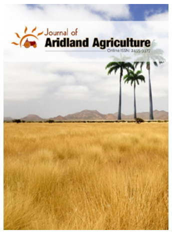
Journal of Aridland Agriculture 2025, 11: 44-53
doi: 10.25081/jaa.2025.v11.9572
https://updatepublishing.com/journal/index.php/jaa

Research Article



ISSN: 2455-9377

Effect of wool pellets on soil fertility and lettuce growth in three soil types

Lina Maria Correa[1,2]*, Giordano Catenacci Aguilera[1], Marcela Gómez Ceruti[1]

[1]Universidad Santo Tomás, Centro de Innovación de Ovinos para el Secano-OVISNOVA, Talca, Chile, [2]Universidad Santo Tomás, Faculty of Natural Resources and Veterinary Medicine, Talca, Chile

ABSTRACT

Since 2010, South America has been experiencing a prolonged megadrought, with a 40% reduction in annual rainfall, further intensified by climate change. This situation has led to a severe decline in water reserves, impacting agriculture and food security. To mitigate these effects, the adoption of sustainable agricultural practices, such as the use of sheep wool as an organic fertilizer, has been explored. This study evaluated the impact of wool pellets on lettuce growth and soil properties across different substrates. Lettuce seedlings were cultivated in 1 L pots with various soil types (sand, clay, and peat) and different wool pellet doses: a control group (C), a group with 5 g/L (W5), and one with 10 g/L (W10). Plant growth parameters and soil properties were monitored over a period of 120 days. The addition of wool pellets improved soil moisture retention and chemical properties, with moisture levels increasing by 3% to 25% compared to the control, particularly during dry periods. An increase in nitrate (41-54%) and potassium (10-53%) concentrations was observed in both soil and lettuce leaves (1.4 times) compared to the control, particularly in sandy and clay soils. Lettuce growth was significantly enhanced under the W10 treatment, which showed the highest increases in plant weight (2.5 times), leaf number (1.4 times), and height (1.4 times) compared to the control. Wool pellets may thus serve as an effective tool for optimizing soil management in low-fertility environments, promoting more sustained and resilient plant growth under variable water availability.

Received: February 06, 2025
Revised: April 25, 2025
Accepted: May 02, 2025
Published: May 19, 2025

***Corresponding author:**
Lina Maria Correa
E-mail: lcorrea2@santotomas.cl

KEYWORDS: Agroecology, Lettuce, Organic fertilizer, Soil amendment, Wool pellets, Wool

INTRODUCTION

The megadrought Chile has faced since 2010 has led to a precipitation deficit of up to 40% (Garreaud *et al.*, 2020). This phenomenon, combined with increased evaporation due to rising temperatures from climate change (Araya-Osses *et al.*, 2020) and desertification affecting 23% of the country's surface, has drastically reduced water reserves, especially in central-southern Chile, limiting irrigation security for agriculture. Regional Development Strategies (RDS) nationwide have responded by promoting efficient and sustainable water use in the agriculture and forestry sectors, spurring efforts to reduce irrigation water consumption and foster innovative alternatives for conserving agricultural water use.

Global population growth is raising food demand, which increases pressure on soil and agriculture. This demand has led to a significant rise in synthetic fertilizer use. In Chile, synthetic fertilizer use increased from 30 kg/ha in 1980 to 290 kg/ha in 2020 (Ritchie *et al.*, 2022), with negative impacts on the environment, human health, and the sustainability of agroecosystems. In response, various agriculture-related entities are promoting sustainable, eco-friendly agricultural practices.

Climate change and population growth challenges necessitate a shift from conventional agriculture to more sustainable systems that can continue to produce food efficiently over time (Hunter *et al.*, 2017). Developing and using agricultural products from forestry and agricultural waste improves production sustainability and promotes the circularity of agroecosystems (Kumar Sarangi *et al.*, 2023). Utilizing such waste as fertilizer enhances crop yields while reducing reliance on synthetic fertilizers.

Sheep farming in Chile primarily involves meat breeds that produce low-quality wool, which currently lacks demand and is treated as waste. Approximately 400 tons of wool are produced annually in central-southern Chile (ODEPA, 2017), often accumulating, being burned, or disposed of in landfills, thereby impacting the environment (ODEPA, 2014). However, using wool in agriculture can improve soil quality and increase water retention, aiding farmers in mitigating the adverse impacts of water scarcity and reducing chemical fertilizer use (Sharma *et al.*, 2019).

Wool, an animal fiber, acts as a soil conditioner that improves water retention, bulk density, and other soil quality characteristics. Wool can hold up to 20 times its weight in water, potentially reducing irrigation needs by up to 25% (Wen *et al.*, 2009; Haque & Naebe, 2022). When saturated, wool added to soil enhances its porosity, allowing roots to extend, grow, and become deeper and stronger. Wool is also nitrogen-rich and takes approximately six months to decompose fully (Bradshaw & Hagen, 2022), making it a slow-release nutrient source that continuously supplies plants year-round. Furthermore, since 50% of wool's weight is carbon, incorporating it as a soil amendment offers an opportunity for carbon sequestration (Abdallah *et al.*, 2019a).

This study aims to assess the impact of wool pellets on plant growth and on the physical and chemical properties of soils used for lettuce cultivation in sandy, clay, and peat substrates. Evaluating the effects of wool pellets on different substrates provides a comprehensive understanding of their performance and suitability under varied edaphic conditions, ensuring broader applicability and more robust agronomic recommendations.

MATERIALS AND METHODS

Soil Collection and Research Site

The experiment was conducted on an experimental site in the municipality of Villa Alegre (-35.629269, -71.744880) in the Maule Region, Chile. The site experiences a temperate Mediterranean climate with hot, dry summers and cool, wet winters. Precipitation, minimum and maximum temperatures, and relative humidity levels during the experimental period are shown in Figures 1, 2, and 3, respectively.

The experiment began in March 2024 (late summer) using lettuce seedlings (Lactuca sativa) of the 'Marina' variety, each with three leaves and grown in a commercial nursery system (América Vivero, Maule, Chile). In the study, three different substrates were used: sandy soil, clay soil, and peat. The sandy and clay soils used in this study were sourced from a local supplier in Maule, Chile, while the peat was a commercial product (KEKKILÄ, Protekta). The chemical and physical properties of the soils are presented in Table 1. Experimental units were established using 1-liter pots filled with each type of substrate, with one lettuce seedling planted per pot, and maintained under open field conditions.

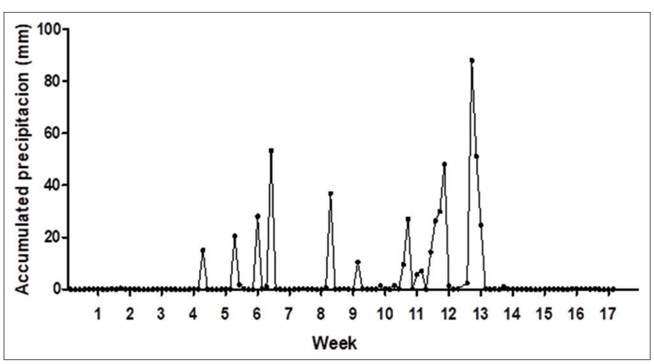


Figure 1: Accumulated precipitation during the evaluation period of lettuce cultivated with Wool Pellets on different soil types.

