

## Research Article

# The Effectiveness of Biochar as a Mulch for Weed Control and Soil Moisture Retention in Strawberry Cultivation

Konstantin Olegovich Ponomarev <sup>1,\*</sup> , Arina Nikolaevna Pervushina <sup>1</sup> ,  
Alina Aleksandrovna Dryagina <sup>1</sup> , Daria Sergeevna Krasnova <sup>1</sup> ,  
Roman Borisovich Tabakaev <sup>2</sup> , Ilya Aleksandrovich Zhovanik <sup>1</sup> ,  
Alexander Sergeevich Petuhov <sup>1</sup> , Gulnoz Akhmedovna Hisamutdinova <sup>1</sup> 

<sup>1</sup> Tyumen State University, 6 Volodarskogo Street, Tyumen, 625003, Russian Federation

<sup>2</sup> National Research Tomsk Polytechnic University, 30 Lenin Ave, Tomsk, 634050, Russian Federation

\*Corresponding author: [k.o.ponomarev@utmn.ru](mailto:k.o.ponomarev@utmn.ru)

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### Abstract

**Purpose:** Weed control and soil moisture retention are critical challenges in plant cultivation requiring effective solutions. This study aims to assess the impact of biochar produced from pine nut shells as a mulch for weed composition, biomass, and soil moisture retention compared to widely used spunbond covering material in strawberry cultivation.

**Method:** The experiment with six weed species was conducted using a growth chamber over two months with sixteen replicates for each of the three treatments: control (no mulch), soil with a 2 cm layer of biochar mulch, and soil with spunbond.

**Results:** In the control treatment, six weed species germinated, whereas only five and three species were observed in the biochar and spunbond treatments, respectively. Both mulching treatments significantly ( $p < 0.05$ ) reduced the height of grass weeds, stinging nettles, and shepherds' purse, as well as the mass of dry above-ground and root biomass of shepherds' purse, rapeseed, and stinging nettle by 52–100%. Spunbond mulch demonstrated superior soil moisture retention overall. However, during the initial three days of a simulated dry period, biochar retained 7% more water compared to spunbond (2%). The application of spunbond mulch completely suppressed the emergence of rapeseed and burdock, while both biochar and spunbond effectively controlled fennel. Both mulching treatments significantly reduced the height of grasses, stinging nettles, and shepherds' purse by different mechanisms.

**Conclusion:** Biochar can be useful for reducing the weed count and increasing the water retention in the soil.

**Keywords:** Mulch; Biochar; Spunbond; Weeds; Moisture retention; Plant protection

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## 1. Introduction

Weed control is a critical challenge in agriculture, particularly in horticultural systems where manual or chemical weed management can be labor-intensive, costly, or environmentally detrimental. Weeds compete with crops for light, water, nutrients, and can reduce yields by over 60% (Abouzienna and Haggag, 2016; Rhioui et al., 2023). Traditional methods of weed control include mechanical weeding, herbicide application, and mulching (Yaseen and Long, 2024). However, mechanical weeding requires frequent interventions, increases labor costs, and may damage crop roots, while herbicide use raises concerns about environmental contamination, herbicide resistance, and chemical residues in horticultural produce (McCool et al., 2018; Yaseen and Long, 2024).

Moisture retention is another key concern, particularly under the growing threat of water scarcity driven by climate change and increasing competition for irrigation resources. Soil moisture deficits not only stress plants directly but also reduce nutrient uptake and crop resilience (Horvath et al., 2023). Techniques to conserve water in the root zone include irrigation scheduling, soil conditioners, and mulching (Amin et al., 2025). Nevertheless, irrigation scheduling demands continuous monitoring and may be ineffective under erratic rainfall, while soil conditioners are often expensive and may not provide long-term benefits without repeated application (Wen et al., 2017; Amin et al., 2025).

Thus, a dual solution to the problems of weed control and moisture retention is mulching. By covering the soil surface, mulches suppress weed emergence, reduce evaporation, and moderate soil temperature (Farzi et al., 2017). Inorganic mulches such as polyethylene films and spunbond are widely used due to their durability and efficiency. However, they are derived from non-renewable sources and pose disposal issues (Teasdale and Mohler, 2000; Kasirajan and Ngouajio, 2012; Garagurbanli et al., 2024). Organic mulches, such as straw or bark, are biodegradable and improve soil organic matter but decompose quickly, often need replenishment, and may harbor weed seeds or negatively affect soil pH (Moreno et al., 2016; Demo and Asefa Bogale, 2024).

