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Determination of the Effects of Pelletized Sheep Wool on Blossom-End Rot in Tomatoes Using Fourier Transform Infrared Spectroscopy

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ABSTRACT

Blossom-end rot (BER) is a physiological disorder in tomatoes caused by calcium (Ca) deficiency, often due to factors like poor irrigation, salinity, and high humidity that disrupt transpiration of plants. This study evaluated the effects of Pelletized Sheep Wool (PSW) on BER in tomatoes, enhancing fruit yield, and influencing mineral nutrition. PSW was applied to tomato plants at levels of 5, 10, and 20 g kg⁻¹, and the number of BER, as well as the concentrations of Ca, Mg, N, K, and B in the leaves and fruits, were determined. FTIR analysis was conducted on the upper and bottom parts of the tomato fruits to assess the effects of the treatments on the fruit's functional groups. PSW treatments effectively reduced BER, with 0% BER observed in the PSW 5 and 10 g kg⁻¹ doses, and only 5.26% in the PSW 20 g kg⁻¹ dose, compared to 20% in the control group. PSW treatments increased tomato fruit weight, with fruit fresh weight rising from 164 g in control to 239 g in the PSW 20 treatment. While PSW positively affected Ca, B, and N concentrations. FTIR analysis showed that PSW treatments influenced the biochemical composition of the fruits, with significant changes in lipid and protein content, particularly in the bottom parts of the fruits. These findings suggest that PSW is a promising natural amendment for improving tomato fruit yield and preventing BER, with potential impacts on cell walls and metabolic processes.

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Boron; calcium deficiency;
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Introduction

Blossom-end rot (BER) is one of the most severe physiological disorders affecting various crops, particularly tomato, as well as pepper, watermelon, and eggplant (Hagassou et al. 2019; Zhang et al. 2019). This disorder is primarily caused by Ca deficiency, often exacerbated by moisture stress, irregular watering practices, high relative humidity, and saline soil conditions (Hagassou et al. 2019; Reitz, Shackel, and Mitcham 2021). Water uptake, movement, and plant-water relations play essential roles in Ca absorption and distribution within plant tissues, plants absorb Ca from the soil or growing media and transfer it to the root xylem and further transport in leaves or fruits occurs via both apoplastic and symplastic pathways (Clarkson 1984; Hocking et al. 2016; Sethi, Dhaka, and Bari 2024)

Calcium is a key nutrient required for the cell wall structure, signaling and stress response, cell growth, plant tissue development, and membrane stability (Dodds, Kudla, and Sanders 2010). Regulation of Ca ion concentrations in the cytoplasm, apoplast, and organelles is used by the plant as a signaling mechanism (Marschner 2012). Furthermore, Ca stabilizes the plasma membrane and pectin constituents in the cell wall (Hocking et al. 2016).

Tomato fruit growth and development are predominantly associated with cytosolic Ca concentration. Several studies signify that the main cause of BER is a localized deficiency of Ca in the distal fruit tissue, due to defective local Ca transport or imbalanced incorporation of Ca with the pectin, a cell wall component (Adams and El-Gizawy 1988; de Freitas et al. 2012; Taylor and Locascio 2004).

Growing global waste generation is one of the most pressing environmental challenges today. This trend is primarily driven by population growth, economic development, and rapid urbanization, particularly in developing countries. It is projected that by 2050, annual global waste generation will reach 27 billion tons (Kumar and Agrawal 2020). As a result, there is an urgent need for effective solutions and technologies to minimize waste, focusing on proper waste disposal management and waste-to-value processes (Akca et al. 2023; Midolo et al. 2024). Sheep wool is a keratin-rich by-product of sheep farming and the textile industry. Due to the complex structure of keratin, these wastes are highly resistant to degradation (Petek and Marinšek Logar 2021). As a result, most of these waste materials are either incinerated or sent to landfills, raising environmental concerns. However, these wastes hold potential as effective fertilizers and soil conditioners (Akca et al. 2023). As SW is increasingly becoming a waste material, recent studies have been conducted to determine the effectiveness of this valuable material as a fertilizer and soil conditioner (Akca et al. 2023; Broda et al. 2023; Cetin Karaca, Chalabee, and Saba 2023; Taskin 2024). Among these studies, Akca et al. (2023) and Taskin (2024) found that the application of SW positively affected Ca nutrition in sugar beet leaves. The improvement in Ca nutrition in sugar beets may be attributed to the ability of SW to increase and maintain the availability of usable water in the soil. Under normal conditions, SW is a hydrophobic material (Erkmen and Sari 2023; Rajabinejad, Bucişcanu, and Maier 2019), however, when compressed into pellets, it becomes an organic material with high water retention capacity. When applied to soil, SW can provide the following advantages. The fibrous structure of sheep wool allows it to retain water in the soil, making it available for plant roots (Haque and Naebe 2022; Marczak et al. 2023). This is particularly beneficial in light textured soils, where it can prevent rapid drainage and enhance the water-holding capacity of soils. As an organic material, SW improves the physical structure of soils, helping water to distribute more evenly (Juhos et al. 2023; Kadam et al. 2014). This facilitates deeper water infiltration and reduces water loss through evaporation. When SW is applied as a surface layer, it can reduce water evaporation and help maintain soil moisture for extended periods (Sharma, Sahoo, and Chand 2019). A more stable moisture level in the soil can facilitate the uptake of Ca and other nutrients by plant roots (Marschner 2012). This, in turn, contributes to the prevention of physiological disorders such as BER in tomato. These effects can vary depending on factors such as the decomposition rate of the SW, the application rate, and the initial properties of the soil. This study aims to evaluate the effectiveness of PSW as a soil amendment in mitigating BER in tomatoes by improving Ca availability and plant transpiration under conditions.