Factors considered included soil type and wool pellet application rate to provide supplemental nutrition beyond the soil's nutrient capacity. Wool pellets were sourced from WoolChip® (Villa Alegre, Chile) and analyzed prior to treatment applications at Agrolab Laboratory (Santiago, Chile) (see Table 2).

Experimental Design

The experiment comprised nine treatments, detailed in Table 3, with a total of 90 plants divided into three soil-type groups: sandy soil (S), clay soil (C), and peat (P). Each group was further divided into three sub-groups, each receiving increasing wool pellet doses: a control group with no wool pellets (C), a group with 5 g wool pellets per liter of soil (W5), and a group with 10 g wool pellets per liter of soil (W10). Each treatment included nine replicates, with each replicate consisting of one lettuce plant. No additional fertilizers were applied beyond the wool pellets. Drip irrigation was provided every other day, adjusted to field capacity for each pot, which ranged from 10% to 60% depending on the soil type.

Soil Physico-Chemical Analysis

Weekly, over the 120-day trial period, volumetric water content (VWC) was recorded using portable time-domain reflectometry (TDR) sensors (FieldScout 300, Spectrum Technologies, Aurora, IL) with 0.2 m rods on all plants. On day 120, composite soil samples were collected from three plants per treatment and soil type (n=9), and subsequently transported to Soil, Plant, and Water Laboratory (Faculty of Agronomy, University of Concepción, Chile), for further analysis. The soil texture (clay, silt, and sand) was determined using the hydrometer method

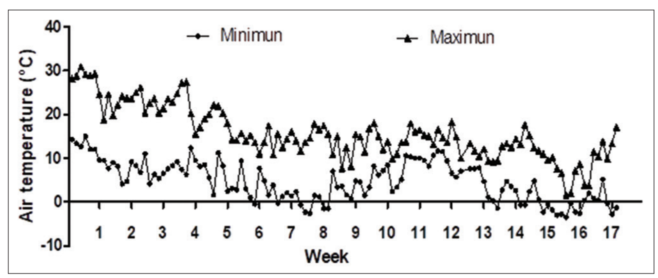


Figure 2: Average weekly minimum and maximum temperature during the evaluation period of lettuce cultivated with Wool Pellets on different soil types.

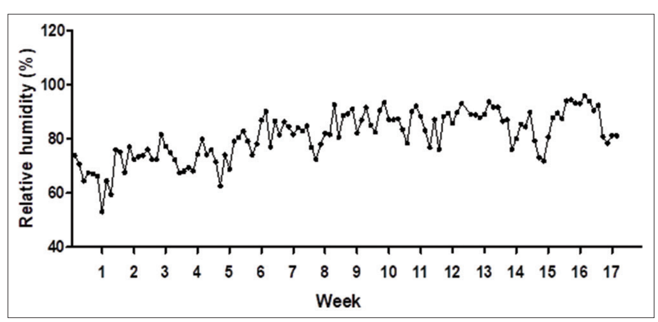


Figure 3: Relative air humidity during the evaluation period of lettuce cultivated with Wool Pellets on different soil types.

Table 1: Physico-Chemical properties of the soil before application of wool pellets

	Sandy	Clay
Texture	SL	CL
pH	6	5.8
Bulk density (g/cm^3)	1.6	1.7
Org. Matter (g kg^{-1})	1.7	0.3
Organic Carbon Content (%)	1	0.2
Ca (cmol kg^{-1})	10.8	10
Mg (cmol kg^{-1})	2.4	9
K (cmol kg^{-1})	0.5	0.1
Na (cmol kg^{-1})	0.3	0.7

Table 2: Laboratory analysis of wool pellets (WoolChip®, Chile)

	Wool Pellet
Total N (%)	10.2
Total C (%)	48.6
C/N	4.8
P_2O_5 (%)	0.5
K_2O (%)	4.2
Dry matter (%)	86

Table 3: Experimental groups: combinations of soil types and wool pellets

Soil Type	Treatment	Wool Pellet (g)
Sandy	SC	0
	SW5	5
	SW10	10
Clay	CC	0
	CW5	5
	CW10	10
Peatmoss	PC	0
	PW5	5
	PW10	10

(Gee & Bauder, 1986). The soil classified as sandy consisted of 60% sand, 18% clay, and 22% silt, while the soil classified as clay comprised 30% sand, 40% clay, and 30% silt.

Physic-chemical properties of the soil amended with wool pellets were analyzed following the methodology described by Sadzawka *et al.* (2006). Soil pH was determined in 1:2.5 (w/v) ratio of soil-water extracts. Organic matter content was quantified via wet combustion using sodium dichromate and sulfuric acid without heat application. Nitrate (N-NO_3^-) and ammonium (N-NH_4^+) concentrations were measured using colorimetric methods. Olsen P was extracted with 0.5 M $NaHCO_3$ (pH 8.5) and measured colorimetrically using a spectrophotometer (Thermo Spectronic model Genesys TM 5, Vernon Hills, IL, USA). Exchangeable potassium was quantified following extraction with 1 mol L^{-1} ammonium acetate (NH_4OAc), and subsequent measurement by atomic absorption spectrophotometer (Unicam, Solaar 9000).

Plant Growth Assessment

Lettuce plants were harvested 120 days after establishment by cutting each plant at soil level (seven plants per treatment). Fresh weight of the aerial portion was measured using a digital scale (accuracy of 0.1 g), and the number of fully developed leaves was recorded. Additionally, stem diameter was measured with a digital vernier caliper, and both length and diameter of each plant were measured with a ruler.

Plant Physiological Parameters

On days 50 and 120, foliar measurements were conducted to assess total chlorophyll content and the Normalized Difference Vegetation Index (NDVI). A CL-01 standard chlorophyll meter (Hansatech Instruments, Norfolk, UK) was used to determine relative total chlorophyll content per leaf area on all lettuce plants (Yudina *et al.*, 2023). CL-01 values are linearly correlated with chlorophyll concentrations biochemically estimated by leaf area (Cassol *et al.*, 2008).

NDVI was assessed using a portable PlantPen PRI 210 (Photon Systems Instruments, Drásov, Czech Republic), measuring one mature leaf per plant (6 replicates per plant). NDVI values, which range from -1 to 1, allow the estimation of plant health and growth status, with -1 indicating a stressed or dead plant and 1 indicating healthy plants with high photosynthetic activity (Spadoni *et al.*, 2020).

On day 120, three lettuce plants from each treatment group were transported to Soil, Plant, and Water Laboratory (Faculty of Agronomy, University of Concepción, Chile), for further foliar analysis. Macronutrient elements were determined as follows: nitrogen (N) by the Kjeldahl method, phosphorus (P) by photocolorimetry, and potassium (K) by atomic absorption spectrophotometry, following the procedures described by Sadzawka *et al.* (2007).