Among novel mulch alternatives, biochar has gained attention as a sustainable, carbon-rich material produced through pyrolysis of biomass (Arain et al., 2024). Its porous structure enhances water retention and nutrient adsorption (Obia et al., 2016; Igaz et al., 2018; Ponomarev et al., 2022; Xiang et al., 2022; Dobrokhotov and Kozyreva, 2023), while its chemical properties can influence soil microbial communities and allelopathic interactions (Trezzi et al., 2016; Saha et al., 2018; Alshahrani and Suansa, 2020). Research has demonstrated

that when mixed into soil, biochar may suppress certain weed species and improve crop performance (Smith and Cox, 2014; Eizenberg et al., 2017; Saady et al., 2021). However, the potential of biochar as a surface-applied mulch, which would leverage both its physical and chemical properties, remains underexplored, particularly in perennial crops such as Strawberries (*Fragaria × ananassa* L.).

Strawberries (*Fragaria × ananassa* L.) are a large-fruited species of plants belonging to the rose family. Strawberry cultivation is widespread across temperate regions of Russia, including the area where this study was conducted, and is commonly challenged by weed pressure and insufficient moisture retention in the root zone (Broda et al., 2024). These challenges make it essential to explore alternative, sustainable mulching strategies that reduce environmental impact while maintaining agronomic efficiency.

The objective of this study was to evaluate the potential of biochar derived from pine nut shells as a surface mulch in strawberry cultivation. Specifically, the study compared the effects of biochar and spunbond mulch on weed suppression and soil moisture retention, to assess whether biochar can serve as an environmentally friendly alternative to conventional inorganic mulches.

## 2. Materials and methods

### 2.1. Soil characterization

The soil used in this study was collected from a private site in Tyumen, Tyumen Oblast, Russia (57°155' N, 65°523' E). According to N. A. Kachinsky's classification, the soil is characterized as heavy loam, consisting of 29% sand, 43% silt, and 28% clay. It has a neutral pH of 7.06 (measured in water) and a moderate carbon content of 2.8%. Granulometric composition was determined using the sedimentation method with a Pario particle analyzer (METER Group, USA). Soil acidity (pH) was measured using the potentiometric method with a stationary pH meter STARTER 3100 (OHAUS, USA). The carbon content was determined by the dry combustion method in an oxygen stream using a UNICUBE analyzer (Elementar, Germany). Thermophysical properties of the soil were measured using a TEMPOS device (METER Group, USA) equipped with TR-3 and SH-3 probes. The results were as follows: thermal conductivity  $K = 0.353 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$ , volumetric heat capacity  $C = 1.380 \text{ MJ} \cdot \text{m}^{-3} \cdot \text{K}^{-1}$ , thermal diffusivity  $D = 0.275 \text{ mm}^2 \cdot \text{s}^{-1}$ , and specific thermal resistance  $R = 343.979 \text{ K} \cdot \text{cm} \cdot \text{W}^{-1}$ . The measured thermophysical parameters fall within literature-reported values heavy loam soils (Arkhangelskaya, 2020), confirming the accuracy of the methodology. Concentrations of heavy metals (Cr = 0.2 mg/kg, Pb = 0.5 mg/kg, Cd = 0.2 mg/kg,

Ni = 1.7 mg/kg, Co = 0.2 mg/kg) were determined using an inductively coupled plasma atomic emission spectrometer Plasma Quant PQ 9000 (Analytik Jena, Germany). All concentrations were below the maximum permissible limits (Alhaj Hamoud et al., 2024).

## 2.2. Soil sterilization

Soil was sterilized by enclosing it in sealed black polyethylene bags and exposing it to ambient temperatures of 30 to 39 °C for seven days (Kaewruang et al., 1989; Dai et al., 2016). Following sterilization, the soil was transferred into vegetation pots with a volume of 2.5 L, height of 13.5 cm, and diameter of 16.5 cm. Strawberry seedlings (*Fragaria × ananassa* L.) were pre-treated by soaking for 24 hours in a solution of liquid complex fertilizer Fertika Lux to enhance nutrient uptake and initial root development prior to planting. The fertilizer composition included total nitrogen (N) – 16.0%, nitrate nitrogen (N-NO<sub>3</sub>) – 8.1%, phosphorus (P<sub>2</sub>O<sub>5</sub>) – 20.6%, potassium (K<sub>2</sub>O) – 27.1%, iron (Fe) – 0.1%. The fertilizer solution was homogenized using an orbital shaker US-13500 (ULAB, China). Plants were irrigated with the fertilizer solution at a rate of 150 mL per pot every two days for a month to facilitate root establishment and enhance nutrient assimilation.

