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Short-Term Effects of Spent Mushroom Substrate Mulching Thickness on the Soil Environment, Weed Suppression, Leaf Nutrients, and Nut Characteristics in a Hazelnut Orchard

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Abstract: Worldwide, a huge amount of solid fermented waste is produced every year during mushroom production. The rational utilization of spent mushroom substrate (SMS) is conducive to environmental protection and the sustainable development of agriculture. The aims of this work were to analyze the effects of the SMS mulching thickness on the soil environment, weed suppression, leaf nutrients, and nut traits in a hazelnut plantation and provide a theoretical basis for the scientific and reasonable utilization of SMS. An SMS mulching experiment with four mulching thickness treatments (MT1: 5 cm, MT2: 10 cm, MT3: 15 cm, and CK: 0 cm) was conducted in a semi-arid area of North China in 2019. The soil properties, weed control efficiency, leaf nutrient content, and nut yield and quality characteristics of these treatments were all measured and analyzed. The results showed that (1) the average soil temperatures of MT2 and MT3 at different soil depths were 0.73–1.78 °C and 1.18–2.50 °C lower than when no mulch was used in warm weather and 0.67–1.05 °C and 0.99–1.56 °C higher than when no mulch was used in cold weather. The average soil moisture content of MT1, MT2, and MT3 at different soil depths was 6.27–8.13%, 10.66–17.23%, and 7.26–12.81% higher than that of CK, respectively. There were no significant differences in the soil bulk density or porosity among the four treatments. The average soil nutrient contents (soil organic matter and available N, P, and K) of MT1, MT2, and MT3 were 7.05–15.23%, 14.90–38.93%, and 17.42–40.11% higher than those of CK, respectively. Soil enzymatic activities of these treatments followed the order MT3 ≈ MT2 > MT1 > CK. (2) MT2 and MT3 both had high levels of weed control efficiency: 55.66–92.93% and 70.43–97.90%, respectively. (3) The leaf N, P, K, and SPAD increased significantly under MT2 and MT3 by about 10% compared with the CK. (4) MT2 effectively increased the nut size, nut and kernel mass, and crude fat content of the nut (CFC). In general, the short-term field experiment clearly showed that SMS is a superior mulching material for improving the soil environment and plant growth, and 10 cm thickness is suitable for mulching practice.

Keywords: spent mushroom substrate; mulching measures; soil properties; weed control; nut traits

1. Introduction

The genus *Corylus* L. (hazelnut) includes about 20 species that are widely distributed among temperate regions of Asia, Europe, and North America. It is regarded as one of the most prevalent nut crops in the world. According to the FAO statistics from 2017, the total production of in-shell hazelnuts worldwide exceeded 1 million tons, and the main world producers were Turkey (675,000 t), Italy (131,281 t), Azerbaijan (43,000 t), USA

(29,030 t), and China (27,044 t) [1]. Hazelnut is a nutrient-dense food owing to its rich concentrations of protein and oil. In addition, hazelnut provides appreciable amounts of sterols, tocopherols, polyphenols, essential minerals, and B-complex vitamins [2]. Owing to its pleasant nutty taste and flavor, hazelnut is widely used for confectionery and bakery products [3]. In recent years, hazelnut planting has been vigorously developed in China, mainly in North China and Northeast China. Although the planting area and yield have increased rapidly, outstanding problems (improper agricultural management, seasonal drought stress, soil degradation, and so on) still restrict the development of the planting industry.

Many studies have shown that mulching is an effective strategy for soil management as it improves the tillage quality by increasing the soil's biological activity, regulating the soil temperature, controlling weed growth, reducing soil evaporation, and preventing nutrient leaching [4]. It also provides benefits for growth, annual and perennial yield, and the health of plants, and its low cost makes it a widespread technique. Different mulching methods and materials have different effects on soil properties and plant growth. A meta-analysis was conducted based on 266 peer-reviewed publications from China, and the results showed that black film mulching is more favorable to crop growth and an increase in the crop yield and water use efficiency (WUE) in arid areas [5]. However, in the long term, the application of plastic film may cause serious soil pollution, and hence have negative effects on crop production [6]. Compared with inorganic mulches, organic mulching could have more benefits for soil health and sustainable development through supplementing with soil organic matter, increasing the water holding capacity, releasing nutrients and enhancing soil aggregation, and promoting soil biological activity [7]. The selection of an appropriate organic mulching material is strongly affected by the local climate, cost-effectiveness, and feasibility for the crop [8].