Statistical Analysis

Data were statistically analyzed using GraphPad Prism version 8.0.0 for Windows (GraphPad Software, San Diego, CA, USA). Data normality was confirmed with the Kolmogorov–Smirnov test. Plant growth and physiological parameters were analyzed via two-way ANOVA, followed by Tukey's multiple comparison test. Data were presented as mean±standard deviation, with statistical significance set at $p \leq 0.05$.

RESULTS

Soil Physicochemical Properties with Wool Pellets

Figure 4 illustrates how wool pellet application impacts moisture retention across different soil types (sand, clay, and peat) over 17 weeks, with all three treatments compared alongside weekly precipitation levels. Average soil moisture percentages for each soil type were as follows over the 17-week period: in sandy soils, 11.6%, 12.0%, and 12.4%; in clay soils, 12.7%, 14.2%, and 13.7%; and in peat, 10.8%, 12.3%, and 14.3%, for control, W5, and W10 treatments, respectively. Overall, the addition of wool pellets (W5 and W10) improved water retention capacity, particularly during weeks with minimal rainfall. Average moisture across all soil types was 6.9% prior to rainfall and 17.3% post-rainfall. In sandy soils, treatments with wool pellets increased soil moisture by 3-7% compared to the control, especially from week 7 onward after rainfall, with W10 retaining the most moisture. In clay soils, moisture retention was consistently higher with pellet treatments, increasing by 7-10% with significant differences observed in several weeks. In peat soils, W10 led to a 25% increase in moisture retention compared to the control and a 12% increase over W5, particularly toward the experiment's end.

Table 4 presents a comparative analysis of soil chemical properties based on soil type (sand, clay, and peat) and different treatments (C, W5, and W10). Key parameters measured included pH, organic matter content, nitrate ($N\text{-}NO_3$), ammonium ($N\text{-}NH_4$), available nitrogen, phosphorus (Olsen), available potassium, and exchangeable potassium. pH values ranged from 6.29 to 7.13, with sandy soils being more acidic and clay soils slightly more alkaline.

Organic matter content was notably high in peat, reaching 82.29% in the control treatment (Table 4). In sandy soils, nitrate concentrations increased with the application of wool pellets, rising from 1.0 mg/kg in the control to 1.1 mg/kg in the W5 treatment and 1.7 mg/kg in the W10 treatment, representing a 41% increase in W10 compared to the control (Table 4). Additionally, ammonium levels rose by 7-30% in treated groups (Table 4). Available nitrogen levels were also higher in W5 and W10 treatments. This increase was especially notable in clay soils, where available nitrogen rose by 54% in the W10 treatment (Table 4). In peat soils, available nitrogen increased progressively with wool pellet application, rising from 59.3 mg/kg in the control to 64.1 mg/kg in W5 and reaching 96.2 mg/kg in the W10 treatment (Table 4).

Olsen phosphorus concentrations did not follow a consistent increasing trend in response to wool pellet treatments. Instead, variations were observed across the different soil types, with some treatments resulting in increases while others showed slight reductions, indicating a variable response to the applied doses. However, an overall increase in available and exchangeable potassium concentrations was observed in W5 and W10 treatments. Available potassium in W10 soils increased by 10% (sand), 40% (clay), and 53% (peat) compared to the control. Enhanced potassium availability is crucial for plant development, as this nutrient plays a vital role in water balance regulation and photosynthesis.

Plant Growth Assessment

Figure 5 illustrates the effects of different wool pellet treatments on the fresh weight of the aerial part, number of leaves per plant, crown diameter, plant height, and plant diameter, as measured across the various soil types. All variables increased with rising wool pellet doses, with the highest dose (W10=10 g of wool pellet per liter of soil) showing the most substantial values in these growth parameters ($P<0.05$). However, in peat soil, no significant differences were observed among treatments for some variables ($P>0.05$). Overall, lettuce plants grown in sandy soil showed the most pronounced differences across treatments and the control for all variables, including fresh weight (C=21.6±5.2 g, W5=38.5±5.9 g, W10=53.7±9.3 g;

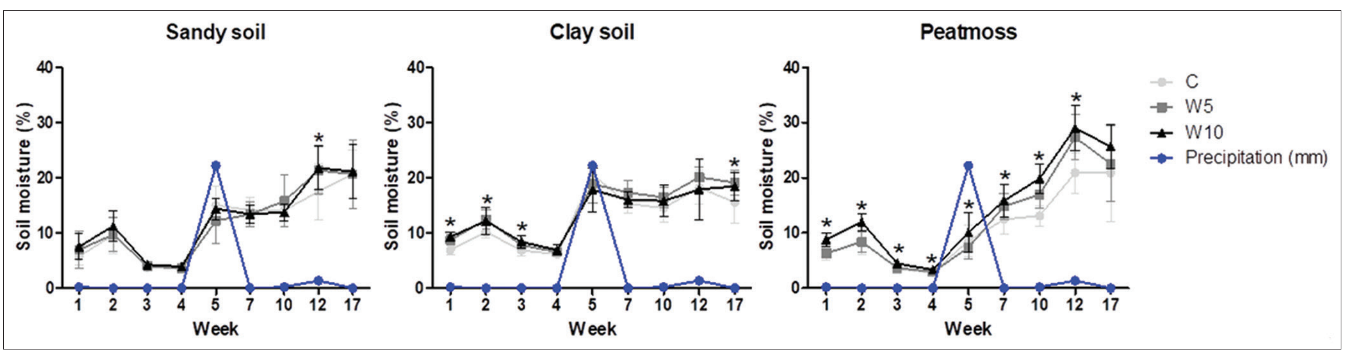


Figure 4: Effect of wool pellets on the moisture of lettuce soils for 17 weeks. C=wool pellet-free control. W5=5 g of wool pellet/liter of soil and W10=10 g of wool pellet/liter of soil. *Indicate significant differences between treatments according to Tukey's test ($P<0.05$). The vertical bars correspond to a standard deviation. Replicas by soil type n=10.

Table 4: Physico-Chemical properties of the soil with Wool Pellet

Soil Type	Treatment	pH	Organic Matter (%)	Nitrates ($N\text{-}NO_3$) mg/Kg	Ammonium ($N\text{-}NH_4$) mg/Kg	Available Nitrogen mg/Kg	Olsen Phosphorus mg/Kg	Available Potassium mg/Kg	Exchangeable Potassium cmol/Kg
Sand	C	6.34	1.03	1	2.8	3.8	16.2	195.7	0.5
	W5	6.3	1.17	1.1	3	4.1	13.7	212.7	0.55
	W10	6.29	1.55	1.7	3.5	5.2	16.1	216.7	0.56
Clay	C	7	0.27	0.4	3.3	3.7	4.5	47.9	0.12
	W5	7.12	0.28	0.6	3.8	4.4	3.9	53.9	0.14
	W10	7.13	0.83	4.2	4	8.1	5	79.9	0.2
Peat	C	6.55	82.29	16.1	43.3	59.3	122	385.4	0.99
	W5	6.59	82.65	10.5	53.6	64.1	136.1	724.8	1.86
	W10	6.77	83.2	34.5	61.7	96.2	112.3	820.7	2.1

P<0.05), leaf count (C=19±3, W5=24±2, W10=26±3; P<0.05), stem diameter (C=8.0±1.2 mm, W5=9.2±1.2 mm, W10=11.4±1.3 mm; P<0.05), plant height (C=12.5±1.6 cm, W5=14.9±1.5 cm, W10=17.6±1.7 cm; P<0.05), and plant diameter (C=21.6±5.2, W5=38.5±5.9, W10=53.7±9.3; P<0.05).

