Article

Not peer-reviewed version

Thermoregulation and Soil Moisture Management in Strawberry Cultivation Mulched with Sheep Wool

Jan Broda *, Andrzej Gawlowski, Monika Rom, Tomasz Kukulski, Katarzyna Kobiela-Mendrek

Posted Date: 14 October 2024

doi: 10.20944/preprints202410.1075.v1

Keywords: strawberry; sheep wool; mulch; microclimate; biodegradation

Article

Thermoregulation and Soil Moisture Management in Strawberry Cultivation Mulched with Sheep Wool

Jan Broda *, Andrzej Gawłowski, Monika Rom, Tomasz Kukulski and Katarzyna Kobiela-Mendrek

Faculty of Materials, Civil and Environmental Engineering, University of Bielsko-Biala, Willowa 2, 43-309 Bielsko-Biala, Poland

* Correspondence: jbroda@ubb.edu.pl; Tel.: +48 33 8279117

Abstract: The application of wool as mulch in strawberry cultivation was analysed to find a solution for the rational use of wool from mountain sheep. In the plantation, the experimental plots mulched with wool, straw and bark were appointed. The plots were monitored during the experiment, while the soil temperature and moisture content were measured. The data collected in two-hour intervals were analysed, taking into account air temperature and falls registered in the local meteorological station. Additionally, the progress of mulch biodegradation was tracked. The changes in the wool morphology that occurred by biodegradation were observed during microscopic examinations using the Scanning Electron Microscope (SEM). It was stated that wool mulch plays an essential role in thermoregulation of the soil surface, prevents the overheating of the soil during the summer heat and protects it against excessive cooling during cold nights. The wool mulch minimises the fluctuations between the soil's day and night temperature. The fluctuations do not exceed 2 - 3 degrees on hot summer days, which are five times smaller than for the control plot. The wool retains large amounts of rainwater several times its weight. The water is then slowly released, providing the growing plants a moist environment during a longer rainless period. Moreover, wool is difficult to biodegrade and maintain its properties for a long time, lasting longer than one vegetation season. Compared to straw and bark, the temperature fluctuations recorded for wool are two times smaller, and its effectiveness in water management is considerably better. The beneficial impact of the wool mulch ensuring favourable conditions for strawberry growth was explained by the specific wool structure and its unique properties.

Keywords: strawberry; sheep wool; mulch; microclimate; biodegradation

1. Introduction

Strawberries are among the most popular fruits worldwide, valued for their delightful flavour and aromatic qualities. In cultivation, carried out in different parts of the world, a mulching of strawberry plants is commonly applied. The application of mulch has several benefits, which increase the yield and quality of strawberry fruits. The mulch helps suppress weed growth around strawberry plants, reducing competition for nutrients, water, and sunlight [1,2]. The mulching materials spread around the plants directly protect the soil against the action of wind and solar radiation. The mulch regulates the soil temperature, keeping it cooler on hot summer days and warmer in cold weather. The mulch reduces water evaporation from the soil surface and helps retain moisture, which is essential for shallow strawberry roots susceptible to water deficit [3–5]. During heavy rains, mulch prevents rainwater from leaching nutrients and reduces soil erosion, which can damage and expose strawberry roots. Additionally, mulch prevents fruits from coming into direct contact with the soil. Thus, mulch helps control diseases and pests more significantly, reduces the risk of fruit rot, and helps keep them clean.

For many years, in the cultivation of strawberries as a common mulching material, plastic mulch, mainly polyethylene film, was applied [6–8]. Applying synthetic materials generates massive non-biodegradable waste and potential pollution of the soil with plastic residues. Due to environmental concerns, plastic mulch must be eliminated, and biodegradable and renewable materials should be applied instead. In the literature, numerous examinations on the application of straw, shredded leaves, grass clippings, wood chips, bark, paper, or cardboard are reported [9–12]. All mentioned

 doi:10.20944/preprints202410.1075.v1

mulching materials are plant-origin, which are composed of cellulose. Under natural conditions, these materials decompose relatively quickly in less than one year [13].

The alternative to using plant-origin materials is the application of organic materials of animal origin. The natural potential material that could be used is wool obtained annually by sheep shearing. Nowadays, wool obtained from local breeds, once a precious raw material for producing textiles, is often discarded and treated in many countries as a waste of sheep farming. New application areas have been explored for this wool, and several new products have been developed. The highest importance has gained thermal and acoustic insulating materials, geotextiles and fertilisers [14–20]. Applying wool as mulch is the next possible option.

The literature presents a few studies on using sheep wool for mulching strawberries, lettuce, eggplant, and pepper in different soil types. It is reported that wool, similar to other mulch materials, suppresses weed growth, regulates the microclimate in the plant's root zone, prevents soil erosion, and impacts the soil's microbial activity [21,22].

Like cellulosic mulching materials, the wool gradually degrades in a humid environment in contact with the soil, adding to it organic matter. In contrast to cellulose-based materials, wool is more resistant to enzymatic attack due to the compact structure of wool keratin, and therefore, its bio-degradation occurs relatively slowly [23]. In contact with soil, wool decomposition lasts much longer, usually longer than one vegetation season [24]. During wool biodegradation, the keratin is decomposed into nitrogen-rich organic compounds. The compounds are gradually released into the soil, significantly improving soil fertility and promoting intense plant growth [25]. Additionally, wool has better thermal insulation properties and higher water absorption capacity than cellulosic materials. Due to these unique properties, wool mulch should provide better soil thermoregulation and help retain moisture more effectively.

Continuing previous research on the rational use of local resources of coarse wool obtained from mountain sheep, the possibility of using wool as a mulch in strawberry cultivation was tested. The test plots covered with wool and other plant-origin materials were prepared, and the effectiveness of wool mulch in regulating soil temperature and moisture content compared to other traditional organic mulch materials was examined. Simultaneously, the course of wool biodegradation was tracked while the changes in wool morphology were analysed.

2. Materials and Methods

2.1. Preparation of Experimental Plots

The effectiveness of wool as mulching material was examined in experimental plots prepared in strawberry plantations of the Ducat variety. The plots were situated in southern Poland in the Silesian region, at the foothills of the Beskids Mountains, at an altitude of 360 m above sea level (GPS coordinates: 49.7351592, 18.6734962).

The site was located in a temperate climate zone. According to data from the local meteorological station collected in the 30-year normal period 1991-2020 and calculated according to the WMO Guidelines on the Calculation of Climate Normals, the average annual temperature in this place equals 9°C, while the rainfall reaches 998 mm. The summers are mild, sunny and partly cloudy, with frequent showers and thundershowers. In the summer months, June and July, the average temperature is 16.8 °C and 18.5 °C, respectively. July has the highest number of rainy days. The average rainfall in this month is the highest in the year and equals 143.2 mm. The winters are freezing, snowy, windy, and mostly cloudy. In the winter months, January and February, the average temperature drops to -0.9 and 0.2 °C, respectively [26].

Four plots with an area of 5 m^2 in soil of average quality and a pH of 5.5 were prepared. In each plot, the strawberry seedlings were planted at an interval of 40 cm in two rows 60 cm apart. The greasy wool of mountain sheep not subjected to any additional treatment was spread between seedlings on the field's surface, forming a layer of ca. 5 cm thickness. The wool layer was covered with a thin layer of bark to avoid being blown away by the wind. The control plot without mulch and

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 14 October 2024 doi:10.20944/preprints202410.1075.v1

plots covered with other traditional mulch materials, such as straw and bark, were prepared for comparison (Figure 1).

(a) (b)

Figure 1. The experimental plot mulched with various materials in a strawberry.plantation: (a) wool + bark; (b) straw.

The plots were established in the summer of 2022. During the experiment, the plantation was maintained in natural conditions without additional irrigation.

2.2. Methods

The plantation was regularly monitored during strawberry growth and harvest and later during autumn and winter. At this time, the microclimate on the soil's surface was controlled. For this purpose, the HOBO MX Soil Moisture and Temperature (MX2307) data loggers were installed. The soil moisture and temperature measurements were carried out in the thin soil subsurface layer at a depth of 10 cm regularly in two-hour intervals. The logged data were transmitted wirelessly and collected on a computer.