Materials and methods

Chemical analysis and characterization of sheep wool

Pelletized sheep wool (PSW) used in this study was purchased from a private company. PSW was digested with an acid mixture of $\text{HNO}_3\text{-HClO}_4$ (4:1) on a hot plate at 100°C . P, K, Ca, Mg, Fe, Zn, Cu, Mn and B concentrations in the digested sample were determined by ICP-OES (Perkin Elmer Optima 2100 DV, USA). Total N was determined according to the Kjeldahl method (Moore et al. 2010). The total macro and micro element concentration of SW was given in Table 1. The functional groups of PSW were analyzed using Fourier Transform Infrared Spectroscopy (FTIR). IR spectra within the range of $500\text{--}4000\text{ cm}^{-1}$ were obtained using a Shimadzu Infinity FTIR Spectrometer equipped with three reflective ATR units.

Table 1. Some physical and chemical properties of the experimental soil and pelletized sheep wool (PSW).

Properties (Method)	Soil	PSW
Texture (Bouyoucos)	C	–
pH (1:2.5 water/1:5 water)	8.28	9.55
EC (1:2.5 water/1:5 water), dS m ⁻¹	0.32	13.7
CaCO ₃ (Scheibler), g kg ⁻¹	82.1	–
Organic matter (Walkley-Black), g kg ⁻¹	10.5	–
Organic matter (loss of weight 550 °C), g kg ⁻¹	–	827
Total N, g kg ⁻¹	3.30	98.0
P (NaHCO ₃), mg kg ⁻¹	3.93	–
Total P, g kg ⁻¹	–	1.43
K (NH ₄ OAc-extractable), mg kg ⁻¹	868	–
Total K, g kg ⁻¹	–	47.3
Ca (NH ₄ OAc-extractable) mg kg ⁻¹	6811	–
Total-Ca, g kg ⁻¹	–	21.4
Mg (NH ₄ OAc-extractable), mg kg ⁻¹	1321	–
Total Mg, g kg ⁻¹	–	4.78
Zn (DTPA-extractable), mg kg ⁻¹	0.42	–
Total Zn, mg kg ⁻¹	–	139
Fe (DTPA-extractable), mg kg ⁻¹	1.90	–
Total Fe, g kg ⁻¹	–	3711
Cu (DTPA-extractable), mg kg ⁻¹	1.70	–
Total Cu, mg kg ⁻¹	–	14.2
Mn (DTPA-extractable), mg kg ⁻¹	5.58	–
Total Mn, mg kg ⁻¹	–	101
B (NaOAc-extractable), mg kg ⁻¹	1.50	–

Plant growth conditions and treatments

The experiment was conducted in 12 kg pots (29.5 cm length, 34.0 cm top and 25.5 cm bottom diameter) under controlled greenhouse conditions at the Department of Soil Science and Plant Nutrition, Ankara University, Turkey, from May 19, 2023, to August 18, 2023, with tomato (*Solanum lycopersicum*, cv. Tomks) plant. The soil used in this study was obtained from the plow layer (0–20 cm) of an experimental field located at the Department of Soil Science and Plant Nutrition, Ankara University, Turkey (coordinates: 39° 57' 44.51" N, 32° 51' 46.95" E). The soil samples were air-dried and sieved to a particle size of 2 mm to determine chemical properties, following the method described by Page and Keeney (1982) and some soil properties were presented in Table 1. In the experiment, no basic fertilization was applied, only KNO₃ fertilizer was applied in solution form with 100 mg N kg⁻¹ as top-dressing fertilizer. The treatments included: (i) Control (ii) 5 g kg⁻¹ PSW; (iii) 10 g kg⁻¹ PSW; (iv) 20 g kg⁻¹ PSW. The selected doses, previously used in our study (Akca et al. 2023), were weighed accordingly, and the specified amounts of PSW were thoroughly mixed into the soil. One tomato seedling was sown in each pot. During the experiment, randomly selected pots were weighed every day. Tap water was added to all pots at the volume required to reach 70% of field capacity. During the harvest period, shoot and fruit sections were sampled separately. Shoot and fruit fresh weights were determined, and then the shoot and fruit samples were washed with tap and distilled water and then dried (65 °C) in an air-forced oven until moisture was completely removed. To determine the dry weight, dried shoot and whole fruits were weighted with precision balance (accuracy: 0.001 g). The dried samples were ground and passed through a 0.20-mm sieve for further analysis.

Chemical analysis in shoots and fruits

Plant samples were digested with HNO₃-HClO₄ acid mixture (Kalra1997). Total Ca, Mg and B concentrations were determined by ICP-OES (Perkin Elmer Optima 2100 DV, Waltham, MA, USA) and total N was determined according to the Kjeldahl method (Moore et al. 2010). The peach leaves received from the National Institute of Standards and Technology were used

as the standard reference material with the code of 1547. The nutrient content was calculated as a function of their concentration and respective dry weights. The functional groups of dried tomato fruits (upper and bottom parts) were analyzed using FTIR. A Shimadzu Infinity FTIR Spectrometer, equipped with three reflective ATR units, was used to obtain IR spectra in the range of 4000–500 cm^{-1} .

Experimental design and statistical analysis

The experimental design was a randomized complete plot design (RCPD) with four treatments and four replications. The significance of treatments was determined with one-way ANOVA, using ORIGINPRO 2021 software (Origin Lab Inc., Northampton, MA, USA). The significant differences among the treatment means were calculated by Tukey's honestly significant difference (HSD) test at $p < .05$ and descriptive statistics (\pm SE). The principal component analysis (PCA) was created using ORIGINPRO 2021 software.

Results

FTIR spectra of pelletized sheep wool

Fourier transform infrared spectra of biological materials like PSW are used to determine the presence of various functional groups and chemical bonds (Figure 1). The PSW used in the study exhibited distinct peaks at 3275, 2918, 2850, 2357, 2328, 1633, 1541, 1394, 1026, and 873 cm^{-1} .

Blossom end-rot symptoms

During the experiment, the percentage of fruits affected by BER among the total fruit count was determined. Accordingly, BER was observed in 20% of the fruits in the control group, whereas in the PSW 5 and 10 g kg^{-1} treatment doses, the BER rate was 0, and in the highest PSW dose, it was determined to be 5.26%.