In plants grown in peat, wool pellet treatments resulted in a significant increase in fresh weight (Figure 5a), number of leaves per plant (Figure 5a) and plant diameter (Figure 5e) at the highest dose (W10) compared to the control (P<0.05). However, variables such as crown diameter (Figure 5c) and plant height (Figure 5d) showed no significant differences between groups (P>0.05). Plants grown in clay showed less growth overall compared to the other soils, with significant differences observed in all variables only in the W10 treatment relative to the control. The W10 treatment in sandy soil yielded plant weights and leaf counts similar to those seen in W10 for peat, despite the differing nutritional profiles of these soils (Figures 5a & 5b).

Figure 6 illustrates the appearance of lettuce plants cultivated in sandy, clay, and peat soils under the three different treatments (C, W5, and W10) over 120 days. Notable differences in the size of lettuce plants grown in sandy and clay soils emerged with increasing wool pellet doses, while lettuce grown in peat showed no marked differences across treatments.

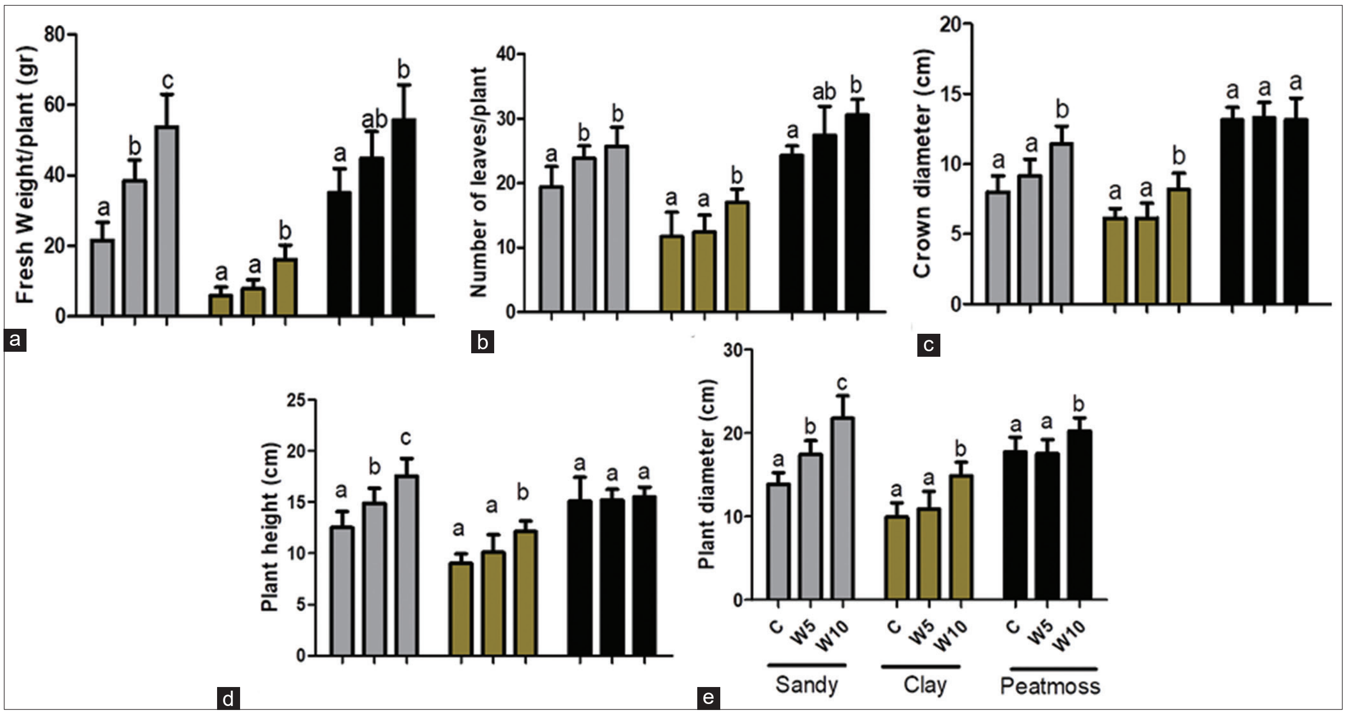


Figure 5: Yield of lettuce cultivated with Wool Pellets on different soil types. a) fresh weight of the aerial plant part, b) number of leaves per plant, c) crown diameter, d) plant height and e) plant diameter. C=wool pellet-free control. W5=5 g of wool pellet/liter of soil and W10=10 g of wool pellet/liter of soil. Different letters on the bars corresponding to the same type of soil indicate significant differences between treatments according to Tukey's test (P<0.05). The vertical bars correspond to a standard deviation. Plants per group n=7.

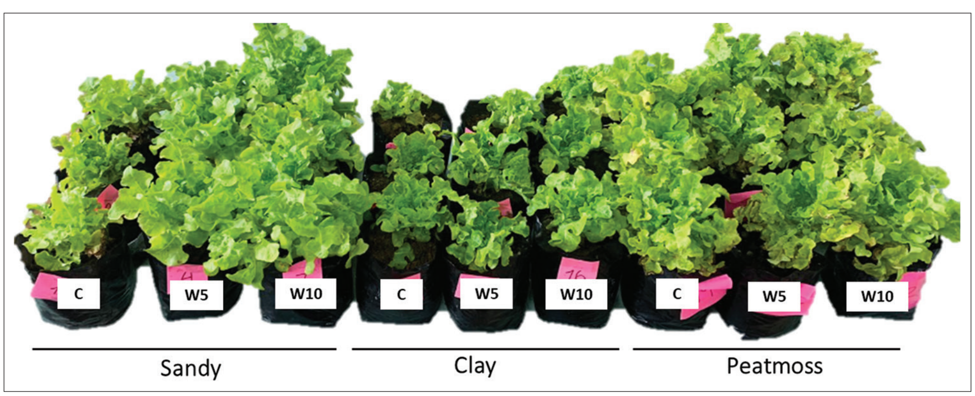


Figure 6: Appearance of lettuce cultivated with Wool Pellets on different soil types. C=wool pellet-free control. W5=5 g of wool pellet/liter of soil and W10=10 g of wool pellet/liter of soil.