Mushrooms have drawn a lot of interest owing to their nutritional and medicinal value, and they have been widely cultivated. Nowadays, a total of 34 billion kg of mushrooms are produced annually throughout the world [9]. As the largest edible mushroom producer and exporter in the world, China's main production areas are Henan, Fujian, Shandong, and Hebei province. Pingquan County, which belongs to Hebei Province, is the main *pholiota nameko* production base in northern China. After the mushroom fruiting bodies are harvested, a huge amount of solid fermented waste is produced. Because a high level of organic matter remains present in the spent mushroom substrate (SMS), it should be properly disposed of to avoid environmental pollution problems. Previously, the major applications of SMS were animal fodder, composting material, and bioenergy feedstock [10]. However, most SMS is still stacked on farmland or incinerated at will. SMS has become the biggest challenge for mushroom farms in terms of disposal management, although studies have confirmed that SMS is a good biofertilizer or soil improver for crop production thanks to its high amounts of macro- and micronutrients, high cation exchange capacity, near-neutral pH, high porosity, and high water-holding capacity [11]. SMS, with its biodegradability, availability, and sustainability, could be a promising alternative to traditional plastic mulch in the context of global plastic-reduction behavior.

At present, there is little information about the use of SMS as a mulching material and the assessment of the effects of mulching thickness on the soil–plant system. The efficacy of SMS mulch needs to be verified and evaluated. Keeping the above facts in mind, this study focused on four aspects regarding the short-term effects of mulching thickness: (1) the physico-chemical and biological properties of the soil, (2) weed suppression, (3) leaf nutrients, and (4) nut characteristics. The purpose of this study is to find a suitable SMS mulching measure to improve the soil health and nut quality. The results of this study could be used as references for SMS utilization and environmentally friendly mulching practices.

2. Materials and Methods

2.1. Description of Experimental Sites and Plant Materials

The field experiment was conducted from October 2018 to December 2019 in the North experiment station of Beijing Forestry University (118°40′46″ E, 41°13′18″ N), Sudayingzi village, Pingquan County, Hebei Province, China. It is located in a temperate monsoon climate zone. The annual average temperature in the past ten years has been about 7.5 °C. The average annual rainfall in the past ten years has been about 540 mm, and this has been mainly concentrated in summer. The average number of annual sunshine hours in the past ten years has been about 2500 h with a frost-free period of 120–130 d. The local agrometeorological data for 2019 are depicted in Table 1. The soil texture of the experiment plot is sandy loam soil. The soil total nitrogen, available phosphorus, available potassium, alkali hydrolyzed nitrogen, and organic matter contents are 0.83 ± 0.06, 15.67 ± 2.41, 105.56 ± 10.63, 32.13 ± 2.45, and 13.43 ± 1.17, respectively; the soil pH value is 6.5. The hazelnut plantation is mainly planted with the hybrid hazelnut *Corylus heterophylla* × *Corylus avellana* '82-11′. This cultivar was planted in 2013 with plant and row spacings of 2 and 3 m, respectively.

Table 1. The local agrometeorological data for 2019.

Month	Average Temperature (°C)	Average Relative Humidity (%)	Average Rainfall (mm)	Average Sunshine Hours (h)
Jan.	−10	50.6	2.2	195.1
Feb.	−5.6	44.6	3.8	195.0
Mar.	2.1	40.6	9.1	229.2
Apr.	10.4	41.2	20.3	225.2
May.	16.8	48.0	51.6	240.4
June.	20.7	65.2	97.8	188.5
July.	23.5	75.4	152.7	182.1
Aug.	21.8	74.6	121.2	195.7
Sept.	16.7	70.2	46.6	206.9
Oct.	8.4	64.0	20.3	209.0
Nov.	−0.5	57.1	7.5	184.5
Dec.	−7.8	53.9	2.5	178.9

2.2. Experimental Design and Treatments

The mulching experiment was conducted in October 2018 with a total of four treatments. The treatments were non-mulching control (CK), a mulch thickness of 5 cm (MT1), a mulch thickness of 10 cm (MT2), and a mulch thickness of 15 cm (MT3). This experiment had a randomized complete block design, where each mulching treatment was replicated three times and the plot area of each treatment was 40 m^2 (8 m × 5 m). A diagram of the experimental design is shown in Figure 1. The mulching material used was residue from the local production of *Pholiota nameko*. The main component of the residue was sawdust from the branches of *Robinia pseudoacacia* that had not been completely decomposed. The total nitrogen content, available potassium content, organic matter content, and pH value of the SMS were 30.74 ± 2.36, 232.78 ± 20.64, 421.69 ± 30.82, and 5.4, respectively.

	protective rows			
	Block I	Block II	Block III	
protective rows	MT2	MT2	CK	protective rows
	CK	MT3	MT1	
	MT1	CK	MT2	
	MT3	MT1	MT3	
	protective rows			

Figure 1. Schematic diagram of the randomized block experiment design. CK, control; MT, mulch thickness.

2.3. Sampling

The soil located 0–20 cm under the mushroom mulch was sampled with a stainless-steel cylindrical drill at 15-day intervals from May to December in 2019. Five soil sampling points were selected in each experimental plot by the S-shape sampling method. In each plot, one soil sample was composed of five individual samples, and about 1 kg of soil was reserved by the coning and quartering method. The samples from different treatments were dried in a ventilation place and then sieved by stainless-steel sieves with pore sizes of 1.00 and 0.25 mm. The pH value, available nutrient content, and enzyme activity of the soil samples (<1.00 mm) were used. The soil samples (<0.25 mm) were used to determine the total nutrient content and organic matter content of soil.