## 2.3. Weed collection and treatment

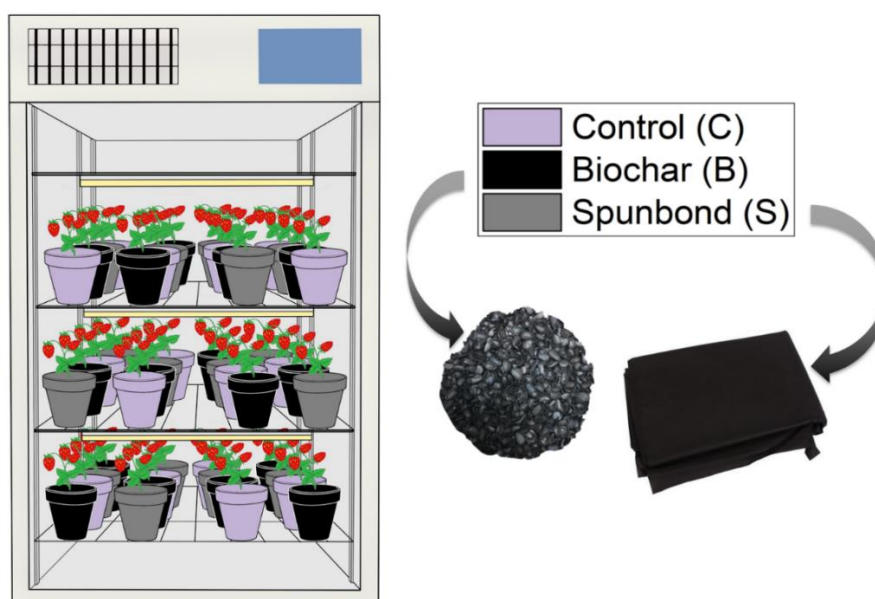
Weeds and their seeds were collected from a nearby site. The plant community at the collection site predominantly consisted of grass weeds (*Poaceae* L.), rapeseed (*Brassica napus* L.), stinging nettle (*Urtica dioica* L.), burdock (*Arctium lappa* L.), shepherd's purse (*Capsella* L.), and

fennel (*Foeniculum* L.). Weed seeds were collected, mixed, and added at 0.5 g per vegetation pot. The weed seeds were homogenized through thorough mixing and introduced into the experimental pots at a standardized rate of 0.5 g per pot.

## 2.4. Experimental design

The experiment was conducted over two months with sixteen replicates for each of the three treatments: soil without mulch – control (C), soil with a 2 cm layer of biochar mulch (B), and soil with black covering material traditionally used in strawberry cultivation – spunbond (S). The experiment duration of two months was selected based on established data in the literature (Anugroho and Kitou, 2011; Brito et al., 2013) and preliminary experimental studies. Sixteen replicates for each variation were selected based on the high variability observed in the preliminary plant growth experiments. This count of replicates and two-month duration ensure the detection of reliable ( $p < 0.05$ ) differences in weed suppression among different mulches (Roveda-Hoyos and Moreno-Fonseca, 2019; Gouble et al., 2022; Leng et al., 2023). The biochar was obtained from pine nut shells using a fixed-bed pyrolysis process at 600 °C (Gorshkov et al., 2021; Astafev et al., 2022).

All vegetation pots ( $n = 48$ ) were arranged in a growth chamber PGI-850RH (MRC LTD, Israel) according to a randomized complete block design under strictly controlled environmental conditions: a temperature regime of 19/14 °C (day/night), a photoperiod of 16/8 hours (light/dark), illumination intensity of 12000 lux, and relative humidity maintained of 60% (Fig. 1).



**Figure 1.** Schematic representation of the experimental study. The diagram depicts the spatial arrangement of pots within the growth chamber, emphasizing the three treatment groups: control (no mulch), biochar mulch, and spunbond mulch

## 2.5. Measurements and data collection

Each pot was irrigated with 150 ml of distilled water every two days to maintain consistent moisture levels. After the two-month experimental phase, the species composition of the weeds was identified, and the average weed count per pot was recorded. The average weed height per pot (cm) was measured using a calibrated ruler with 1 mm precision. The weeds were then categorized by species, and their fresh above-ground and root biomass was quantified using an OHAUS Pioneer PX224 analytical balance (OHAUS, USA) with a precision of 0.01 g. Following this, the weeds were oven-dried at 60 °C for 7 days to determine their dry mass, recorded as average dry above-ground biomass per pot (g) and average dry root biomass per pot (g).

## 2.6. Moisture retention assessment

After the initial two-month experimental phase, a drought simulation phase was initiated by discontinuing irrigation. The growth chamber temperature was increased to 25.5 °C, while the humidity was maintained at 40-50%. The selected temperature corresponds to the average maximum temperature during dry periods of June and July in Tyumen Oblast over the past three years. The parameters were averaged using data from the database of the meteorological station located in Tyumen (Tyumen Oblast, Russia), at latitude 57.12, longitude 65.43, and altitude 102 m above sea level. Soil moisture dynamics were monitored over a 9-day period using two methods: (1) the gravimetric method, which involved measuring changes in the total weight of the pots, including substrate and plants (g), and (2) a MEGEON 35280 soil analyzer (MEGEON, Russia). The soil analyzer categorizes moisture levels into three zones: Red zone (1–3) – dry or slightly moist soil, Green zone (3–8) – slightly moist or moist soil, and Blue zone (8–10) – very moist soil (Rasheed et al., 2022).