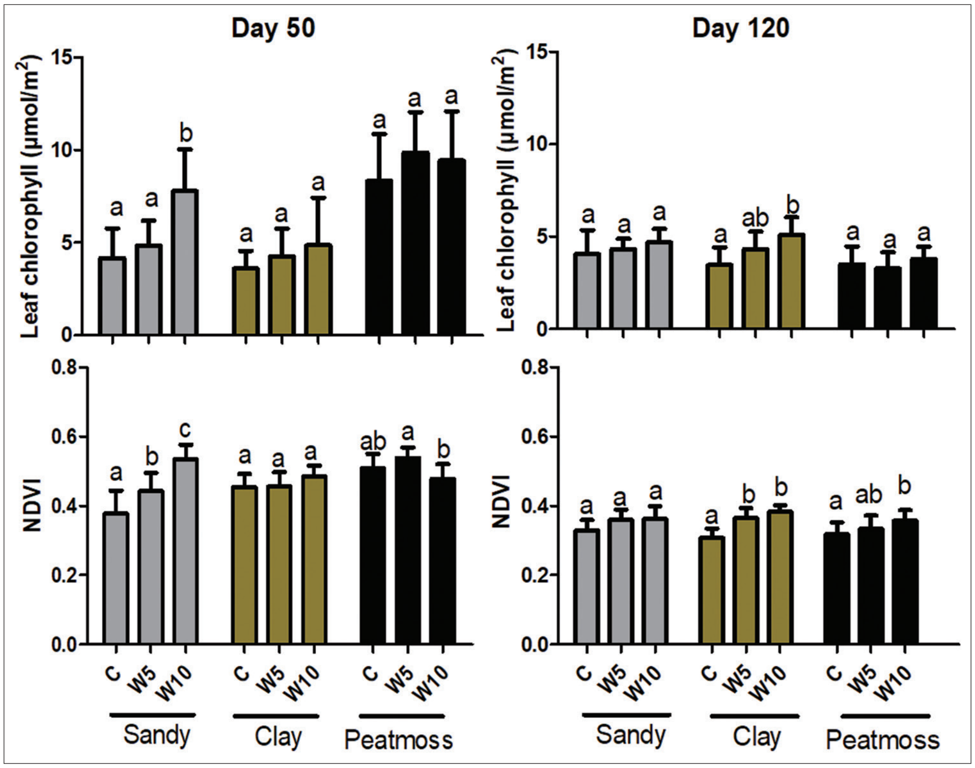


Figure 7: Relative total chlorophyll content and Normalized Difference Vegetation Index (NDVI) of lettuce cultivated with wool pellets in different soil types. C=wool pellet-free control. W5=5 g of wool pellet/liter of soil and W10=10 g of wool pellet/liter of soil. Different letters on the bars corresponding to the same type of soil indicate significant differences between treatments according to Tukey's test (P<0.05). The vertical bars correspond to a standard deviation. Plants per group n=10.

Plant Physiological Parameters

Figure 7 illustrates the effects of different treatments (C, W5, and W10) on chlorophyll concentration and NDVI index across three substrates (sand, clay, and peat) at two growth stages: day 50 and day 120. In terms of chlorophyll concentration (μmol/m^2), no significant differences were observed across treatments and substrates at 50 days, except in sand, where the W10 treatment showed a higher concentration (7.8±2.3 μmol/m^2) compared to the control (4.2±1.6 μmol/m^2) ($P<0.05$). By day 120, these trends persisted, with a notable increase in chlorophyll concentration in the W10 clay treatment (5.1±1.0 μmol/m^2) relative to the control (3.5±1.0 μmol/m^2) ($P<0.05$).

For NDVI, at 50 days, the sandy substrate showed the greatest variability, with W10 treatment showing higher values (0.5±0.04) compared to the control (0.4±0.1) ($P<0.05$). Differences in NDVI were less marked across the other substrates. By day 120, NDVI decreased across all treatments and substrates, particularly in sand, where W10 values reached approximately 0.2, while values in clay and peat remained around 0.3. In most cases, no significant differences emerged among treatments, as indicated by the statistical grouping letters.

Table 5 displays the effects of wool pellet treatments and soil type on leaf nutrient concentrations (nitrogen, phosphorus, and potassium) in lettuce. In sandy soils, the W10 treatment (10 grams of wool pellets) resulted in the highest nitrogen (1.96%) and potassium (5.92%) concentrations, whereas phosphorus showed no significant differences among treatments. In clay soils, W10 also increased nitrogen levels (2.39%) relative to the control, though phosphorus and potassium concentrations were lower. In peat, nutrient concentrations were relatively consistent across treatments, with few significant differences.

Table 5: Effect of Wool Pellet and soil type in Lettuce Leaf nutrient concentration. Distinct letters in the row indicate significant differences between treatments according to Tukey's test (P≤0.05). Mean±standard deviation.

Soil Type	Treatment	N%	P%	K%
Sandy	C	1.87 ± 0.39^{a}	0.39 ± 0.05^{a}	5.22 ± 0.86^{a}
	W5	1.74 ± 0.27^{a}	0.32 ± 0.04^{a}	5.10 ± 0.36^{a}
	W10	1.96 ± 0.08^{a}	0.33 ± 0.00^{a}	5.92 ± 0.33^{a}
Clay	C	1.51 ± 0.25^{a}	0.28 ± 0.06^{a}	3.50 ± 0.50^{a}
	W5	2.16 ± 0.22^{ab}	0.25 ± 0.07^{a}	5.07 ± 0.64^{b}
	W10	2.39 ± 0.14^{b}	0.28 ± 0.04^{a}	4.72 ± 0.38^{ab}
Peatmoss	C	1.66 ± 0.14^{a}	0.52 ± 0.07^{a}	5.05 ± 0.27^{a}
	W5	1.57 ± 0.13^{a}	0.45 ± 0.02^{a}	5.70 ± 0.33^{a}
	W10	1.86 ± 0.07^{a}	0.43 ± 0.01^{a}	5.49 ± 0.27^{a}

DISCUSSION

The use of wool pellets in lettuce cultivation proved effective in enhancing soil physical and chemical properties, significantly increasing the availability of essential nutrients such as nitrogen and potassium. Furthermore, it contributed to improved plant growth variables, with the most notable effects observed in sandy soils.

The addition of wool pellets markedly improved moisture retention across sandy, clay, and peat soils, as illustrated in Figure 4. The moisture levels in pellet-treated soils, particularly at a dose of 10 g of wool pellets per liter of soil (W10), align with findings from studies highlighting the ability of fibrous materials to enhance soil water retention properties (Marczak *et al.*, 2022). In this study, the pellets increased soil moisture by 13.1±7.1% compared to the control, with the greatest effect occurring during periods of low rainfall. In clay soils, which typically retain more water due to their high cation exchange capacity (Dontsova *et al.*, 2004; Song *et al.*, 2022), the use of pellets increased water retention by 7-10%. This effect is likely due to the combination of the soil's inherent properties and the pellets' porous structure, which adds further water-holding capacity (Rawls *et al.*, 2003; Sharma *et al.*, 2019). Lastly, in peat substrate already known for its high water-holding capacity—W10 demonstrated a remarkable 25% increase in moisture retention compared to the control. In addition, the organic matter content was notably high in peat (Table 4), indicating a greater capacity of peat soils to retain water and nutrients compared to sandy and clay soils, which exhibited significantly lower values. This finding aligns with previous studies indicating that wool can enhance moisture retention in organic or high organic matter soils by acting as a sponge (Haque & Naebe, 2022; Marczak *et al.*, 2022). Therefore, wool pellets serve not only as a soil conditioner by increasing water retention but also have a more pronounced effect in weeks with low precipitation (Figure 4), making them a valuable tool for improving crop resilience to water variability.