Data registration was initiated in May 2023, approximately one month before the strawberry harvest. In the following months, data on temperature and soil moisture were collected. Additionally, historical data on air temperature and falls registered in the local meteorological station were used to analyse the results.

The paper presented the results of measurements during strawberry ripening and harvest in June 2023 and dormancy in January 2024. The months were chosen for analysis to demonstrate the mulch's impact on soil thermoregulation and moisture in summer and winter, during and beyond the vegetation season.

During the experiment, wool samples were periodically taken for microscopic observations. Before observations, the wool was mechanically cleaned from the remnants of soil and then covered with a thin layer of gold in the Leica EM ACE 200 low-vacuum coater (Wetzlar, Germany). The observations were carried out with the high-resolution Phenom ProX SEM microscope (PhenomWorld, Netherlands), operated in a backscattered electron mode.

3. Results

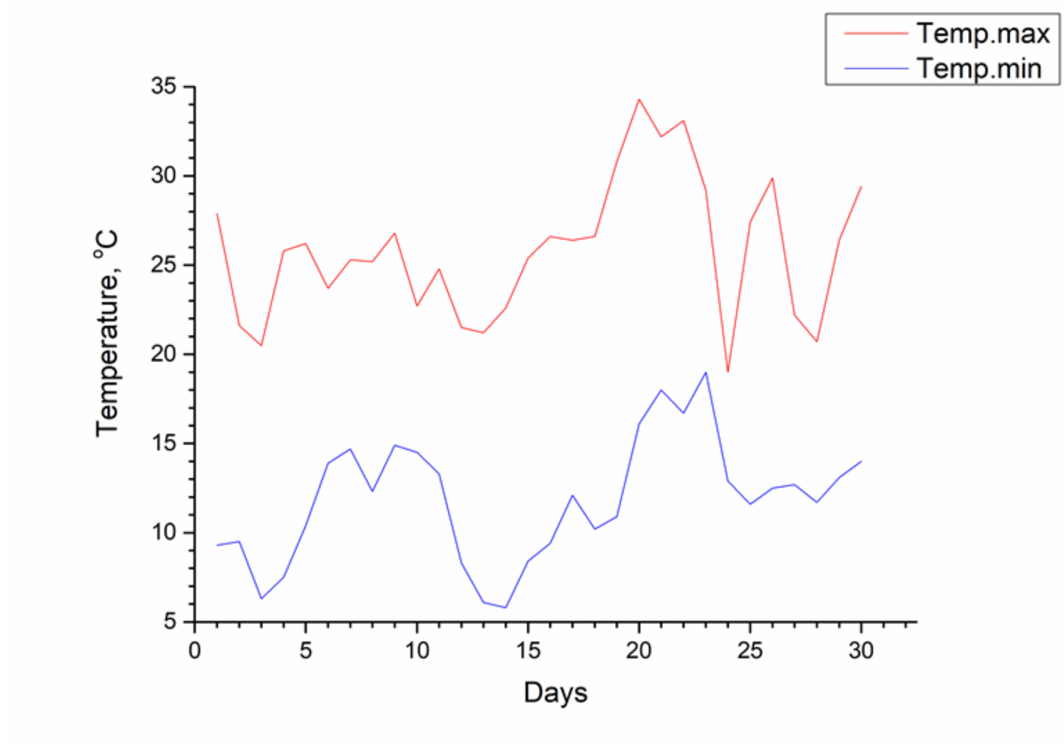
3.1. Soil Temperature

Figure 2 presents the results of temperature measurements in June 2023, at the beginning of Polish summer and the time for strawberry harvest. This month, the daytime air temperatures ranged between 20 and 30 °C. The day temperature of the soil for plots not covered with mulch fluctuated following air temperatures and reached values between 20 and 25 °C. In the hottest days, between 20 and 23 June, the soil temperature was the highest and exceeded 25 °C. For plots covered with mulch,

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 14 October 2024 doi:10.20944/preprints202410.1075.v1

the day temperatures of the soil were significantly lower. On average, the soil temperature for mulched plots was a few degrees lower than that of the control plot. For some days, the difference exceeded even 5 degrees.

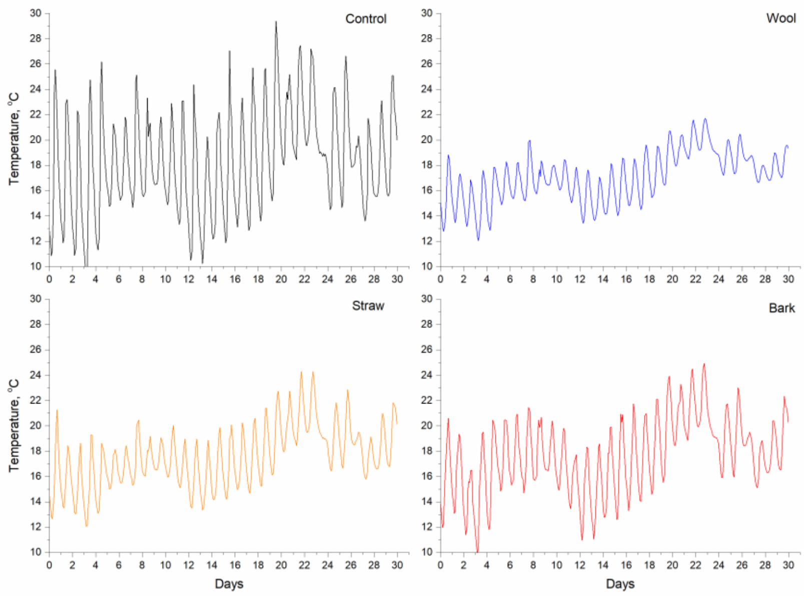
Cold nights with temperatures below 15 °C occurred throughout the month. For a few nights, the temperature decreased rapidly, reaching only 5 °C. As the air temperature dropped at night, a corresponding decrease in soil temperature was observed. In the control plot, which was not covered with mulch, the night temperature decreased more strongly. For mulched plots, the decrease in night temperature was lower. Almost every day, the night temperature was approximately two degrees higher than that of the control plot.



.

(**a**)

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 14 October 2024 doi:10.20944/preprints202410.1075.v1



(**b**)

Figure 2. Daily temperature graph during June 2023; (a) the air temperature measured in the local meteorological station; (b) soil temperature recorded for experimental plots.

For the whole month, the difference between day and night temperatures ranged between 10 and 15 degrees, which is exceptionally high for the temperate Polish climate. For the control plot, the differences in soil temperatures were on the same level as those in the air temperature (Figure 3).