## 2.7. Statistical analysis

The collected data on weed count, height, and biomass were subjected to one-way analysis of variance (ANOVA) to assess the effects of different mulching treatments. Significant differences among treatment means ( $p < 0.05$ ) were further analyzed using Tukey's honestly significant difference (HSD) post-hoc test to identify specific pairwise comparisons.

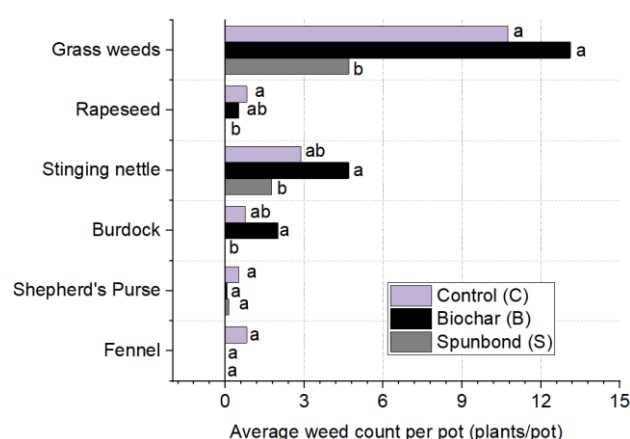
## 3. Results and discussion

### 3.1. Effect of mulch on weed counts

The results demonstrate that the surface application of biochar and spunbond significantly influenced the emergence patterns of weed species in strawberry cultivation (Fig. 2).

In the control treatment (no mulch), all six target weed species germinated: grass weeds (*Poaceae* L.), rapeseed (*Brassica napus* L.), stinging nettle (*Urtica dioica* L.), burdock (*Arctium lappa* L.), shepherd's purse (*Capsella* L.), and fennel (*Foeniculum* L.), indicating that the environmental conditions within the growth chamber were conducive to weed establishment and not a limiting factor for seed activation. By contrast, the application of biochar mulch on the soil surface fully suppressed the emergence of fennel while spunbond eliminated fennel, rapeseed, and burdock. Species like fennel, whose seeds exhibit positive photoblastism, are highly sensitive to light cues, and their suppression here likely reflects this light limitation (Huber et al., 1996; Vandeloos et al., 2012). Complete suppression of burdock and rapeseed in spunbond treatment suggests the same mechanism: being an opaque, non-porous synthetic fabric, completely blocked light, and seeds with emergence dependency on surface cues are particularly vulnerable to such a barrier as light limitation (Teasdale and Mohler, 2000; Kasirajan and Ngouajio, 2012; Garagurbanli et al., 2024). The dark fragmented structure of biochar partially obstructs incoming radiation, which is critical for photoblastic seed of rapeseed, and burdock germination (Teasdale and Mohler, 2000).

The success of the emergence of other weed species through mulches, especially grass weeds and stinging nettle, was related to the capacity of seedlings to grow around obstructing mulch elements under limited light conditions. This suggests lower seed sensitivity to photoblastic suppression (Teasdale and Mohler, 2000).



**Figure 2.** Average ( $n = 16$ ) weed count per pot. Bars on graphs labeled with the same letter indicate no statistically significant differences ( $p = 0.05$ ) based on Tukey's HSD test.

### 3.2. Effects of mulch on fresh weed mass

The accumulation of fresh biomass provides an integrative view of weed development and physiological activity under different mulching treatments. Fresh above-ground and root biomass varied significantly across treatments (Table 1).

**Table 1.** Masses of fresh above-ground and root biomass of weeds

Treatment	Grass weeds	Rapeseed	Stinging nettle	Burdock	Shepherd's Purse	Fennel
Above-ground biomass (g)						
Control	203.4	141.8	48.1	2.4	10.5	3.4
Biochar	294.8	51.1	5.6	17.7	0.4	0
Spunbond	65.5	0	2.4	0	0.6	0
Root biomass (g)						
Control	31.5	7.8	2.4	0.3	2.2	1.1
Biochar	54	2.5	0.8	2.2	0.1	0
Spunbond	14.6	0	0.5	0	0.1	0