Vegetative and fruit weights of tomato

The fresh weight of tomato shoots decreased in the PSW5 and PSW10 treatments, while at the PSW20 dose, the dry weight of the plants was the same as that of the control group. The dry weight of the shoots was lower only in the SW10 treatment compared to the other treatments. Unlike the shoot part, the fruit weight of tomatoes significantly increased with SW treatments compared to the control. While the fresh fruit weight in the control group was 164 g, it was determined to be 199 g, 221 g, and 239 g with the SW5, SW10, and SW20 treatments, respectively (Table 2). The shoot dry weight and fruit dry weights were also highly consistent with the fresh weights. The reason we have provided the fresh weights of the fruits here is to be able to determine the nutritional value of tomato fruits in their fresh state, if necessary.

Calcium, magnesium, nitrogen and boron concentration of tomato shoots

Pelletized sheep wool applications significantly increased the shoot calcium concentration in tomatoes. Similarly, the application of 5 g kg^{-1} increased the boron concentration in tomato shoots compared to the control. In contrast, PSW applications did not have a significant effect on the shoot magnesium and nitrogen concentrations (Table 3).

Table 5. The effect of increasing doses of pelletized sheep wool (PSW) applications on boron (B) and nitrogen (N) concentration and content of bottom and upper part of tomato fruits.

PSW Treatments, g kg ⁻¹	Bottom part of fruit			
	B concentration, mg kg ⁻¹	B content, µg fruit ⁻¹ , dw	N concentration, g kg ⁻¹	N content, mg fruit ⁻¹ , dw
0	20.2 ± 2.15	162 ± 22.9	28.9 ± 1.89 b	240 ± 45.3
5	23.4 ± 3.25	236 ± 48.0	30.9 ± 0.79 ab	303 ± 19.8
10	34.1 ± 7.03	347 ± 64.7	33.9 ± 3.18 a	357 ± 33.1
20	29.5 ± 1.32	279 ± 33.7	32.9 ± 1.68 ab	310 ± 33.7
F	2.34 ^{ns}	2.98 ^{ns}	4.64*	1.96 ^{ns}
	Upper part of fruit			
0	26.7 ± 2.68	179 ± 24.5 c	26.4 ± 0.66 b	177 ± 17.6 c
5	39.9 ± 2.06	332 ± 6.60 b	28.4 ± 1.34 ab	318 ± 21.4 b
10	32.7 ± 3.07	458 ± 24.8 a	31.4 ± 0.31 a	478 ± 24.2 a
20	26.2 ± 2.78	325 ± 33.0 b	29.7 ± 0.71 ab	372 ± 36.7 ab
F	1.30 ^{ns}	22.1**	6.41*	19.2**

The values are means of four replicates ± standard errors. Different letters in each column represent significant difference at $p < .05$ level based on Tukey's honestly significant difference (HSD) test. ns: not significant; * $p < .05$; ** $p < .01$. dw: Dry weight.

The Mg concentrations and contents in the upper parts of the fruits increased regardless of the PSW doses. No significant difference was observed in the Mg concentrations and contents in the bottom parts of the fruits (Table 4).

While PSW treatments had a positive effect on the B concentration in both the upper and bottom sections of the fruits, these effects were not statistically significant. However, the B content in the upper parts of the fruits significantly increased with PSW applications (Table 5).

The N concentration in the fruits significantly increased with the 10 g kg⁻¹ dose of PSW compared to the control. The N contents also increased in response to increasing PSW doses (Table 5).

FTIR spectra of upper and bottom part of tomato

The peaks obtained by FTIR reflect the functional groups of the chemical components present in the tomato fruit. In tomatoes grown in the control group, the peaks identified at 2920 and 2850 cm⁻¹ correspond to C-H stretching vibrations, which are found in organic compounds such as lipids and carbohydrates (Figure 2(A)). These peaks can be specifically associated with saturated and unsaturated fatty acids. They were prominently measured in both the upper and bottom parts of the fruits. Similar peaks were also observed in PSW treatments (Figure 2(B–D)). In the control group, the peak observed around 1732 cm⁻¹ in the upper part of the fruit corresponds to C = O (carbonyl) stretching vibrations, which are characteristic of functional groups found in esters or lipids. In the bottom part of the fruit, this peak was detected at 1718 cm⁻¹, where it appeared weaker. However, in PSW treatments, especially at 5 and 10 g kg⁻¹ doses of PSW, these peaks were found to reappear around 1735 cm⁻¹ in the bottom part of the fruit. In the control group, the peak identified around 1606 cm⁻¹ is associated with aromatic C = C bonds or amide I bands in proteins. It was found to be more prominent at 1612 cm⁻¹ in the bottom part of the fruit. These peaks were observed closer to 1600 cm⁻¹, and they were more pronounced in both the upper and bottom parts of the fruit in PSW treatments. The C-H bending vibrations at 1394 and 1361 cm⁻¹ were detected in both parts of the fruit. Similar peaks were also observed in PSW treatments at nearby spectral regions. The C-O stretching vibration at 1230 cm⁻¹ may be related to phosphate groups or polysaccharides, which are particularly found in cell wall components. This peak was weakened in the lower part of the fruit. Similar peaks in close spectral regions were also observed in PSW treatments. The C-O and C-O-C stretching vibrations at 1037 cm⁻¹ are common in carbohydrates and polysaccharides, originating from cellulose, hemicellulose, and pectin. Similar peaks in close spectral regions were also detected in PSW treatments (Figure 2).