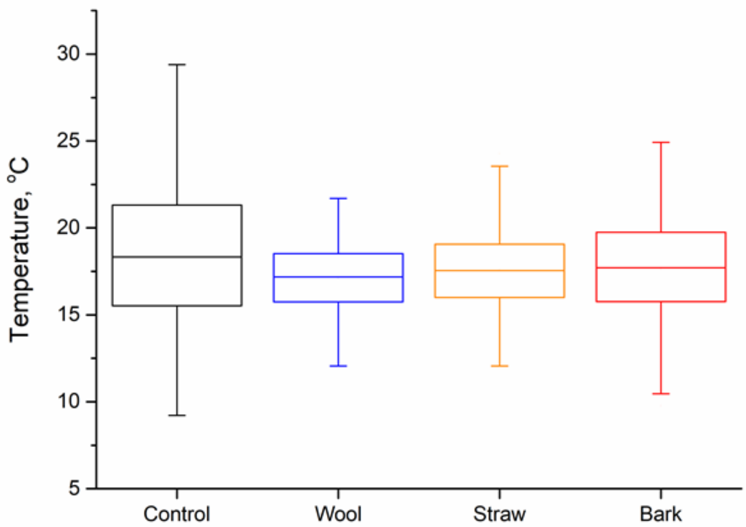
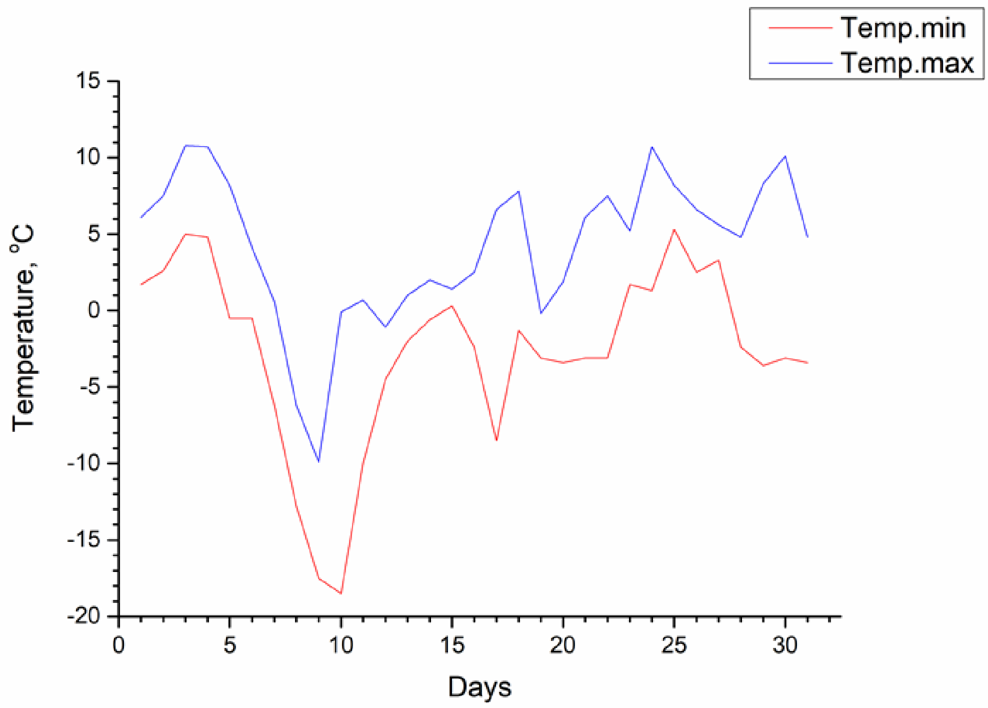


Figure 3. The daily difference in soil temperature for plots mulched with various materials in June 2023.

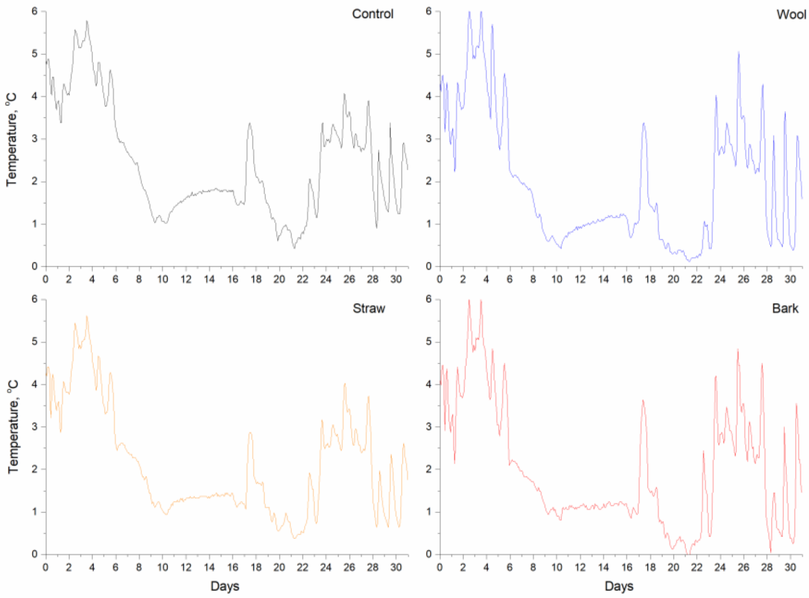
Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 14 October 2024 doi:10.20944/preprints202410.1075.v1

The differences between day and night soil temperatures were twice or three times lower for the mulched plots. When comparing different mulch materials, the most minor differences occurred in plots covered with wool. In this case, the difference between day and night soil temperatures for several days equalled only 2 or 3 degrees. The difference was slightly higher on other days, not exceeding 5 degrees. For plots mulched with straw and bark, the average difference fluctuated around 5 degrees.

Figure 4 presents the results of temperature measurements in January 2024 in the middle of winter. At the beginning and end of January 2024, plus temperatures were recorded. During the day, the air temperature ranged from 0 to 10 °C, while at night, it oscillated around 0 °C. In the middle part of the month, between 7 and 15 January, the temperature dropped below 0 °C. The day temperature dropped below -5 °C in a few days, and night temperatures reached almost -20 °C.



(**a**)



(**b**)

Figure 4. Daily temperature graph during January 2024; a/ the air temperature measured in the local meteorological station; b/ soil temperature recorded for experimental plots.

At the beginning of the month, according to the air temperature, the soil temperature ranged between 2 and 6 °C. Then, the soil temperature decreased to 1 °C with the beginning of the frosty days. In the days of the heaviest frost, when the air temperature at night reached -20 °C, the soil temperature remained unchanged. During this period, the field was covered with a layer of snow with a thickness of 12 cm. After a few warmer days, by light frosty days with temperatures oscillating around 0 °C, the soil temperature dropped to a temperature close to 0 °C. In the last week, the soil temperature rose with the air temperature to 3 - 4 °C and then slightly decreased to 1 - 2 °C.

The soil temperature was above zero throughout the month, so the soil remained unfrozen. When the field was covered with snow in the middle of the month, the day and night temperatures were even each other, so no differences between day and night temperatures were detected. At this time, the soil temperature was minimally lower for plots mulched with bark and wool. Differences between day and night temperatures were observed during the snowless periods at the month's beginning and end. For most days, the differences were slight and did not exceed 2 degrees. Differences in day and night temperatures were similar for both control and mulched plots. Compared to summer months, the observed differences in the soil temperature were a few times smaller (Figure 5).

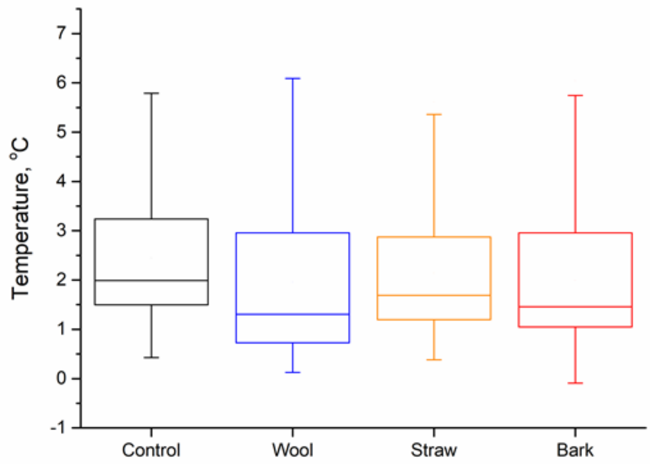
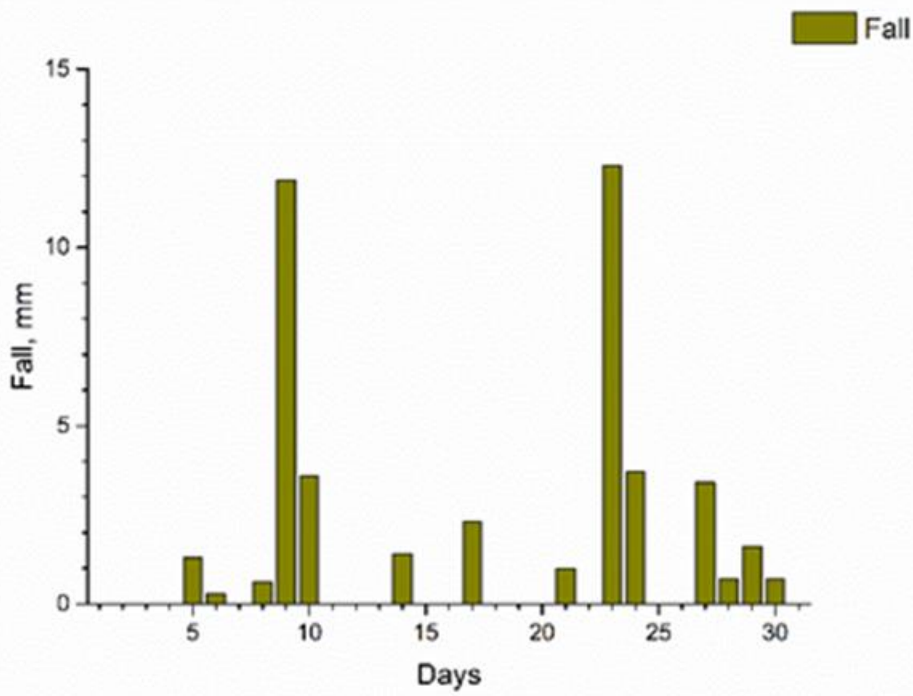


Figure 5. The daily difference in soil temperature for plots mulched with various materials in June 2023.

