance

between air-filled and water-filled pores. Additionally, the incorporation of SW likely reduced soil bulk density and improved aggregation, thereby slowing water loss through evaporation and drainage. The observed decrease in stomatal resistance and increase in stomatal density further indicate reduced drought stress. These physiological responses suggest that improved soil moisture availability under SW treatments allowed plants to maintain stomatal function and transpiration, thereby supporting photosynthetic activity under water-limited conditions.

Our findings also demonstrate that SW application enhanced water use efficiency in maize, as evidenced by thermal imaging and increased pot weights. Remarkably, clear increases in plant biomass were observed at soil/SW mixing ratios of 97.5:2.5 or 98:2. However, higher SW proportions reduced biomass. This response can be explained by potential trade-offs in soil physical conditions; excessive SW may increase macroporosity and reduce soil-root contact, or temporarily immobilize nitrogen due to microbial activity associated with keratin degradation. Thus, the effectiveness of SW appears dose-dependent. This dose-dependent behavior highlights the importance of optimizing SW application rates to balance improved water retention with adequate aeration and nutrient availability.

When plant-available water is retained for longer periods, nutrient uptake is also expected to increase (Marschner 2012). In addition, SW contains essential nutrients such as N, K, and S, which may be gradually released during mineralization (Akca et al. 2023; Taskin et al., 2024). In our study, SW applications increased N, P, Mn, and Zn concentrations in plant tissues. This suggests that SW may act as a slow-release nutrient source; however, the absence of direct measurements of decomposition rate and mineralization dynamics limits confirmation of this mechanism. It is also likely that improved soil moisture enhanced nutrient diffusion and mass flow toward roots, contributing to increased uptake independently of direct nutrient release from SW.

Although not consistent across both experiments, Ca and Cu uptake appeared to improve in the second experiment. These inconsistencies between the two experiments may reflect variations in environmental conditions (e.g., temperature, evaporation rates), microbial activity, or differences in SW decomposition stage over time. It is well known that Ca uptake is closely related to soil moisture, as it is transported primarily via mass flow. Therefore, differences in soil moisture dynamics between experiments may explain the variable responses observed for Ca and Cu. Such variability highlights the complexity of SW-soil–plant interactions and indicates that responses may not be uniform across different conditions. Another important aspect is the role of microbial activity in SW decomposition. Keratin is a recalcitrant protein that requires specialized microorganisms for degradation such as keratinolytic bacteria and fungi. Therefore, the rate of SW mineralization and subsequent nutrient release is likely governed by microbial community composition and activity, which were not assessed in this study. This represents a key limitation in understanding the mechanistic basis of the observed plant responses. Finally, it is important to acknowledge that this study was conducted under controlled pot conditions, which may not fully represent field environments. Pot experiments restrict root growth, alter soil structure, and may exaggerate water retention effects compared to field soils. Therefore, while the results provide clear evidence of SW effects on soil moisture and plant response, their magnitude and consistency under field conditions remain uncertain.

Conclusion

Sheep wool (SW) unsuitable for the textile industry is commonly disposed of through incineration despite its potential agronomic value. This pot-based study indicates that SW application can improve soil water retention and plant water status in maize under controlled greenhouse conditions, suggesting its potential as a soil amendment in water-limited systems. These findings are strictly limited to pot-scale observations and should be interpreted with caution when considering field applications. The observed improvements in plant performance are primarily attributed to changes in soil physical properties, including enhanced water-holding capacity, improved pore structure, and potentially increased soil aggregation. Although the keratin-rich composition of SW suggests a contribution to nutrient supply, the lack of direct measurements of decomposition rates and nutrient-release dynamics prevents definitive conclusions regarding its role as a fertilizer source. Additionally, microbial processes governing keratin degradation were not evaluated,

further limiting mechanistic interpretation. Inconsistencies observed between the two experiments indicate that SW effects may vary depending on environmental conditions and system dynamics, highlighting the need for further investigation under more variable conditions. Furthermore, the absence of field-level validation represents a major limitation, as soil heterogeneity, climate variability, and management practices may significantly influence SW performance. Accordingly, no broad agronomic recommendations can be made at this stage. SW should be considered a promising but still experimental soil amendment whose effectiveness must be validated beyond controlled conditions. Future research should focus on quantifying SW decomposition rates, characterizing nutrient-release patterns, and elucidating the role of microbial communities in keratin mineralization. Long-term field experiments are essential to evaluate the stability, agronomic efficiency, and economic feasibility of SW under realistic farming conditions. This study provides preliminary evidence of the potential of SW as a sustainable soil amendment, with its broader applicability dependent on further mechanistic understanding and field-scale validation.

Author contributions Ozge Sahin: Data curation; Formal analysis; Methodology; Funding acquisition; Investigation; original draft; Writing; Selver Kan: Formal analysis; Investigation; Fatma Gokmen Yılmaz: Formal analysis; Gamze Cakirer Seyrek: Formal analysis. Mohd Kamran Khan: Writing-editing; Sait Gezgin: Formal analysis; Writing-editing; Aydin Gunes: Conceptualization; Methodology; Data curation; Investigation; Roles/Writing – original draft; Writing–editing;

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Data availability The data that support the findings of this study are available from the corresponding author upon reasonable request.

Declarations

Conflict of interest The authors declare that they have no competing interests.

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