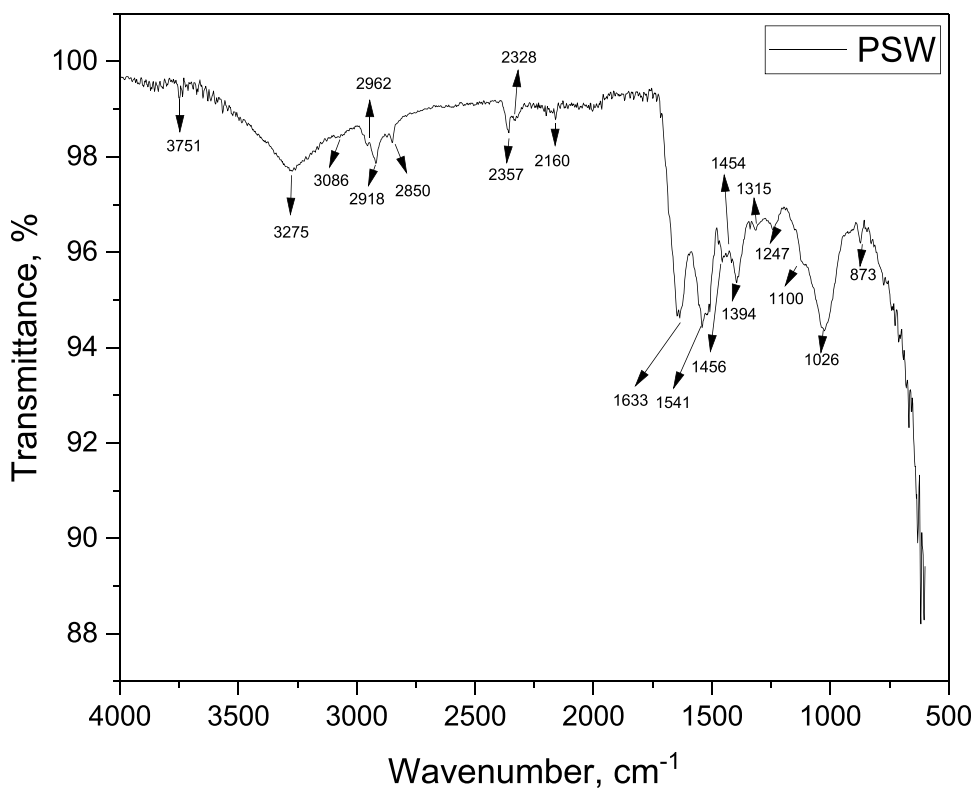


Figure 1. Fourier transform infrared spectroscopy spectrum of pelletized sheep wool (PSW).

Principle component analysis of experiment

Two components were derived from the PCA analysis of the tomato plant's upper and bottom mineral concentrations, accounting for 55.6% (PC1 = 38.1%; PC2 = 17.5%) (Figure 3). The component loadings indicated that shoot DW had the highest score (0.37) on component 1, followed by shoot FW (g) (0.34), upper N (g kg^{-1}) (0.33), and fruit DW (g) (0.32). Loads on component 1 indicate a positive correlation of fruit DW with fruit FW, upper Ca, upper Mg, upper N, upper B, bottom N, bottom B, shoot Ca, and shoot Mg; fruit DW (g) indicates a negative correlation with shoot DW, bottom Ca, bottom Mg, shoot N and shoot B (Figure 3).

Discussion

The FTIR peak identified at 3275 cm^{-1} in PSW corresponds to N-H stretching vibrations (amino groups), indicating the presence of amino groups or proteins such as keratin in the wool. The peaks at 2918 cm^{-1} and 2850 cm^{-1} correspond to C-H asymmetric and symmetric stretching vibrations and can be associated with the fats in the wool. The distinct peaks at 2357 cm^{-1} and 2328 cm^{-1} correspond to C=O stretching vibrations, which may indicate the presence of carbonates or organic acids. The peak at 1633 cm^{-1} represents the Amid I band, which points to protein structures, particularly keratin. The Amid II band peaks observed at 1541 cm^{-1} confirm the presence of protein structures in the sheep wool. The C-H bending vibration observed at 1394 cm^{-1} is related to the bending motion of methylene groups and indicates the presence of alkyl groups or lipids in the sheep wool. The C-O stretching vibration identified at 1026 cm^{-1} in the FTIR spectrum could indicate the presence of carbohydrates or alcohols in the wool. Since wool contains both protein and sugar components, this band could refer to wool structures. Finally, the

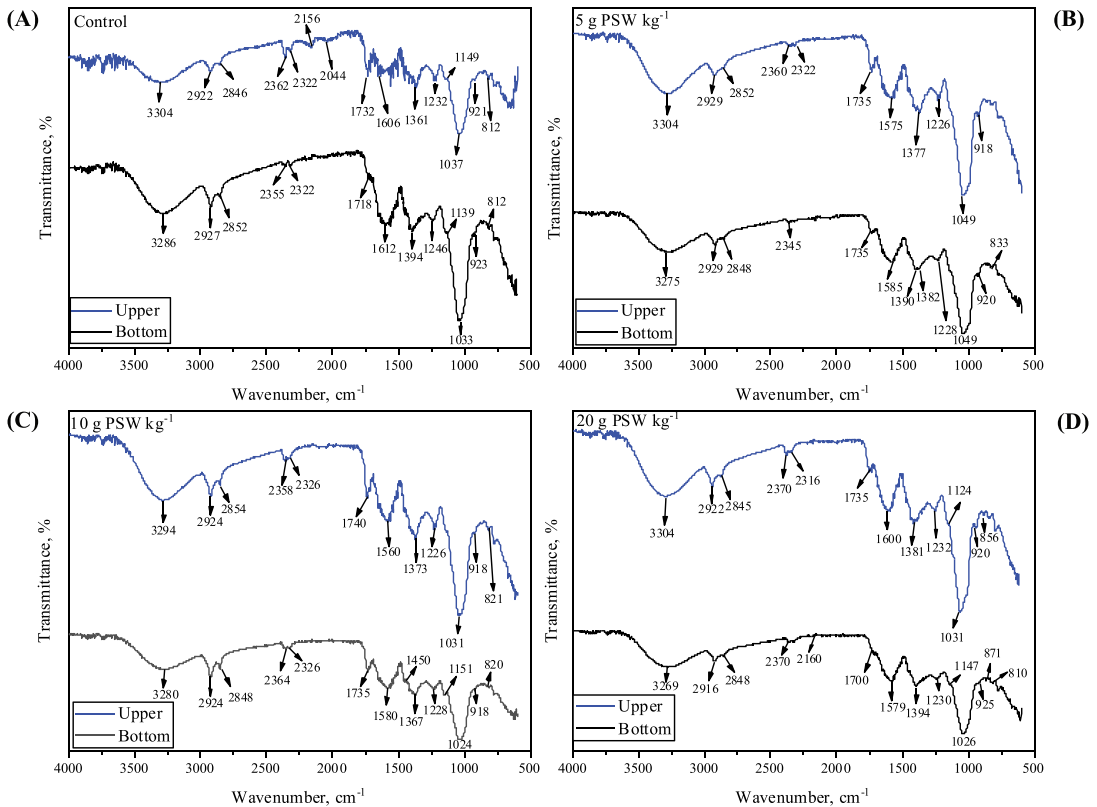


Figure 2. Fourier transform infrared spectroscopy spectrum of tomato fruits.