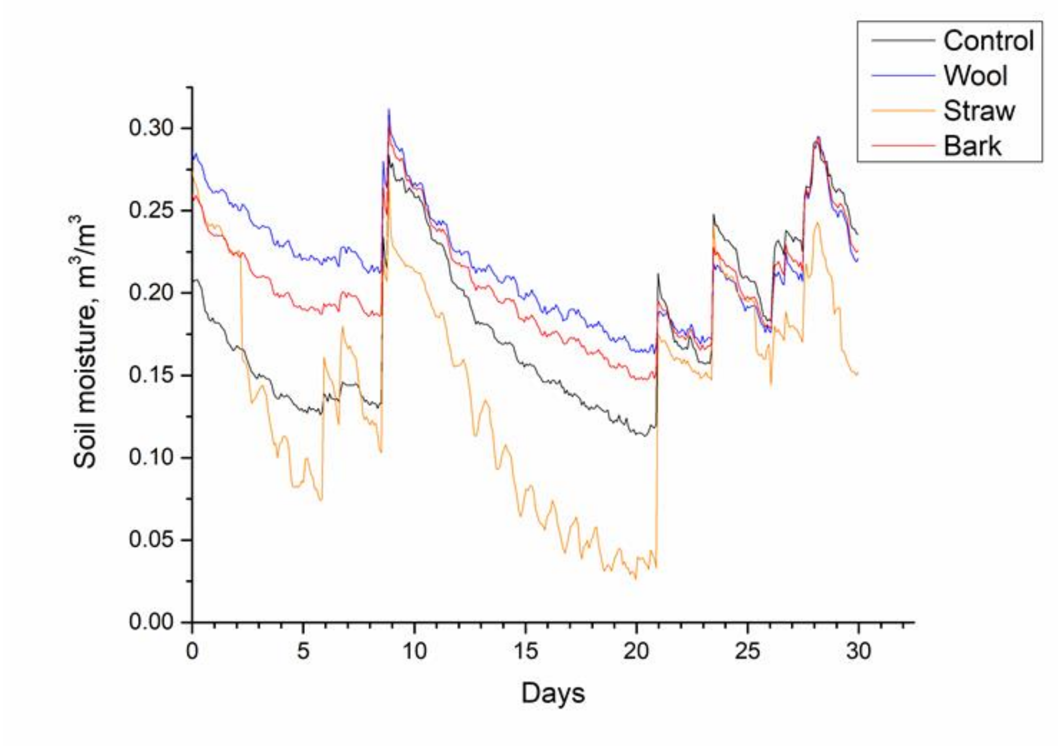
3.2. Soil moisture

Figure 6 presents the registered data concerning atmospheric precipitation and soil moisture in experimental plots in June 2023. This month, the total precipitation was 45 mm, much less than the average rainfall for this area. Throughout the month, the more extensive rainfall above 12 mm was registered on two rainy days, which occurred approximately two weeks apart in the first and second half of the month. Between these days, a period without or only light rain was noted. Then, at the end of the month, a few rainy days with low precipitation below 4 mm were recorded.



(a)

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 14 October 2024 doi:10.20944/preprints202410.1075.v1



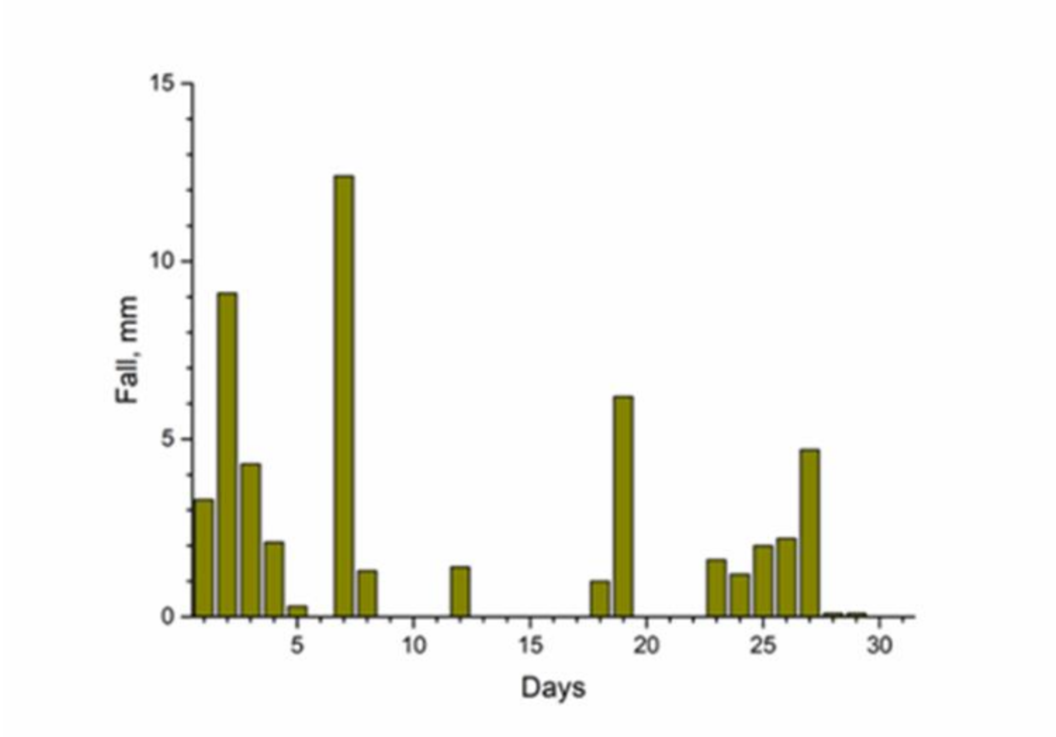
(**b**)

Figure 6. Daily rainfall and soil moisture during June 2023; (**a**) the fall registered in the meteorological station; (**b**) the soil moisture for experimental plots.