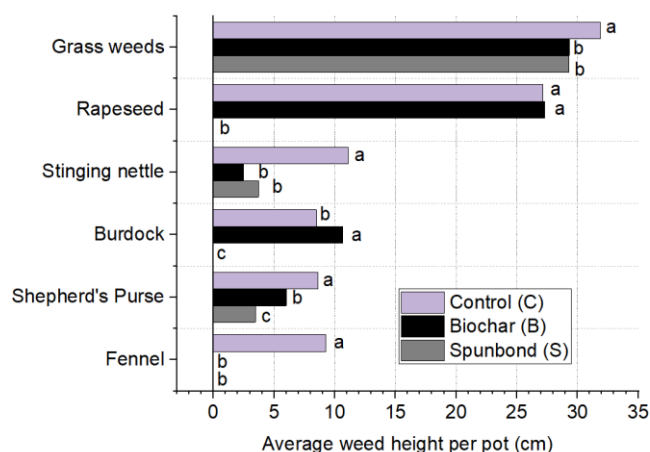
In control pots, grass weeds exhibited the highest fresh above-ground biomass (203.4 g/pot), followed by rapeseed (141.8 g/pot) and stinging nettle (48.1 g/pot). Biochar mulch increased grass weed biomass by 45% compared to the control, likely by reducing leaching and enhancing weed competitiveness (Major et al., 2005). However, biochar reduced fresh biomass of rapeseed by 64% and stinging nettle by 88%, suggesting selective suppression of broadleaf weeds. Spunbond reduced grass weeds biomass by 68%, consistent with its role as a barrier to germination (Teasdale and Mohler, 2000; Kasirajan and Ngouajio, 2012; Garagurbanli et al., 2024).

It should be noted that any mulch limits the access to light and air, which creates unfavorable conditions for photosynthesis of weeds. In this case, the plant directs more resources to the development of the root system. While in the control treatment weeds grow in normal conditions without restrictions (they receive sufficient light, which stimulates their photosynthetic activity, growth of stems and leaves). In the study, root-to-shoot ratios under spunbond treatment ranged from 0.18 to 0.22, exceeding those observed in the control (0.05) and biochar (0.13) treatments. This implies that light deprivation—an unfavorable condition for photosynthesis—in the spunbond and biochar treatments forced weeds to allocate more resources to root growth, a survival strategy associated with the shade-avoidance response (Major et al., 2005; Morison et al., 2008).

### 3.3. Effects of mulch on weed height

After analyzing germination as the initial stage of weed competition and assessing the fresh biomass of the germinated and developed weeds, it is appropriate to evaluate the morphometric response of the weeds to treatment with two mulch treatments. The application of mulches significantly affected the vertical growth of emerged weeds (Fig. 3). In the control group (no mulch), weed height was maximal for all species, reflecting optimal

conditions for emergence and unimpeded early development. When applying biochar and spunbond, the significant reductions in height ( $p < 0.05$ ) were observed for grass weeds (of 8% with the two treatments), stinging nettle (of 77.9% and 66.6%, respectively), and shepherd's purse (of 30.3% and 59.9%, respectively) (Fig. 3).



**Figure 3.** Average ( $n = 16$ ) weed height per pot. Bars on graphs labeled with the same letter indicate no statistically significant differences ( $p = 0.05$ ) based on Tukey's HSD test