C-H bending vibration observed at 873 cm^{-1} is associated with the bending of alkyl groups (especially methyl and methylene groups), which may be linked to some structural components found in wool fibers. These peaks reveal the complex biological structure of PSW (proteins, fats, carbohydrates, and other organic compounds) and the presence of various functional groups. The FTIR spectrum is an effective tool for determining the structural characteristics and chemical groups of these components. The FTIR spectra identified in this study are in accordance with our previous work (Akca et al. 2023) and the findings of other researchers (Atbir et al. 2023; Enkhzaya et al. 2021).

This study investigated the effectiveness of PSW treatments in preventing BER in tomatoes. The analysis focused on Ca, Mg, B, and N, both in the plant and in the upper and bottom parts of the tomato fruits. Additionally, for the first time in the literature, FTIR measurements were conducted on tomato fruits to identify the changes caused by Ca deficiency. Blossom-end rot in fruits is primarily caused by insufficient Ca transport to the fruit, a critical element for cell wall strength and stability. Calcium deficiency leads to cell breakdown and tissue decay. However, this deficiency is often not due to a lack of Ca in the soil but rather to inadequate transport within the plant. Factors such as irregular watering, whether the soil is too dry or too wet, can impede Ca uptake. Furthermore, excessive N fertilization accelerates plant growth, favoring leaf development over fruit growth, thus hindering Ca allocation to the fruits. Salinity also suppresses Ca absorption (Hagassou et al. 2019; Reitz, Shackle, and Mitcham 2021). Both Ca and B significantly influence various fruit quality parameters, such as fruit cracking, color, firmness, BER, and sugar content in crops like tomatoes and strawberries (Huang and Snapp 2009; Wójcik and Lewandowski 2003). The occurrence of BER is influenced not only by Ca but also by B (Ashraf et al. 2018).

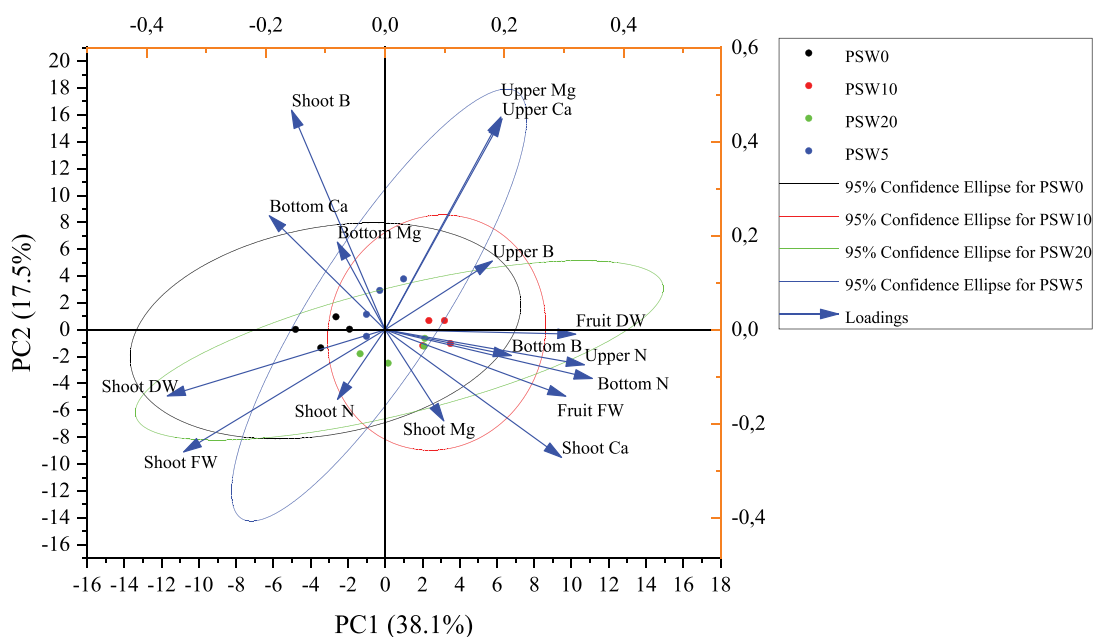


Figure 3. The biplots of principal component analyses (PCA) of increasing doses of pelleted sheep wool (PSW) applications on tomato plants.

The study assessed the effects of PSW treatments on BER, fruit yield, mineral nutrition and FTIR spectrums of tomatoes. Data collected during the experiment showed that PSW applications significantly reduced BER. While 20% of the control fruits exhibited BER, this percentage was reduced to zero in the PSW5 and PSW10 applications, and only 5.26% in the PSW20 applications. This indicates that PSW is highly effective in preventing BER, particularly at low and medium doses. Blossom end-rot is a physiological disorder linked to Ca deficiency, which arises from various environmental and nutritional factors that affect Ca transport to the fruits (Hagassou et al. 2019; Reitz, Shackel, and Mitcham 2021). The study showed that PSW treatments increased Ca concentration in tomatoes, and the increased fruit size led to a rise in total Ca content. Although PSW applications caused a slight increase in Ca concentration in the upper part of the fruit, this change was not statistically significant. However, PSW applications resulted in a two-fold increase in Ca content compared to the control plants. The lower Ca concentrations in the bottom sections of the fruit compared to the upper sections are essential for understanding BER formation and support previous studies on the impact of Ca distribution in fruit on BER development (Franco, Bañón, and Madrid 1994; Topcu, Nambeesan, and van der Knaap 2022) In our previous study (Akca et al. 2023) and in the studies conducted by Taskin (2024) with sugar beet, it was determined that PSW applications increased the Ca concentration in the sugar beet leaves.