Previous studies have demonstrated that wool can enhance the water retention capacity of soils due to its porous structure, which allows for the absorption and gradual release of water depending on environmental conditions (Ordiales *et al.*, 2016; Bradshaw & Hagen, 2022). In sandy soils, water retention capacity is often limited due to high permeability and low water-holding capacity; however, the incorporation of organic materials, such as wool pellets, can offset these deficiencies by increasing porosity and improving water absorption capacity (Abdallah *et al.*, 2019b).

The chemical analysis presented in Table 4 highlights how the application of wool pellets at both 5 g per liter of soil (W5) and 10 g per liter of soil (W10) positively impacts soil chemical properties, improving key factors such as pH, organic matter content, and the availability of nitrogen and potassium. Soil pH directly influences nutrient solubility and thus the capacity of plants to absorb these nutrients (Penn & Camberato, 2019). Sandy soils, with a more acidic pH (6.29), tend to limit the availability of some essential nutrients like phosphorus, while clay soils, with a more alkaline pH (up to 7.13), may reduce the availability of micronutrients such as iron and zinc (Neina *et al.*, 2019; Barrow *et al.*, 2020). A slightly acidic pH, as observed in clay soils treated with W5 and W10, favors increased availability of most nutrients.

The high organic matter content observed in peat underscores its superior capacity to enhance water and nutrient retention, consistent with various studies that show how organic matter in this substrate improves soil structure and cation exchange capacity (Rezanezhad *et al.*, 2016). Due to its elevated organic composition, peat enables greater water and nutrient retention than sandy and clay soils, which have lower porosity and organic matter content and consequently reduced water and nutrient-holding capacities (Rawls *et al.*, 2003; Murphy *et al.*, 2015). This attribute is essential for promoting the availability of vital nutrients for plant growth.

The findings also suggest the advisability of using substrates with lower inherent nutrient content in future amendment studies. This recommendation is based on the need to avoid substrate effects, such as those from peat, which could obscure or interfere with the assessment of the tested product's impact on soil physical and chemical properties. Such an approach would allow for a more precise characterization of the specific effects of the applied amendment.

In sandy soils, the addition of wool pellets in both treatments (W5 and W10) shows a significant increase in nitrate concentration, which aligns with the nitrogen content supplied by the wool pellet (Table 2). This increase may be related to enhanced mineralization of the added organic matter, resulting in the gradual release of nitrates, as soil microorganisms break down organic nitrogen compounds into ammonium, which is then oxidized to nitrate through nitrification (Masunga *et al.*, 2016; Clivot *et al.*, 2017). Wool pellets have been described as a slow-release fertilizer due to their high water and nutrient retention capacity and gradual decomposition (Bradshaw & Hagen, 2022; Haque & Naebe, 2022). Composed of nitrogen-rich organic matter, wool pellets decompose slowly in the soil, releasing nutrients progressively. This process is supported by microbial activity that mineralizes nitrogen and other essential nutrients for plants, thus enhancing soil fertility over time. Organic matter mineralization is essential for converting organic nitrogen into plant-available forms, such as nitrate ($N\text{-}NO_3$), a primary nitrogen source for plant growth (Cabrera *et al.*, 2005; De Neve, 2017).

The effective mineralization process is also reflected in the elevated ammonium ($N\text{-}NH_4$) levels observed in soils treated with wool pellets (Table 4), suggesting increased microbial activity and an accelerated decomposition of organic matter. This boost in biological activity may be favored by improved soil conditions derived from the wool pellet addition as an organic amendment. These findings are consistent with previous studies on other crop types, which have similarly documented the positive influence of organic amendments on nitrogen mineralization and ammonium dynamics in soil (Böhme *et al.*, 2010; Vončina & Mihelič, 2013; Ordiales *et al.*, 2016).

The increase in available nitrogen levels in W5 and W10 treatments, particularly in clay soils, indicates a substantial improvement in soil fertility. Due to their compact structure and high clay content, clay soils exhibit greater nutrient retention capacity and more efficient cation exchange (Leeds-Harrison *et al.*, 1986; Rabot *et al.*, 2018). Adding wool pellets as an organic matter source not only enhances this nutrient retention ability but also promotes biological activity and nitrogen availability—a key nutrient for plant growth, especially in soils with low fertility and limited organic matter content.

In all soil types, growth variables such as fresh weight, leaf number, stem diameter, and plant height significantly improved with the application of wool pellets, with the highest effect observed at the higher dosage (W10) (Figures 5 & 6). This aligns with studies reporting that slow-release fertilizers enhance plant growth by providing sustained nutrient availability (Bradshaw & Hagen, 2022; Haydar *et al.*, 2024). In sandy soils, plant fresh weight increased from 21.6 g to 53.7 g, an improvement of over 40%, suggesting that wool pellet addition enhances both water and nutrient retention in this type of soil, which is typically low in these attributes. These results are consistent with research indicating that organic amendments improve the physical properties of sandy soil, increasing its capacity to retain water and essential nutrients for plant growth (Abdallah *et al.*, 2019b).

In clay soils, which tend to be compact and restrict water and air movement, the W10 treatment also produced a significant positive impact on all plant growth variables compared to the control, supporting the idea that wool pellets enhance soil structure and create a more favorable environment for nutrient uptake, as seen in similar studies (Haque & Naebe, 2022; Dal Prà *et al.*, 2024). In contrast, plants grown in peat soil, already rich in organic matter, showed smaller differences between treatments. Variables like crown diameter and plant height showed no significant differences between groups ($P>0.05$), suggesting that peat soil already provides optimal conditions for plant growth without requiring substantial additional intervention (Rezanezhad *et al.*, 2016).

The fact that plants grown in sandy soil with W10 reached similar values to those in peat in terms of weight and leaf number (Figures 5a & 5b), despite nutritional differences between these soils, highlights the wool pellet's effectiveness in compensating for typical deficiencies in sandy soil. This can be attributed to the pellet's ability to release nutrients slowly and steadily, enhancing plant nutrition over time and reducing nutrient loss through leaching a critical advantage in sandy soils (Bradshaw & Hagen, 2022; Haque & Naebe, 2022; Dal Prà *et al.*, 2024).

Chlorophyll concentration measurement serves as an effective tool to assess plant physiological status, as it is directly related to photosynthetic capacity (Cassol *et al.*, 2018). In this study, a significant increase in chlorophyll content was observed in lettuce crops with wool pellet addition, particularly in sandy soils, showing increases of over 80% compared to the control, indicating a favorable response in this substrate. These findings are consistent with previous studies that evaluated sheep wool residues (both carbonized and non-carbonized) in sunflower and maize, where soil-wool mixtures significantly increased chlorophyll content relative to the control (Abdallah *et al.*, 2019a). This underscores the potential of wool residues as amendments to improve soil fertility and plant photosynthetic performance. Regarding NDVI, the greater variability observed in sand may be due to the physical properties of the substrate, especially since plant growth responds strongly to fertilizer under nutrient-limited conditions (Blaes *et al.*, 2016).