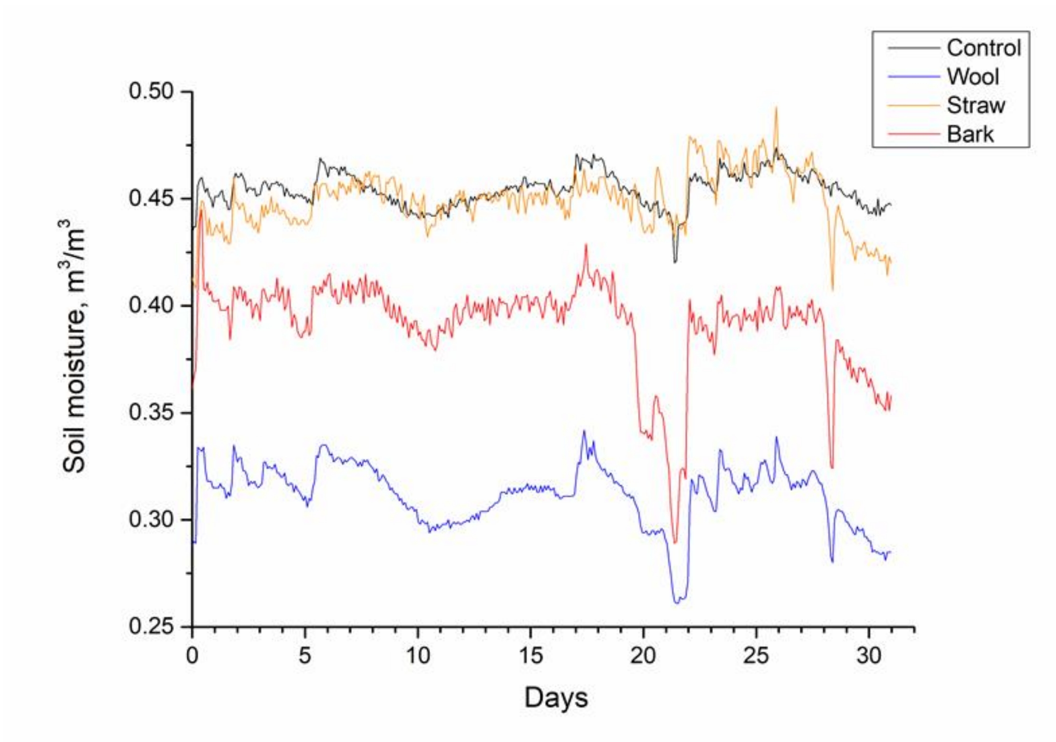
A rapid increase in soil moisture was detected on days with heavy rainfall. On 9 June, the day of the most intense rain, the soil moisture jumped to 0.3 m^3/m^3 for all unmulched and mulched plots. Then, after the rainfall stopped, the soil moisture gradually decreased. On the dry days between 10 and 20 June, before the second day with higher precipitation, the moisture content gradually decreased to 0.12 m^3/m^3 for the control plot. For mulched plots, the soil moisture decreased to 0.18, 0.15 and 0.03 m^3/m^3 for wool, bark and straw, respectively. The moisture content in the plot mulched with wool decreased slowly, much slower than in the control plot and in the plots covered with bark and straw.

Figure 7 presents the data of atmospheric precipitation and soil moisture in experimental plots measured in January 2024, during the middle of winter. The total fall reached 53 mm. In the first five days, slight rainfall was recorded for each day. On 7 January, with the decrease in temperature, snowfall occurred. The 12 cm thick layer of snow remained unchanged until the end of the frosty period. After that, with the increase in temperature, the snow melted, and several days of light rain were recorded.

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 14 October 2024 doi:10.20944/preprints202410.1075.v1



(**a**)



(**b**)

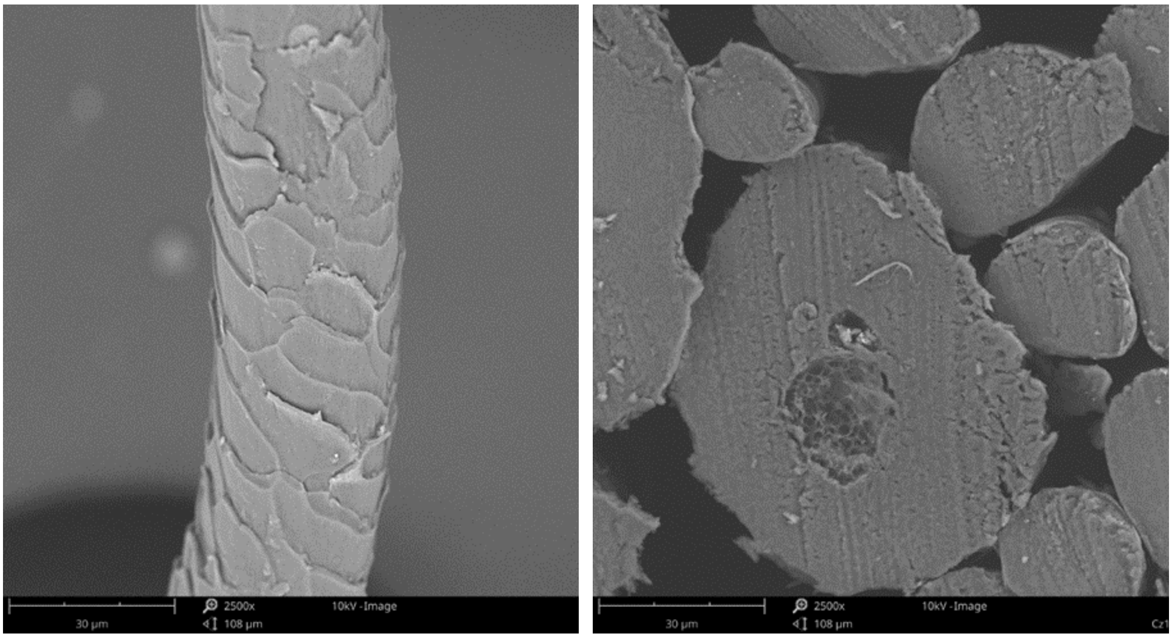
Figure 7. Daily rainfall and soil moisture during January 2024; (**a**) the fall registered in the meteorological station; (**b**) the soil moisture for experimental plots.

During January, the soil moisture for the control plot remained constant at a high level of 0.45 m^3/m^3. The high moisture remained unchanged for the month, independently of rain or snow precipitation. The plot mulched with straw had moisture similar to the control plot. The soil moisture for the plot mulched with bark and wool was significantly lower, reaching 0.40 and 0.30 m^3/m^3, respectively.

3.3. Wool Morphology

The wool used for mulching was obtained from mountain sheep. The fibres have diameters between 20 and 90 µm and lengths between 30 and 120 mm. The morphology of raw wool is typical for coarse wool obtained from local primitive breeds. The outer cuticle layer of the fibres is formed from flat cells forming characteristic scales arranged in a mosaic pattern on the surface (Figure 8a).

The inner cortical layer, the main component occupying an essential part of the fibre cross-section, is formed from spindle-shaped cells. Additionally, for many fibres in the central part, the inner medulla with a diameter between a few to a dozen µm is observed (Figure 8b). Apart from these fibres, a small amount of so-called kemp, for which the medulla is more than half of the cross-section, is encountered. The medulla is formed from empty cells or cells filled with air.

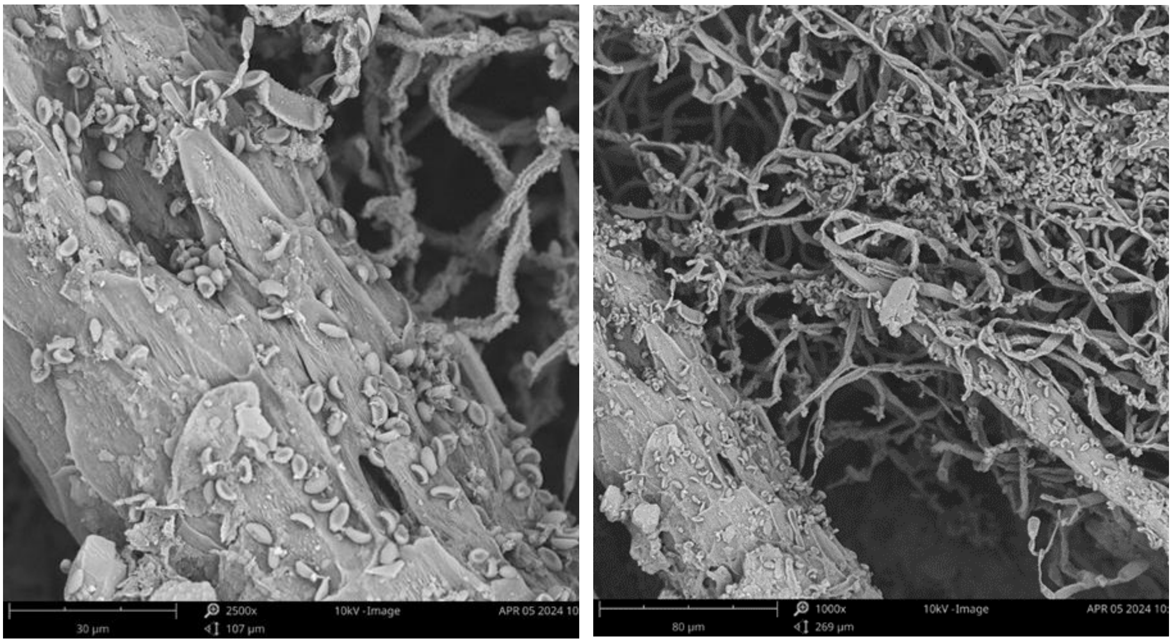


(**a**) (**b**)

Figure 8. The morphology of the mountain sheep wool; (**a**) scales occurring on the fibre's surface;. (**b**) the cross-section of medullated fibres.