In terms of shoot growth, fresh weight decreased in the PSW5 and PSW10 treatments, while the dry weight in the PSW20 treatment remained like the control group. PSW applications had a significant positive effect on fruit yield, with the average fruit weight increasing from 164 g in the control group to 199 g, 221 g, and 239 g in the PSW5, PSW10, and PSW20 treatments, respectively. This highlights the fruit size-enhancing effect of PSW. Some studies on sheep wool indicate that it has growth-promoting effects, particularly in sugar beet (Akca et al. 2023; Taskin 2024), pepper (Cetin Karaca, Chalabee, and Saba 2023) and wheat (Broda et al. 2023).

Pelleted sheep wool treatments increased Ca and B concentrations in tomato shoots but had no significant effect on Mg and N. In fruit tissues, Mg concentrations and contents in the upper sections of the fruit increased independently of PSW applications, whereas no significant changes were found

in the lower sections. PSW applications positively influenced B concentrations in both the upper and lower parts of the fruit, although the effects were not statistically significant. However, B content in the upper parts of the fruit increased significantly with PSW applications. Regarding nitrogen, the PSW10 application significantly raised N concentration in the fruits compared to the control. Nitrogen content also increased linearly with higher PSW doses, suggesting that PSW could potentially contribute to N supply. The positive effects of PSW applications on Ca and B, which are immobile elements in the phloem, can be explained by PSW's ability to ensure that water remains available to the plant for a longer period in the soil (Haque and Naebe 2022; Kadam et al. 2014; Sharma, Sahoo, and Chand 2019).

The FTIR analysis of tomato fruits provided valuable insights into the chemical composition and structural differences between the control group and PSW-treated samples. The spectral data revealed characteristic peaks corresponding to major biochemical constituents such as lipids, carbohydrates, proteins, and polysaccharides. The presence of C-H stretching vibrations at 2920 and 2850 cm^{-1} in both the upper and lower parts of the fruit indicate the abundance of lipids and carbohydrates. These peaks were also observed in PSW-treated samples, suggesting that the treatment did not significantly alter the overall lipid and carbohydrate composition but maintained the presence of these organic compounds. Given that these vibrations are associated with saturated and unsaturated fatty acids, it can be inferred that lipid metabolism remained largely unaffected by PSW treatment. A distinct carbonyl (C=O) stretching peak was identified at 1732 cm^{-1} in the upper part of the fruit in the control group, while a weaker peak at 1718 cm^{-1} was detected in the bottom part. This peak corresponds to functional groups found in esters and lipids, potentially arising from pectin, fatty acids, and carbohydrate derivatives. Notably, in PSW treatments, particularly at 5 and 10 doses, the reappearance of this peak around 1735 cm^{-1} in the lower part of the fruit suggests a possible reinforcement of ester-linked compounds, which could be linked to modifications in cell wall structure or lipid composition under treatment conditions. The peak at 1606 cm^{-1} in the control group, associated with aromatic C=C bonds and amide I bands in proteins, was found to be more pronounced at 1612 cm^{-1} in the lower part of the fruit. This peak is indicative of phenolic compounds and protein structures. The shift observed in PSW-treated samples, where the peak appeared closer to 1600 cm^{-1} and became more distinct in both fruit regions, suggests an increase in phenolic content or modifications in protein conformation, potentially due to the impact of PSW treatment on metabolic pathways related to secondary metabolites. The peaks at 1394 and 1361 cm^{-1} , corresponding to C-H bending vibrations associated with carboxylate salts and lipids, were present in both fruit regions and were similarly observed in PSW-treated samples. These findings indicate the continued presence of pectin, cellulose, and polysaccharides, essential components of the fruit's structural integrity. The maintenance of these peaks across treatments suggests that PSW does not significantly alter the fundamental polysaccharide composition. The 1230 cm^{-1} peak, indicative of C-O stretching vibrations related to phosphate groups or polysaccharides found in cell walls, showed a weakening in the lower part of the fruit in the control group. The presence of similar peaks in PSW-treated samples suggests that while some variations may occur, the overall integrity of the phosphate-containing polysaccharides remains consistent across treatments. The peak at 1037 cm^{-1} , corresponding to C-O and C-O-C stretching vibrations in carbohydrates and polysaccharides, was detected in both control and PSW-treated samples. This peak, associated with cellulose, hemicellulose, and pectin, highlights the structural components of the tomato fruit. The consistency of this peak in PSW-treated samples suggests that the treatment does not negatively impact carbohydrate integrity but may contribute to maintaining cell wall stability. Overall, the FTIR results indicate that PSW treatment does not drastically alter the fundamental biochemical composition of tomato fruits but may influence specific structural and metabolic pathways. The observed peak shifts and intensities suggest potential modifications in lipid composition, phenolic content, and cell wall components. There is no study attempting to explain the relationship between Ca nutrition and BER using FTIR. However, the fundamental FTIR spectra we identified in our

study were consistent with previous studies (Bunghez et al. 2011; Skolik, McAinsh, and Martin 2019) that determined FTIR analysis results for tomato fruit based on different criteria.

Conclusion

Pelletized Sheep Wool significantly reduced the occurrence of BER in tomatoes, demonstrating its potential as an effective tool for managing this Ca deficiency-related disorder. The results highlighted the role of PSW in improving Ca and B concentrations in tomato plants, which contributed to enhanced fruit quality and increased fruit yield. Additionally, FTIR analysis provided valuable insights into the structural and biochemical composition of the fruit, revealing modifications in lipid, phenolic, and polysaccharide content due to PSW treatment. Further studies are needed to investigate the long-term effects of PSW on nutrient dynamics and plant metabolism to fully understand its potential as a sustainable agricultural amendment.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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CRediT authorship contribution statement

Aydin Gunes: Conceptualization, Investigation, Methodology, Validation, Supervision, Writing – original draft, and Review & editing; **Mehmet Burak Taskin:** Formal analysis, review & editing; **Hanife Akca:** Formal analysis, Visualization, Writing– original draft, Review & editing; **Elif Sezen Civelek:** Formal analysis; **Erdal Emir:** Formal Analysis.