The improvement in nitrogen and potassium concentration in lettuce leaves in sandy and clay soils (Table 5) is consistent with the nutrient content provided by the wool pellet (Table 2). These findings indicate that wool pellets may be more effective in sandy and clay soils for increasing nitrogen concentrations, while their impact on phosphorus and potassium varies depending on soil type. This result aligns with the chlorophyll concentration observed in plants treated with wool pellets and can be explained by nitrogen's significant effect on net photosynthesis, chlorophyll synthesis, transpiration rate, and, consequently, plant productivity (Huang *et al.*, 2014).

CONCLUSIONS

The application of wool pellets in lettuce crop soils led to significant improvements in soil physical and chemical properties, particularly enhancing water retention and the availability of essential nutrients like nitrogen and potassium. This effect was most notable in sandy and clay soils, where increased moisture retention and plant growth were observed compared to the control. In sandy soils, wool pellet addition resulted in over a 40% increase in plant fresh weight, highlighting its potential to enhance soil fertility and structure. Additionally, the gradual mineralization of wool pellets boosted nitrate and ammonium concentrations, promoting soil biological activity. However, in peat soils, which are rich in organic matter, the improvements were less pronounced, indicating that wool pellets are most effective in soils with lower nutrient content and retention capacity. Collectively, these results suggest that wool pellets could be a valuable tool for optimizing soil management in low-fertility environments, fostering more sustained and resilient plant growth in response to water variability.

AUTHORS' CONTRIBUTION

Conceptualization: LM.C. Methodology: LM.C, G.CA. Formal analysis: LM.C, G.CA. Investigation: LM.C, G.CA. Writing-original draft: LM.C, G.CA. Writing-review & editing: LM.C, G.CA, M.GC. Supervision: M.GC. Funding acquisition: LM.C, G.CA, M.GC.

ACKNOWLEDGEMENTS

We would like to express our gratitude to CORFO Maule, Chile, for funding the project 23INI7-251237, and to the Fundación para la Innovación Agraria (FIA), Chile, for supporting the project PYT 2023-0672. We also extend our thanks to Ecolchado SpA for providing the facilities used in this study.

FUNDING

This work was supported by to CORFO Maule, Chile (Grant number 23INI7-251237), and to the Fundación para la Innovación Agraria (FIA), Chile (Grant number PYT 2023-0672).

REFERENCES

Abdallah, A. M., Ugolini, F., Baronti, S., Maienza, A., Ungaro, F., & Camilli, F. (2019a). Assessment of two sheep wool residues from textile industry as organic fertilizer in sunflower and maize cultivation. *Journal of Soil Science and Plant Nutrition, 19*, 793-807. https://doi.org/10.1007/s42729-019-00079-y

Abdallah, A., Ugolini, F., Baronti, S., Maienza, A., Camilli, F., Bonora, L., Martelli, F., Primicerio, J., & Ungaro, F. (2019b). The potential of recycling wool residues as an amendment for enhancing the physical and hydraulic properties of a sandy loam soil. *International Journal of Recycling Organic Waste in Agriculture, 8*, 131-143. https://doi.org/10.1007/s40093-019-0283-5

Araya-Osses, D., Casanueva, A., Román-Figueroa, C., Uribe, J. M., & Paneque, M. (2020). Climate change projections of temperature and precipitation in Chile based on statistical downscaling. *Climate Dynamics, 54*, 4309-4330. https://doi.org/10.1007/s00382-020-05231-4

Barrow, N. J., Debnath, A., & Sen, A. (2020). Measurement of the effects of pH on phosphate availability. *Plant and Soil, 454*, 217-224. https://doi.org/10.1007/s11104-020-04647-5

Blaes, X., Chomé, G., Lambert, M.-J., Traoré, P. S., Schut, A. G. T., & Defourny, P. (2016). Quantifying fertilizer application response variability with VHR satellite NDVI time series in a rainfed smallholder cropping system of Mali. *Remote Sensing, 8*(6), 531. https://doi.org/10.3390/rs8060531

Böhme, M., Pinker, I., Grüneberg, H., & Herfort, S. (2010). Sheep wool as fertiliser for vegetables and flowers in organic farming. *Acta Horticulturae, 933*, 195-202. https://doi.org/10.17660/ActaHortic.2012.933.23

Bradshaw, T., & Hagen, K. (2022). Wool pellets are a viable alternative to commercial fertilizer for organic vegetable production. *Agronomy, 12*(5), 1210. https://doi.org/10.3390/agronomy12051210

Cabrera, M. L., Kissel, D. E., & Vigil, M. F. (2005). Nitrogen mineralization from organic residues: Research opportunities. *Journal of Environmental Quality, 34*(1), 75-79. https://doi.org/10.2134/jeq2005.0075

Cassol, D., De Silva, F. S. P., Falqueto, A. R., & Bacarin, M. A. (2008). An evaluation of non-destructive methods to estimate total chlorophyll content. *Photosynthetica, 46*(4), 634-636. https://doi.org/10.1007/s11099-008-0109-6

Clivot, H., Mary, B., Valé, M., Cohan, J.-P., Champolivier, L., Piraux, F., Laurent, F., & Justes, E. (2017). Quantifying in situ and modeling net nitrogen mineralization from soil organic matter in arable cropping systems. *Soil Biology and Biochemistry, 111*, 44-59. https://doi.org/10.1016/j.soilbio.2017.03.010

Dal Prà, A., Ugolini, F., Negri, M., Bortolu, S., Duce, P., Macci, C., Lombardo, A., Benedetti, M., Brajon, G., Guazzini, L., Casini, S., Spagnul, S., & Camilli, F. (2024). Wool agro-waste biomass and spruce sawdust: Pellets as an organic soil amendment. *Sustainability, 16*(6), 2228. https://doi.org/10.3390/su16062228

De Neve, S. (2017). Organic matter mineralization as a source of nitrogen. F. Tei, S. Nicola & P. Benincasa (Eds.), *Advances in Research on Fertilization Management of Vegetable Crops* (pp. 65-83) Cham, Switzerland: Springer. https://doi.org/10.1007/978-3-319-53626-2_3

Dontsova, K. M., Norton, L. D., Johnston, C. T., & Bigham, J. M. (2004). Influence of exchangeable cations on water adsorption by soil clays. *Soil Science Society of America Journal, 68*(4), 1218-1227. https://doi.org/10.2136/sssaj2004.1218

Garreaud, R. D., Boisier, J. P., Rondanelli, R., Montecinos, A., Sepúlveda, H. H., & Veloso-Aguila, D. (2020). The central Chile mega drought (2010-2018): A climate dynamics perspective. *International Journal of Climatology, 40*(1), 421-439. https://doi.org/10.1002/joc.6219

Gee, G. W., & Bauder, J. W. (1986). Particle-size analysis. In A. Klute (Ed.), *Methods of soil analysis: Part 1 Physical and Mineralogical Methods* (2nd ed., pp. 383-411) New York, UK: John Wiley & Sons, Inc. https://doi.org/10.2136/sssabookser5.1.2ed.c15