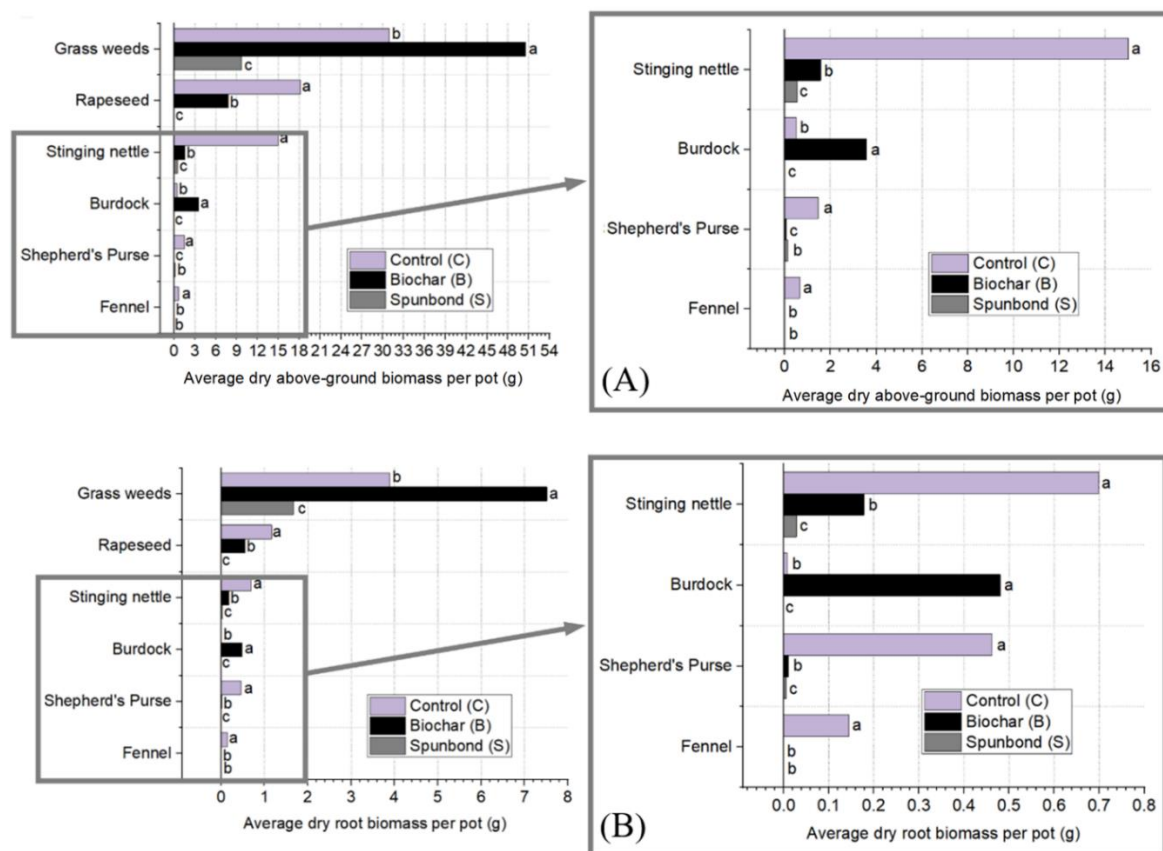
Both biochar and spunbond treatments reduced the average height of surviving weeds, albeit to varying degrees and via different mechanisms. Biochar particles physically suppress stem extension at the soil interface, especially for small-seeded species with limited early biomass. Simultaneously, this suppression may not solely be attributed to direct interference with emergence, but rather to subtle shifts in the microenvironment at the soil surface. Biochar may retain surface moisture longer after watering, which can encourage shallow rooting and reduce seedling vigor (Obia et al., 2016; Igaz et al., 2018). While biochar mulch is not expected to produce significant allelopathic effects in this configuration (i.e., without soil incorporation), the adsorption of plant-derived hormones or microbial signaling compounds at the soil-mulch

interface could still reduce elongation responses (Trezzi et al., 2016; Saha et al., 2018; Alshahrani and Suansa, 2020). Spunbond treatment creates a low-light, diffuse radiation condition (Garagurbanli et al., 2024). The physiological consequence of such shading is often a reduction in photosynthetic activity, leading to slower biomass accumulation and stem elongation, especially in sun-adapted weed species (Batlla and Benech-Arnold, 2014). Moreover, the air gap created a shaded, humid microenvironment that may have delayed soil warming and drying, altering thermal cues for germination and reducing oxygen diffusion (Woolley and Stoller, 1978). Though not a direct barrier, this air gap likely disrupted the complex set of environmental signals required for synchronized weed emergence. While both mulching treatments reduced weed height, the mechanisms were fundamentally different. Biochar acted at the soil surface, modifying thermal and moisture conditions, while spunbond influenced the above-ground light microclimate.

### 3.4. Effects of mulch on dry weed mass

The total dry biomass of weeds shows the result of pressure on culture. Both biochar and spunbond mulch treatments

reduced the dry mass of following weeds: by 52.4-57% and 100% – for rapeseed, respectively; by 74.5-89.5% and 95.9-96.3% – for stinging nettle; by 90.5-96.3% and 97.8-98.9% – for shepherd's purse (Fig. 4). Similar results were reported by Khanh et al. (2005), who highlighted a biomass reduction of 70% to 100% applying plant biomass (cover crops) to control weeds in Southeast Asia. Dong and Zeng (2024) found that cover crops could reduce weed biomass by more than 60%. Additionally, high rates of weed dry mass reduction (74-99%) were observed when using wild oat mulch or several layers of different types of organic mulch (cattail, straw) (Abouzienna et al., 2008), with thicknesses starting from 6 cm. These findings suggest that biochar can become an alternative to application of cover crops or organic mulches to suppress weed growth. Moreover, according to Prats et al. (2021), such mulch will also help mitigate soil erosion. However, it should be noted that the dry biomass of two weed types (grass weeds and burdock) was higher in the biochar treatment than in the control. These findings indicate that when used as a surface mulch, biochar may inadvertently promote the growth of certain weed species, particularly those with high seed energy reserves or low photoblasty (Teasdale and Mohler, 2000). This result can be explained