Data availability statement

The data supporting the findings of this study are available from the corresponding author, Aydin Gunes, upon reasonable request.

References

- Adams, P., and A. M. El-Gizawy. 1988. Effect of calcium stress on the calcium status of tomatoes grown in NFT. *Acta Horticulturae* 222:15–22. doi: [10.17660/ActaHortic.1988.222.1](https://doi.org/10.17660/ActaHortic.1988.222.1).
- Akca, H., M. B. Taskin, M. Tugrul, S. K. Babar, and A. Gunes. 2023. Waste sheep wool and its hydrolysate as a nutritional support for sugar beet. *Sugar Tech* 25 (6):1566–77. doi: [10.1007/s12355-023-01298-5](https://doi.org/10.1007/s12355-023-01298-5).
- Ashraf, M. I., S. Shukat, B. Hussain, M. Sajjad, M. Adnan, and M. Ismail. 2018. Foliar application effect of boron, calcium and nitrogen on vegetative and reproductive attributes of tomato (*Solanum lycopersicum* L.). *Journal of Agriculture and Food Research* 9:199–205.
- Atbir, A., M. Taibi, B. Aouan, A. Khabbazi, O. Ansari, M. Cherkaoui, and T. Cherradi. 2023. Physicochemical and thermomechanical performances study for Timahdite sheep wool fibers application in the building's insulation. *Scientific Reports* 13 (1):5038. doi: [10.1038/s41598-023-31516-9](https://doi.org/10.1038/s41598-023-31516-9).