Haque, A. N. M. A., & Naebe M. (2022). Waste wool powder for promoting plant growth by moisture retention. *Sustainability, 14*(19), 12267. https://doi.org/10.3390/su141912267

Haydar, M. S., Ghosh, D., & Roy, S. (2024). Slow and controlled release nanofertilizers as an efficient tool for sustainable agriculture: Recent understanding and concerns. *Plant Nano Biology, 7*, 100058. https://doi.org/10.1016/j.plana.2024.100058

Huang, W. J., Yang, Q. Y., Peng, D. L., Huang, L. S., Zhang, D. Y., & Yang, G. J. (2014). Nitrogen vertical distribution by canopy reflectance spectrum in winter wheat. *IOP Conference Series: Earth and Environmental Science, 17*(1), 012051. https://doi.org/10.1088/1755-1315/17/1/012051

Hunter, M. C., Smith, R. G., Schipanski, M. E., Atwood, L. W., & Mortensen, D. A. (2017). Agriculture in 2050: Recalibrating targets for sustainable intensification. *Bioscience, 67*(4), 386-391. https://doi.org/10.1093/biosci/bix010

Kumar Sarangi, P., Subudhi, S., Bhatia, L., Saha, K., Mudgil, D., Prasad Shadangi, K., Srivastava, R. K., Pattnaik, B., & Arya, R. K. (2023). Utilization of agricultural waste biomass and recycling toward circular bioeconomy. *Environmental Science and Pollution Research, 30*, 8526-8539. https://doi.org/10.1007/s11356-022-20669-1

Leeds-Harrison, P. B., Shipway, C. J. P., Jarvis, N. J., & Youngs, E. G. (1986). The influence of soil macroporosity on water retention, transmission and drainage in a clay soil. *Soil Use and Management, 2*(2), 47-50. https://doi.org/10.1111/j.1475-2743.1986.tb00678.x

Marczak, D., Lejcuś, K., Kulczycki, G., & Misiewicz, J. (2022). Towards circular economy: Sustainable soil additives from natural waste fibres to improve water retention and soil fertility. *Science of the Total Environment, 844*, 157169. https://doi.org/10.1016/j.scitotenv.2022.157169

Masunga, R. H., Uzokwe, V. N., Mlay, P. D., Odeh, I., Singh, A., Buchan, D., & De Neve, S. (2016). Nitrogen mineralization dynamics of different valuable organic amendments commonly used in agriculture. *Applied Soil Ecology, 101*, 185-193. https://doi.org/10.1016/j.apsoil.2016.01.006

Murphy, B. W. (2015). Impact of soil organic matter on soil properties—a review with emphasis on Australian soils. *Soil Research, 53*(6), 605-635. https://doi.org/10.1071/SR14246

Neina, D. (2019). The role of soil pH in plant nutrition and soil remediation. *Applied and Environmental Soil Science, 2019*(1), 5794869. https://doi.org/10.1155/2019/5794869

ODEPA. (2014). *Estudio: Mercado de la carne y lana ovina en Chile*.

ODEPA. (2017). *Encuesta ganado ovino*.

Ordiales, E., Gutiérrez, J. I., Zajara, L., Gil, J., & Lanzke, M. (2016). Assessment of utilization of sheep wool pellets as organic fertilizer and soil amendment in processing tomato and broccoli. *Modern Agricultural Science and Technology, 2*(2), 20-35.

Penn, C. J., & Camberato, J. J. (2019). A critical review on soil chemical processes that control how soil pH affects phosphorus availability to plants. *Agriculture, 9*(6), 120. https://doi.org/10.3390/agriculture9060120

Rabot, E., Wiesmeier, M., Schlüter, S., & Vogel, H.-J. (2018). Soil structure as an indicator of soil functions: A review. *Geoderma, 314*, 122-137. https://doi.org/10.1016/j.geoderma.2017.11.009

Rawls, W. J., Pachepsky, Y. A., Ritchie, J. C., Sobecki, T. M., & Bloodworth, H. (2003). Effect of soil organic carbon on soil water retention. *Geoderma, 116*(1-2), 61-76. https://doi.org/10.1016/S0016-7061(03)00094-6

Rezanezhad, F., Price, J. S., Quinton, W. L., Lennartz, B., Milojevic, T., & Van Cappellen, P. (2016). Structure of peat soils and implications for water storage, flow and solute transport: A review update for geochemists. *Chemical Geology, 429*, 75-84. https://doi.org/10.1016/j.chemgeo.2016.03.010

Ritchie, H., Roser, M., & Rosado, P. (2022). *Fertilizers*. Our World in Data. Retrieved from https://ourworldindata.org/fertilizers

Sadzawka, R. A., Carrasco, R. M. A., Grez, Z. R., de la Luz Mora, G. M., Flores, P. H., & Reaman, A. (2006). *Métodos de análisis recomendados para los suelos de Chile*. Revisión 2006. Santiago, Chile: Serie Actas - Instituto de Investigaciones Agropecuarias, no. 34. Retrieved from https://hdl.handle.net/20.500.14001/8541

Sadzawka, R. A., Carrasco, R. M., Demanet, F. R., Flores, P. H., Grez, Z. R., Mora, G. M., & Neaman, A. (2007). *Métodos de análisis de tejidos vegetales*. Santiago, Chile: Serie Actas - Instituto de Investigaciones Agropecuarias, no. 40. Retrieved from https://hdl.handle.net/20.500.14001/8570

Sharma, S. C., Sahoo, A., & Chand, R. (2019). Potential use of waste wool in agriculture: An overview. *Indian Journal of Small Ruminants, 25*(1), 1-12. https://doi.org/10.5958/0973-9718.2019.00019.9

Song, X., Chen, C., Arthur, E., Tuller, M., Zhou, H., Shang, J., & Ren, T. (2022). Cation exchange capacity and soil pore system play key roles in water vapour sorption. *Geoderma, 424*, 116017. https://doi.org/10.1016/j.geoderma.2022.116017

Spadoni, G. L., Cavalli, A., Congedo, L., & Munafò, M. (2020). Analysis of Normalized Difference Vegetation Index (NDVI) multi-temporal series for the production of forest cartography. *Remote Sensing Applications: Society and Environment, 20*, 100419. https://doi.org/10.1016/j.rsase.2020.100419

Vončina, A., & Mihelič, R. (2013). Sheep wool and leather waste as fertilizers in organic production of asparagus (*Asparagus officinalis* L.). *Acta Agriculturae Slovenica, 101*(2), 191-200. https://doi.org/10.14720/aas.2013.101.2.14910

Wen, G., Rippon, J. A., Brady, P. R., Wang, X. G., Liu, X., & Cookson, P. G. (2009). The characterization and chemical reactivity of powdered wool. *Powder Technology, 193*(2), 200-207. https://doi.org/10.1016/j.powtec.2009.03.021

Yudina, L., Sukhova, E., Gromova, E., Mudrilov, M., Zolin, Y., Popova, A., Nerush, V., Pecherina, A., Grishin, A. A., Dorokhov, A. A., & Sukhov, V. (2023). Effect of duration of LED lighting on growth, photosynthesis and respiration in lettuce. *Plants, 12*(3), 442. https://doi.org/10.3390/plants12030442