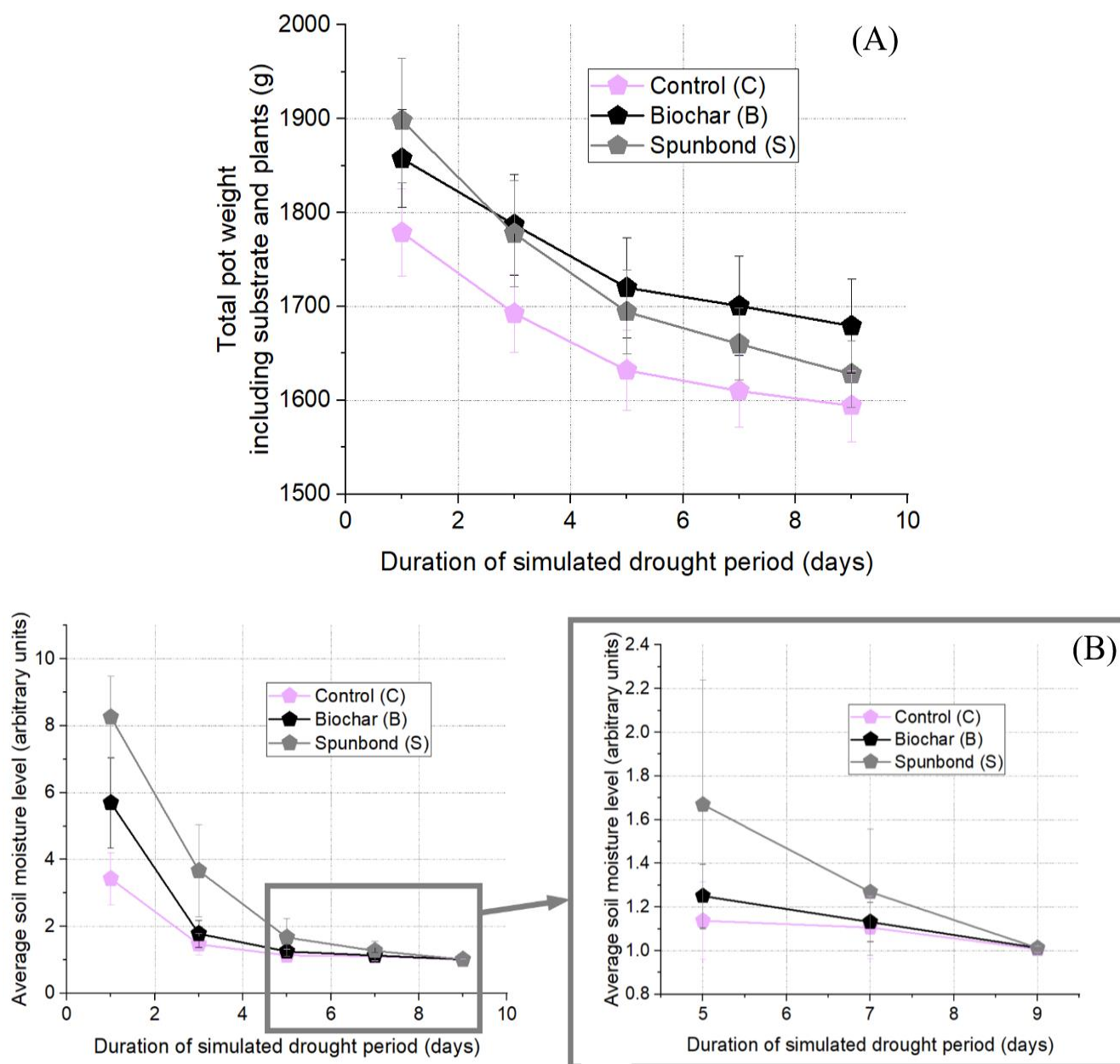
**Figure 4.** Average dry above-ground (A) and root (B) biomass per pot. Bars on graphs labeled with the same letter indicate no statistically significant differences ( $p = 0.05$ ) based on Tukey's HSD test

by several mechanisms. Due to its high porosity and moisture-retentive properties, biochar can enhance surface soil moisture and moderate temperature fluctuations, thereby creating favorable conditions for weed germination and early growth (Obia et al., 2016; Saudy et al., 2021). Unlike opaque synthetic mulches, the loose and discontinuous structure of biochar allows partial light penetration and does not provide a consistent physical barrier, enabling the emergence of robust weed seedlings (Major et al., 2005). Moreover, biochar may adsorb allelopathic compounds or residual herbicides in the soil, potentially reducing natural suppression of weed growth (Alshahrani and Suansa, 2020). These combined factors likely contributed to the enhanced vigor of certain weed

species under biochar mulch, underscoring the need for optimization of mulch thickness and particle size in future applications.

### 3.5. Effects of mulch on soil moisture loss

Under water deficit conditions, weeds can reduce yield by competing for moisture (Morison et al., 2008). Consequently, soil moisture dynamics under mulch application provide critical insights into the abiotic buffering potential of surface treatments – especially relevant in water-limited cultivation or under drought stress scenarios. During a 9-day drought mulching saved between 2% (spunbond) and 7% (biochar) of water in the first three days (Fig. 5 (a)).