When the mulch was spread on the soil, the wool showed no signs of mechanical or biological damage. For all fibres, microscopic observations revealed that the edges of the scales were well adhered to the fibres, and their surface remained smooth without cracks and holes.

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 14 October 2024 doi:10.20944/preprints202410.1075.v1



(**a**) (**b**)

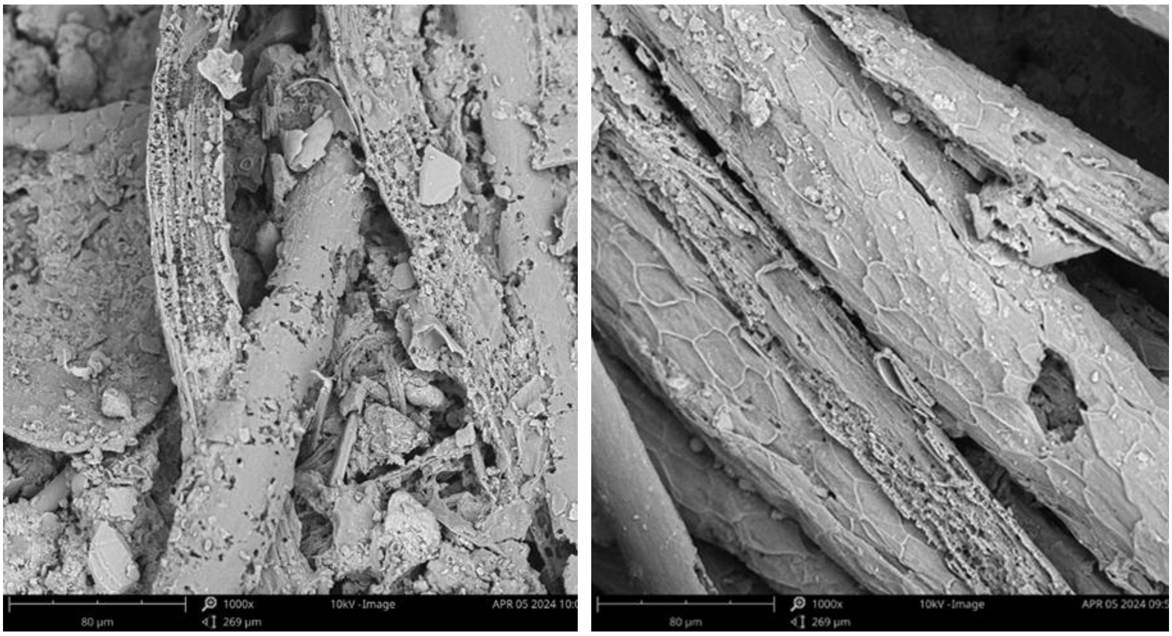
Figure 9. The development of fungi in the wool mulch: (**a**) fungi colonised on the surface of the fibres; (b) the mycelium located between fibres.

During the strawberry vegetation, the wool mulch remained physically unharmed for several months and did not show external signs of damage. At the end of the season, the first discolouration of wool appeared. Simultaneously, the fibres became fragile and could easily be torn in hands.

During microscopic observation, fungi colonised on the surface of the fibres were observed (Figure 9a). With time extension, the number of fungi significantly increased. Simultaneously, intense mycelium growth was observed in the space between fibres. After the following months, the mycelium, forming a network of branching, tube-like filaments a few μm in diameter, became denser and filled almost the entire available space (Figure 9b).

With the emergence of fungi, the biological decomposition of wool was initiated. Initially, in many places on the surface of the fibres, irregularly distributed fine holes with a diameter of less than 1 μm appeared. The visible holes were the entrances of deep channels running into the inner part of the fibres. Later, numerous holes formed a system of interconnected channels and pores, transforming the compact wool structure into a perforating substance (Figure 10a). In addition to the system of inner channels and pores, deep and widerspread cavities were created in some places. The cavities reached large dimensions and extended all fibre layers from the outer cuticle through the cortical layer to the inner medulla (Figure 10b).

 doi:10.20944/preprints202410.1075.v1



(**a**) (**b**)

Figure 10. The biological decomposition of wool fibres; (**a**) the system of interconnected channels and pores; (**b**) the deep cavity extended through all wool layers.

4. Discussion

During the experiment in summer, typically for the Polish climate, the day temperatures ranged between 20 and 30 °C. At the same time, unusually for this season, several cold nights with temperatures below 10 °C occurred. The differences between day and night temperatures exceeded several degrees, which is relatively high for Polish climatic conditions. The high air temperatures and solar operation increased the soil temperature during the days. For mulched plots, the excessive sun-induced heating of the soil's surface was prevented, and the temperature increase during the day was minimised. During cold nights, when the soil temperature rapidly decreased, rapid cooling was suppressed for mulched plots, and the temperature remained a few degrees higher. Consequently, the mulch significantly minimised the daily temperature fluctuations.

Analysing the daily temperature fluctuations for the control plot and plots covered with different materials, the plot mulched with wool showed the lowest differences. The wool most effectively mitigated fluctuations between day and night temperatures. The high thermoregulation capacity of wool mulch results from its good insulating capacities, which have been repeatedly revealed for building insulating materials [27-28]. For these materials, the thermal conductivity is low, equal to 0.038 – 0.054 W/m K [29]. This value is similar to or even lower than commonly used insulating materials and significantly lower than the conductivity of straw bales 0.053 – 0.065 W/m K [30] and bark 0.074 W/m K [31].

Wool products' low thermal conductivity is caused by trapping small air pockets, creating a natural insulating barrier. Due to the unique wool structure, pockets are formed inside kemp and medullated fibres with hollow or porous medulla and in the micropores placed between fibres. The formation of pockets is facilitated by the uneven surface of the fibres covered with characteristic scales. The numerous air pockets reduce heat transfer through conduction and convection. Additionally, heat loss is reduced by the crimp of fibres and the interlocked structure of the mulch layer. This compact structure reduces airflow and, consequently, reduces heat transfer through convection.

In addition to low thermal conductivity, wool has a high specific heat capacity of 1.3 – 1.7 kJ/kg K. This value is similar to the specific heat capacity of bark 1.3 – 1.4 kJ/kg K [31] and much higher than that of straw 0.6 kJ/kg K [32]. Due to its high specific heat capacity, the wool absorbs solar

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 14 October 2024 doi:10.20944/preprints202410.1075.v1

radiation heat on hot summer days, reducing the risk of summer overheating. The stored heat is slowly released on cold nights when the surrounding temperature drops to low values.

Wool mulch's excellent insulation capacity is essential in summer during the vegetation season. During winter, the daily oscillations between minimal and maximal air temperatures are much smaller. Due to low air temperature oscillations, many cloudy days, and lower sun rays' impact on the soil, daily fluctuations in soil temperature are much lower. In winter, the soil temperature is influenced mainly by the weather conditions, and mulching has no greater significance, independent of the type of mulch material applied.

When analysing soil moisture, it is evident that in the absence of artificial irrigation, soil humidity is strictly correlated with weather conditions. For control plots not covered with mulch, raindrops fall between strawberry plants directly on the soil surface, so soil moisture immediately increases during rains. The falling water interacts with mulch material for mulched plots before reaching the soil surface. The interactions involve several physical phenomena, including wetting the material's surface, water transport, and retention.