- Broda, J., A. Gawłowski, M. Rom, and K. Kobiela-Mendrek. 2023. Utilisation of waste wool from mountain sheep as fertiliser in winter wheat cultivation. *Journal of Natural Fibers* 20 (2):2. doi: [10.1080/15440478.2023.2200047](https://doi.org/10.1080/15440478.2023.2200047).
- Bunghze, I. R., M. Raduly, S. Doncea, I. Aksahin, and R. M. Ion. 2011. Lycopene determination in tomatoes by different spectral techniques (UV-VIS, FTIR and HPLC). *Digest Journal of Nanomaterials and Biostructures* 6 (3):1349–1356.
- Cetin Karaca, U., O. A. H. Chalabee, and M. Saba. 2023. The effect of sheep wool fertilizer on some biochemical properties of a clay loam soil. *Communications in Soil Science & Plant Analysis* 54 (1):48–61. doi: [10.1080/00103624.2022.2109662](https://doi.org/10.1080/00103624.2022.2109662).
- Clarkson, D. T. 1984. Calcium transport between tissues and its distribution in the plant. *Plant, Cell & Environment* 7 (6):449–56. doi: [10.1111/j.1365-3040.1984.tb01435.x](https://doi.org/10.1111/j.1365-3040.1984.tb01435.x).
- de Freitas, S. T., A. K. Handa, Q. Wu, S. Park, and E. J. Mitcham. 2012. Role of pectin methylsterases in cellular calcium distribution and blossom-end rot development in tomato fruit. *The Plant Journal* 71 (5):824–35. doi: [10.1111/j.1365-3113X.2012.05034.x](https://doi.org/10.1111/j.1365-3113X.2012.05034.x).
- Dodd, A. N., J. Kudla, and D. Sanders. 2010. The language of calcium signaling. *Annual Review of Plant Biology* 61 (1):593–620. doi: [10.1146/annurev-arplant-070109-104628](https://doi.org/10.1146/annurev-arplant-070109-104628).
- Enkhzaya, S., K. Shiomori, K. Shiomori, and B. Oyuntsetseg. 2021. Adsorption properties of Au (III) and Cu (II) from aqueous solution using chemically treated sheep wool. *The 18th Asian Pacific Confederation of Chemical Engineering Congress APCChE 2019* 333:04006. doi: [10.1051/mateconf/202133304006](https://doi.org/10.1051/mateconf/202133304006).
- Erkmen, J., and M. Sari. 2023. Hydrophobic thermal insulation material designed from hazelnut shells, pinecone, paper and sheep wool. *Construction and Building Materials* 365:130131. doi: [10.1016/j.conbuildmat.2022.130131](https://doi.org/10.1016/j.conbuildmat.2022.130131).
- Franco, J., S. Bañón, and R. Madrid. 1994. Effects of a protein hydrolysate applied by fertigation on the effectiveness of calcium as a corrector of blossom-end rot in tomato cultivated under saline conditions. *Scientia Horticulturae* 57 (4):283–92. doi: [10.1016/0304-4238\(94\)90111-2](https://doi.org/10.1016/0304-4238(94)90111-2).
- Hagassou, D., E. Francia, D. Ronga, and M. Buti. 2019. Blossom end-rot in tomato (*Solanum lycopersicum* L.): A multi-disciplinary overview of inducing factors and control strategies. *Scientia Horticulturae* 249:49–58. doi: [10.1016/j.scienta.2019.01.042](https://doi.org/10.1016/j.scienta.2019.01.042).
- Haque, A. N. M. A., and M. Naebe. 2022. Waste wool powder for promoting plant growth by moisture retention. *Sustainability* 14 (19):12267. doi: [10.3390/su141912267](https://doi.org/10.3390/su141912267).
- Hocking, B., S. D. Tyerman, R. A. Burton, and M. Gilliham. 2016. Fruit calcium: Transport and physiology. *Frontiers in Plant Science* 7:569. doi: [10.3389/fpls.2016.00569](https://doi.org/10.3389/fpls.2016.00569).
- Huang, J., and S. S. Snapp. 2009. Potassium and boron nutrition enhance fruit quality in Midwest fresh market tomatoes. *Communications in Soil Science & Plant Analysis* 40 (11–12):1937–52. doi: [10.1080/00103620902896811](https://doi.org/10.1080/00103620902896811).
- Juhos, K., E. Papdi, F. Kovács, V. P. Vasileiadis, and A. Veres. 2023. The effect of wool mulch on plant development in the context of the physical and biological conditions in soil. *Plants* 12 (3):684. doi: [10.3390/plants12030684](https://doi.org/10.3390/plants12030684).
- Kadam, V. V., L. R. Meena, S. Singh, D. B. Shakyawar, and S. M. K. Naqvi. 2014. Utilization of coarse wool in agriculture for soil moisture conservation. *Indian Journal of Small Ruminants* 20:83–86.
- Kumar, A., and A. Agrawal. 2020. Recent trends in solid waste management status, challenges, and potential for the future Indian cities—a review. *Current Research in Environmental Sustainability* 2:100011. doi: [10.1016/j.crsust.2020.100011](https://doi.org/10.1016/j.crsust.2020.100011).
- Marczak, D., K. Lejcuś, I. Lejcuś, and J. Misiewicz. 2023. Sustainable innovation: Turning waste into soil additives. *Materials* 16 (7):2900. doi: [10.3390/ma16072900](https://doi.org/10.3390/ma16072900).
- Marschner, P. 2012. *Marschner's mineral nutrition of higher plants*, 3rd ed. London: Academic Press.
- Midolo, G., S. M. C. Porto, G. Cascone, and F. Valentí. 2024. Sheep wool waste availability for potential sustainable re-use and valorization: A GIS-based model. *Agriculture* 14 (6):872. doi: [10.3390/agriculture14060872](https://doi.org/10.3390/agriculture14060872).
- Moore, J. C., W. de Vries, M. Lipp, J. C. Griffiths, and D. R. Abernethy. 2010. Total protein methods and their potential utility to reduce the risk of food protein adulteration. *Comprehensive Reviews in Food Science and Food Safety* 9 (4):330–51. doi: [10.1111/j.1541-4337.2010.00114.x](https://doi.org/10.1111/j.1541-4337.2010.00114.x).
- Page, A. L., and D. R. Keeney. 1982. *Methods of soil analysis*. Madison, WI: American Society of Agronomy.
- Petek, B., and R. Marinšek Logar. 2021. Management of waste sheep wool as valuable organic substrate in European Union countries. *Journal of Material Cycles & Waste Management* 23 (1):44–54. doi: [10.1007/s10163-020-01121-3](https://doi.org/10.1007/s10163-020-01121-3).
- Rajabinejad, H., I. I. Bucişcanu, and S. S. Maier. 2019. Current approaches for raw wool waste management and unconventional valorization: A review. *Environmental Engineering and Management Journal* 18 (7):1439–56. doi: [10.30638/eeemj.2019.136](https://doi.org/10.30638/eeemj.2019.136).
- Reitz, N. F., K. A. Shackel, and E. J. Mitcham. 2021. Differential effects of excess calcium applied to whole plants vs. excised fruit tissue on blossom-end rot in tomato. *Scientia Horticulturae* 290:110514. doi: [10.1016/j.scienta.2021.110514](https://doi.org/10.1016/j.scienta.2021.110514).
- Sethi, K., S. S. Dhaka, and V. K. Bari. 2024. Insights into blossom end-rot disorder in tomato (*Solanum lycopersicum*). *Plant Molecular Biology Reporter* 42 (3):492–514. doi: [10.1007/s11105-024-01442-9](https://doi.org/10.1007/s11105-024-01442-9).
- Sharma, S. C., A. Sahoo, and R. Chand. 2019. Potential use of waste wool in agriculture: An overview. *Indian Journal of Small Ruminants* 25 (1):1. doi: [10.1007/s11105-024-01442-9](https://doi.org/10.1007/s11105-024-01442-9).
- Skolik, P., M. R. McAinsh, and F. L. Martin. 2019. ATR-FTIR spectroscopy non-destructively detects damage-induced sour rot infection in whole tomato fruit. *Planta* 249 (3):925–39. doi: [10.1007/s00425-018-3060-1](https://doi.org/10.1007/s00425-018-3060-1).

- Taskin, M. B. 2024. Reducing mineral fertilizer usage: Utilizing sheep wool and alkaline hydrolysate for enhanced sugar beet cultivation. *Sugar Tech* 26 (6):1653–64. doi: [10.1007/s12355-024-01426-9](https://doi.org/10.1007/s12355-024-01426-9).
- Taylor, M. D., and S. J. Locascio. 2004. Blossom-end rot: A calcium deficiency. *Journal of Plant Nutrition* 27 (1):123–39. doi: [10.1081/PLN-120027551](https://doi.org/10.1081/PLN-120027551).
- Topcu, Y., S. U. Nambeesan, and E. van der Knaap. 2022. Blossom-end rot: A century-old problem in tomato (*Solanum lycopersicum* L.) and other vegetables. *Molecular Horticulture* 2 (1):1. doi: [10.1186/s43897-021-00022-9](https://doi.org/10.1186/s43897-021-00022-9).
- Wójcik, P., and M. Lewandowski. 2003. Effect of calcium and boron sprays on yield and quality of “Elsanta” strawberry. *Journal of Plant Nutrition* 26 (3):671–82. doi: [10.1081/PLN-120017674](https://doi.org/10.1081/PLN-120017674).
- Kalra, Y. 1997. *Handbook of Reference Methods for Plant Analysis*. Ed. Yash P. Kalra. New York, Washington DC: CRC press.
- Zhang, L., J. Wang, J. Chen, T. Song, Y. Jiang, Y. Zhang, L. Wang, and F. Li. 2019. Preharvest spraying calcium ameliorated aroma weakening and kept higher aroma-related genes expression level in postharvest “Nanguo” pears after long-term refrigerated storage. *Scientia Horticulturae* 247 (3):287–95. doi: [10.1016/j.scienta.2018.12.038](https://doi.org/10.1016/j.scienta.2018.12.038).