**Figure 5.** Effects of biochar and spunbond treatments on total pot weight (A) and soil moisture (B) during simulated drought

The initial high rate of moisture loss in spunbond treatment, which is close to the control, can be explained by the penetration of turbulent air flow into the mulch layer. However, spunbond maintained higher moisture levels by day 9 (1.3-1.5 times higher than biochar) (Fig. 5 (b)), which corresponds to the efficiency of this type of mulch (Farzi et al., 2017; Garagurbanli et al., 2024). This effect is largely attributed to its role as a physical vapor barrier, which reduced direct light radiation and minimized evaporation (Ekern, 1967). By shielding the soil surface, spunbond decreased the evaporation and helped maintain a more stable soil moisture regime.

In contrast, when applying biochar mulch, the rate of water evaporation in the first three days was lower because particles of carbonaceous material were located closer and had contact with the soil surface. Our data aligns with Wortman et al. (2016): biomulch boosted soil moisture retention by 8% relative to soil without mulch. By the seventh day of drought, the soil moisture level approached that of the control treatment. We assume that biochar's short-term advantage stems from its porosity (Obia et al., 2016; Igaz et al., 2018), which temporarily traps irrigation water but fails to sustain retention under prolonged drought (biochar's open pores allowed gradual moisture escape under prolonged drought). Furthermore, to retain moisture more effectively in the biochar treatment, the thickness of the mulch layer should be increased. Research has demonstrated that an effective organic mulch layer needs to be at least 10 cm thick (Abouzienna et al., 2008; Pavlovskii, 2023).

### Limitations

This study provides valuable insights into the efficacy of biochar as a mulching material for weed suppression and soil moisture retention in strawberry cultivation while also acknowledging certain limitations of controlled-environment experiments. Controlled environmental conditions minimized variability and closely replicated real field conditions, including temperature, humidity, and photoperiod, though the absence of natural factors like precipitation and soil microbial interactions may affect direct field applicability. The two-month duration was selected based on literature and preliminary data as sufficient to capture key plant growth dynamics and soil moisture changes. Spunbond was chosen as the reference mulch due to its widespread agricultural use and consistent performance, while the 2 cm biochar layer represented a practical balance between effectiveness and economic feasibility. Statistical analyses, including normality (Shapiro-Wilk) and homogeneity of variance (Levene's test), confirmed the validity of ANOVA for data interpretation. While long-term field trials remain necessary to assess multi-season impacts, this study

establishes a strong foundation for understanding biochar mulch's potential in sustainable agriculture.

### 4. Conclusion

The study investigated the effectiveness of biochar application as a mulch in comparison with spunbond for weed control and soil moisture retention in strawberry cultivation. The experimental results revealed that applying biochar completely eliminated fennel, whereas spunbond suppressed its growth, rapeseed and burdock. Both mulch treatments significantly reduced the root (of 90.5-96.3%) and above-ground (of 97.8-98.9%) masses of shepherd's purse. In the case of rapeseed germination, biochar reduced its mass by 52.4-57%, and spunbond by 100%. The mass of stinging nettle was reduced by 74.5-89.5% and 95.9-96.3%, when using the biochar and spunbond mulch, respectively. The porous structure of the biochar, derived from nut shells, provided advantages for water retention in the root zone in overhead irrigation systems, since significantly less water passes through spunbond or polyethylene film from precipitation or irrigation systems. Mulch application made it possible to save between 2% (with spunbond) and 7% (with biochar) of water in the first 3 days of the simulated drought period. However, spunbond maintained higher moisture levels by day 9 (biochar's open pores allowed gradual moisture escape under prolonged drought).

Thus, biochar can be used not only as a soil amendment, but also as a mulch for growing strawberries, significantly reducing the weed emergence and increasing water retention in the soil. Moreover, the experimental results suggested that both mulching treatments reduced weed growth, but the mechanisms were fundamentally different. Spunbond influenced the above-ground light microclimate. In contrast, biochar mulch acted at the soil surface, modifying thermal and moisture conditions, but unless optimized in thickness and particle size, may offer only partial efficiency in weed control and soil moisture retention. Nevertheless, a combined application—such as biochar beneath spunbond—may yield synergistic benefits.

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### Authors Contribution

All authors contributed to the study conception and design. The pyrolysis processing experiments were performed by R.B. Tabakaev and K.O. Ponomarev. The experiment was carried out by A.N. Pervushina, A.A. Dryagina, D.S. Krasnova and G.A. Hisamutdinova under the supervision of K.O. Ponomarev. A.S. Petukhov was responsible for analyzing the content of elements in the extract from the considered soil. Material preparation, data collection and analysis were performed by K.O. Ponomarev, R.B. Tabakaev and I.A. Zhovaniuk. The first draft of the manuscript was written by K.O. Ponomarev and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

### Availability of data and materials:

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

### Conflict of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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