The wettability of the raw wool is significantly reduced. The wool contains hydrophobic contaminants, and a waxy coating covers the fibre's surface scales [33-34]. Initially, the wool's surface properties make wetting difficult. Later, after several weeks of mulch exposure to atmospheric conditions, the natural contaminants and the waxy coating are removed, and the cuticle is partially degraded. Then, water molecules' access into the fibres' inner parts is facilitated, and quick wetting of mulch is possible. Other mulching materials, straw and bark, are naturally hygroscopic and easily wetted by liquid water after spreading them on the field.

Water transport through the mulch layer is governed by the geometric configuration of its porous structure [35-36]. Due to small fibre diameters and wool's natural tendency to interlock, the wool fibre network is much denser, and the pores between fibres are much smaller. In this case, water transport through fibre assembly is more complicated and is driven mainly by capillary forces. The pores inside the mulch layer are bigger for straw and bark, so water can be transported easily through the mulch to the soil's surface.

The mulching materials possess various water absorption capacities. Wool immersed or sprayed with liquid water absorbs large amounts of water, several times its weight. The wool absorbency is comparable to bark [37] and several times higher than that of straw [38]. For wool, the water is absorbed in the space between the fibres, where the air trapped in the pores is displaced with liquid water. Additionally, water molecules diffuse across the hydrophobic cuticle and are absorbed in the amorphous matrix surrounding the intermediate filaments in the inner cortical cells. Due to the keratin structure, built mainly from the proteins rich in hydrophilic groups located in the side and main chains, the high amount of water molecules is readily attracted.

During rain, falling drops first wet the mulching material. Then, part of the water is absorbed inside the mulch material, while the rest is transported through the mulch layer to the soil surface. During heavy rainfall, the amount of falling water exceeds mulch absorption capacity. Thus, water not absorbed in the mulch seeps into the soil, raising quickly the soil moisture to a high value. As a result, immediately after heavy rain, for all mulched and unmulched plots, the soil moisture in its subsurface layer is almost the same, independent of the presence and kind of the mulch material.

After rain during dry days, water evaporates from the soil's surface, gradually decreasing the soil moisture. Solar radiation and wind blows cause evaporation relatively quickly in soil not covered with mulch. For plots covered with mulch, the evaporation is less intense, and the soil moisture decreases much slower.

The decrease in soil moisture occurs the slowest in plots mulched with wool. As mentioned above, water transport through the mulch layer occurs slowly. Moreover, wool mulch has an excellent water retention capacity and, on rainy days, absorbs a large amount of rainwater. The water molecules attached to the numerous inner hydrophilic groups of the keratin are hard to remove. Then, the water is slowly released, giving the soil higher humidity for longer. In this way, the wool assures good conditions for plant growth on dry summer days and ensures a favourable environment for soil microbiological activity.

In contrast to straw and bark, wool mulch maintained its properties for several months over a period longer than one growing season. The remarkable durability of wool mulch results from the high resistance of wool to biodegradation. Due to proteins' compact and highly crosslinked structure, wool biodegradation occurs slowly, much slower than for cellulosic-based straw and bark. The first external signs of biodegradation were detected in the layer adjacent to the soil several months after the spreading of mulch in the field. Biodegradation is caused by fungi that are naturally present in the environment. The fungi colonised the wool fibre surface and then, in the moist environment of the mulch, were easily reproduced. According to a mechanism called radial penetration, with the progressive growth over the fibres' surface, fungal boring hyphae penetrate the outer cuticle layer [39-40]. The resulting holes in the wool scales allowed direct hyphal entry into the deeper-layered cortical layer. The hyphae developed further inside this layer, giving rise to flattened, branched fronds of mycelium. The keratinolotic enzymes secreted by the fungi digested the wool keratin, forming a system of interconnected channels and pores inside fibres. For certain fibres, biodegradation occurs without forming the inner channels according to another mechanism. In this case, the vast cuticle and cortical layer fragments are digested. As a result, the big cavities extended over all fibre layers from the cuticle to the inner medulla are formed. The perforated structure of partially degraded fibres is fragile and, under mechanical pressure, easily collapses.

5. Conclusions

Due to its beneficial and unique insulating properties, the wool mulch ensures a proper microclimate on the soil surface, preventing the overheating of the soil during the summer heat and protecting excessive cooling during cold nights. The wool spread on the soil's surface minimises the fluctuations between the soil’s day and night temperature. The fluctuations do not exceed 2 - 3 degrees on hot summer days, which are five times smaller than for the control plot. Due to its excellent absorption capacity, wool mulch ensures high rainwater retention, providing a humid environment during drought. The performance of the wool mulch in the soil thermoregulation and water retention is better than that of other organic mulching materials of plant origin. For wool, the temperature fluctuations recorded in summer are two times more minor. The water retained in wool is released into the soil more slowly, ensuring a longer-term higher water content in strawberries' root zones. In addition to being beneficial for plant growth, wool is difficult to biodegrade and maintain its properties for a long time.

Author Contributions: Conceptualization, J.B. and A.G.; methodology, J.B. and A.G.. validation, J.B., M.R. and K.K.; formal analysis, J.B.; investigation, A.G. and T.K..; resources, J.B..; data curation, A.G..; writing—original draft preparation, J.B.; writing—review and editing, J.B..; visualisation, A.G. and M.R..; supervision, J.B.; project administration, J.B..; funding acquisition, M.R. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Norway Grants 2014-2021 through the Polish National Centre for Research and Development (NOR/POLNOR/WOOLUME/0007/2019-00).

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest. The funders had no role in the study's design, data collection, analysis, interpretation, manuscript writing, or decision to publish the results.

References

1. DeVetter, L.W.; Zhang, H.; Ghimire, S.; Watkinson, S.; Miles, C.A. Plastic Biodegradable Mulches Reduce Weeds and Promote Crop Growth in Day-Neutral Strawberry in Western Washington. *HortScience* 2017, *52* doi:10.21273/HORTSCI12422-17.
2. Saeed, M.; Haroon, M.; Ayaz, A.; Khan, M.J.A.; Khattak, M.K.; Ul Haq, I.; Iqbal, A.; Dawar, K.M. Comparisons of Weed Suppression and Strawberry Yield Obtained with Organic and Synthetic Mulches and Herbicides. *Pak J Bot* 2020, *52*, doi:10.30848/PJB2020-6(45).
3. Kumar, S.; Dey, P. Effects of Different Mulches and Irrigation Methods on Root Growth, Nutrient Uptake, Water-Use Efficiency and Yield of Strawberry. *Sci Hortic* 2011, *127*, doi:10.1016/j.scienta.2010.10.023.

4. Rannu, R.P.; Ahmed, R.; Siddiky, A.; Ali, A.S.M.Y.; Ibn Murad, K.F.; Sarkar, P.K. Effect of Irrigation and Mulch on the Yield and Water Use of Strawberry. *International Journal of Agronomy* 2018, *2018*, doi:10.1155/2018/2903706.
5. Pinto, J.P.; da Cunha, F.F.; da Silva Adão, A.; de Paula, L.B.; Ribeiro, M.C.; Costa Neto, J.R.R. Strawberry Production with Different Mulches and Wetted Areas. *Horticulturae* 2022, *8*, doi:10.3390/horticulturae8100930.
6. Kasperbauer, M.J. Strawberry Yield over Red versus Black Plastic Mulch. *Crop Sci* 2000, *40*, doi:10.2135/cropsci2000.401171x.
7. Lalk, G.T.; Bi, G.; Zhang, Q.; Harkess, R.L.; Li, T. High-Tunnel Production of Strawberries Using Black and Red Plastic Mulches. *Horticulturae* 2020, *6*, doi:10.3390/horticulturae6040073.
8. Johnson, M.S.; Fennimore, S.A. Weed and Crop Response to Colored Plastic Mulches in Strawberry Production. *HortScience* 2005, *40*, doi:10.21273/hortsci.40.5.1371.
9. Bilck, A.P.; Grossmann, M.V.E.; Yamashita, F. Biodegradable Mulch Films for Strawberry Production. *Polym Test* 2010, *29*,doi:10.1016/j.polymertesting.2010.02.007.
10. Costa, R.; Saraiva, A.; Carvalho, L.; Duarte, E. The Use of Biodegradable Mulch Films on Strawberry Crop in Portugal. *Sci Hortic* 2014, *173*, doi:10.1016/j.scienta.2014.04.020.
11. Whitworth, J. STRAW MULCH UNDER STRAWBERRIES REDUCES EROSION AND HAILDAMAGE. *HortScience* 2019, *28*, doi:10.21273/hortsci.28.4.274a.
12. Wang, X.; Shrestha, S.; Tymon, L.; Zhang, H.; Miles, C.; DeVetter, L. Soil-Biodegradable Mulch Is an Alternative to Non-Biodegradable Plastic Mulches in a Strawberry-Lettuce Double-Cropping System. *Front Sustain Food Syst* 2022, *6*, doi:10.3389/fsufs.2022.942645.
13. Kopitar, D.; Marasovic, P.; Jugov, N.; Schwarz, I. Biodegradable Nonwoven Agrotextile and Films—A Review. *Polymers (Basel)* 2022, *14*.
14. Kicińska-Jakubowska, A.; Broda, J.; Zimniewska, M.; Bączek, M.; Mańkowski, J. Effect of Blend Composition on Barrier Properties of Insulating Mats Produced from Local Wool and Waste Bast Fibres. *Materials* 2023, *16*, doi:10.3390/ma16010459.
15. Broda J; Baczek M Acoustic Properties of Multi-Layer Wool Nonwoven Structures . *Journal of Natural Fibers* 2020, *17*, 1567–1581, doi:10.1080/15440478.2019.1584078.
16. Marczak, D.; Lejcuś, K.; Misiewicz, J. Characteristics of Biodegradable Textiles Used in Environmental Engineering: A Comprehensive Review. *J Clean Prod* 2020, *268*.
17. Broda, J.; Gawlowski, A.; Rom, M.; Kobiela-Mendrek, K. Utilisation of Waste Wool from Mountain Sheep as Fertiliser in Winter Wheat Cultivation. *Journal of Natural Fibers* 2023, *20*, doi:10.1080/15440478.2023.2200047.
18. Vončina, A.; Mihelič, R. Sheep Wool and Leather Waste as Fertilizers in Organic Production of Asparagus (*Asparagus Officinalis* L.). *Acta Agric Slov* 2013, *101*, doi:10.2478/acas-2013-0015.
19. Bradshaw, T.; Hagen, K. Wool Pellets Are a Viable Alternative to Commercial Fertilizer for Organic Vegetable Production.*Agronomy* 2022, *12*, doi:10.3390/agronomy12051210.
20. Abdallah, A.M.; Ugolini, F.; Baronti, S.; Maienza, A.; Ungaro, F.; Camilli, F. Assessment of Two Sheep Wool Residues from Textile Industry as Organic Fertilizer in Sunflower and Maize Cultivation. *J Soil Sci Plant Nutr* 2019, *19*,doi:10.1007/s42729-019-00079-y.
21. Juhos, K.; Papdi, E.; Kovács, F.; Vasileiadis, V.P.; Veres, A. The Effect of Wool Mulch on Plant Development in the Context of the Physical and Biological Conditions in Soil. *Plants* 2023, *12*, doi:10.3390/plants12030684.
22. Forcella, F.; Poppe, S.; Hansen, Neil.; Head, W.; Hoover, E.; Propsom, F.; McKensie, J. Biological Mulches for Managing Weeds in Transplanted Strawberry (Fragaria × Ananassa) 1 . *Weed Technology* 2003, *17*, doi:10.1614/wt02-167.
23. Broda, J.; Kobiela-Mendrek, K.; Rom, M.; Grzybowska-Pietras, J.; Przybylo, S.; Laszczak, R. *Biodegradation of Wool Used for the Production of Innovative Geotextiles Designed to Erosion Control*; 2016; Vol. 12; ISBN 9789401775137.
24. Sharma, S.C.; Sahoo, A.; Chand, R. Potential Use of Waste Wool in Agriculture: An Overview. *Indian Journal of SmallRuminants (The)* 2019, *25*, doi:10.5958/0973-9718.2019.00019.9.
25. Lal, B.; Sharma, S.C.; Meena, R.L.; Sarkar, S.; Sahoo, A.; Balai, R.C.; Gautam, P.; Meena, B.P. Utilization of Byproducts ofSheep Farming as Organic Fertilizer for Improving Soil Health and Productivity of Barley Forage. *J Environ Manage* 2020, *269*, doi:10.1016/j.jenvman.2020.110765.
26. Climate Normals Pl, 2024. https://klimat.imgw.pl/pl/climate-normals/TSR_AVE (archived on 26 June 2024).
27. Korjenic, A.; Klaric, S.; Hadžic, A.; Korjenic, S. Sheep Wool as a Construction Material for Energy Efficiency Improvement. *Energies (Basel)* 2015, *8*, doi:10.3390/en8065765.
28. Dénes, O.; Florea, I.; Manea, D.L. Utilization of Sheep Wool as a Building Material. In Proceedings of the Procedia Manufacturing; 2019; Vol. 32.

29. Hetimy, S.; Megahed, N.; Eleinen, O.A.; Elgheznawy, D. Exploring the Potential of Sheep Wool as an Eco-Friendly Insulation Material: A Comprehensive Review and Analytical Ranking. *Sustainable Materials and Technologies* 2024, *39*.
30. Koh, C.H. (Alex); Kraniotis, D. A Review of Material Properties and Performance of Straw Bale as Building Material. *Constr Build Mater* 2020, *259*.
31. Medved, S.; Tudor, E.M.; Barbu, M.C.; Young, T.M. Thermal Conductivity of Different Bio-Based Insulation Materials. *Les/Wood* 2021, *70*, doi:10.26614/les-wood.2021.v70n01a05.
32. Goodhew, S.; Griffiths, R. Sustainable Earth Walls to Meet the Building Regulations. *Energy Build* 2005, *37*, doi:10.1016/j.enbuild.2004.08.005.
33. Hutchinson, S.; Evans, D.; Corino, G.; Kattenbelt, J. An Evaluation of the Action of Thioesterases on the Surface of Wool.*Enzyme Microb Technol* 2007, *40*, doi:10.1016/j.enzmictec.2007.01.016.
34. Evans, D.J.; Lanczki, M. Cleavage of Integral Surface Lipids of Wool by Aminolysis. *Textile Research Journal* 1997, *67*, doi:10.1177/004051759706700608.
35. Hsieh, Y. lo Liquid Transport in Fabric Structures. *Textile Research Journal* 1995, *65*, doi:10.1177/004051759506500508.
36. Hsieh, Y. lo; yu, B. Liquid Wetting, Transport, and Retention Properties of Fibrous Assemblies: Part I: Water WettingProperties of Woven Fabrics and Their Constituent Single Fibers. *Textile Research Journal* 1992, *62*, doi:10.1177/004051759206201108.
37. Gößwald, J.; Barbu, M.C.; Petutschnigg, A.; Tudor, E.M. Binderless Thermal Insulation Panels Made of Spruce Bark Fibres. *Polymers (Basel)* 2021, *13*, doi:10.3390/polym13111799.
38. Marques, B.; Tadeu, A.; Almeida, J.; António, J.; de Brito, J. Characterisation of Sustainable Building Walls Made from Rice Straw Bales. *Journal of Building Engineering* 2020, *28*, doi:10.1016/j.jobe.2019.101041.
39. Marchisio, V.F. Keratinophilic Fungi: Their Role in Nature and Degradation of Keratinic Substrates. *Rev Iberoam Micol* 2000, *17*.
40. Marchisio, V.F.; Fusconi, A.; Rigo, S. Keratinolysis and Its Morphological Expression in Hair Digestion by Airborne Fungi. *Mycopathologia* 1994, *127*, doi:10.1007/BF01103066.