About 30 mature leaves in the upper or middle parts of the branches of the tested trees were also collected from each experimental plot from May to October in 2019. The fresh leaves were dried at a low temperature (35 °C) to ensure their weights were constant. Then, the dried leaves were crushed with a pulverizer. Finally, the classified powder was obtained through a 100-mesh steel sieve and prepared for nitrogen, phosphorus, and potassium analyses.

2.4. Measurements

2.4.1. Soil Moisture and Temperature

A remote real-time monitoring instrument (Patent No. CN202648697U) was installed in each plot to measure soil moisture content (accuracy: ±3%) and soil temperature (accuracy: ±0.5 °C). Each instrument was connected with three moisture sensor probes and three temperature sensor probes. The moisture sensor probes were set at 15, 30, and 45 cm underground, and the temperature sensor probes were set at the surface level of the ground, 10 cm underground, and 20 cm underground. This instrument automatically records data every 10 min. The recorded data can be viewed online through the data transmission module.

2.4.2. Physico-Chemical and Biological Properties of Soil

Undisturbed topsoil cores were collected with a ring knife (diameter, 50.46 mm; length, 50 mm) and dried to a constant weight in an oven at 105 °C to measure the bulk density and total porosity [12]. Soil organic matter (SOM) was determined with the potassium dichromate and sulfuric acid method [13]. Alkaline hydrolysable-nitrogen (AH-N) was measured by the alkali solution diffusion method [14]. Available phosphorus (AP) was extracted with 0.5 mol/L $NaHCO_3$ (pH 8.5) and determined by molybdenum-antimony anti-colorimetry with an ultraviolet spectrophotometer (Lambda750, PerkinElmer Inc., Waltham, MA, USA). Available potassium (AK) was determined in ammonium acetate extracts by flame photometry with an atomic absorption spectrophotometer (AA-240, Varian Inc., Palo Alto, CA, USA) [15].

Urease activity was measured using the phenol sodium hypochlorite colorimetric method and expressed in mg of NH_4^+-N in 1 g of dry soil after 24 h. Invertase activity was determined by the 3,5-dinitrosalicylic acid colorimetric method and shown as mg glucose in 1 g dry soil after 24 h. Catalase activity was determined using the $KMnO_4$ titration method and shown as the consumption volume (mL) of 0.1 mol·L^{-1} $KMnO_4$ in 1 g of dry soil after 20 min [16].

2.4.3. Weed Investigation

In order to determine the effect of mulching measures on weed growth, three small plots of 0.6 m × 0.6 m were randomly selected from each plot to investigate weed suppression in June, August, and October of 2019. Using statistics on the number of weed species and the fresh weight of the weeds, the controlling effect of mulching measures on weeds was reflected. The weed control efficiency (WCE) can be calculated using the following formula [17,18]:

$$WCE = (DMC - DMT)/DMC \times 100$$

where DMC is the dry matter of weeds subjected to CK treatment, and DMT is the dry matter of weeds in a particular treatment.

2.4.4. Leaf Nutrients and Chlorophyll Content

The leaf N concentration was determined using the micro-Kjeldahl method with a nitrogen determinator (Kjeltec™ 8000, FOSS Group, Hiller, Denmark) [19]. The total leaf P concentrations were measured with a molybdate/stannous chloride method with an ultraviolet spectrophotometer (Lambda750, PerkinElmer Inc., Waltham, MA, USA) [20]. The leaf K concentrations were determined by atomic absorption spectrometry with an atomic absorption spectrophotometer (AA-240, Varian Inc., Palo Alto, CA, USA) [21]. The chlorophyll content in leaves was estimated using a hand-held chlorophyll meter (SPAD-502, Konica Minolta Optics, Osaka, Japan) [22].

2.4.5. Nut Traits

Hazelnuts exposed to different mulch treatments were harvested in October 2019, and 100 nuts were randomly selected form each treatment to determine the nut traits. The experimental procedure included the following steps: (1) three linear dimensions of hazelnuts—length (*L*), width (*W*), and thickness (*T*)—were measured in mm with an electronic digital caliper [23]. (2) The nuts were dried in an oven at 40 °C for 5 days to reach a constant weight, and then the dry nuts' mass (*NM*) was weighed with a laboratory balance that was accurate to 0.01 g (Practum5101-1CN, Sartorius Group, Goettingen, Germany). (3) The dry kernels were taken out of the nut shells using a hammer, and the mass of the dry kernels was weighed (*KM*). (4) The kernels were ground via ball milling (Retsch MM400, Verder Group, Haan, Germany) with liquid nitrogen to produce powder samples. (5) The powder samples were used to determine the crude protein, soluble sugar, and crude fat contents (*CPC*, *SSC*, and *CFC*).

The soluble sugar concentration was determined by colorimetry with anthrone reagent in an ultraviolet spectrophotometer at 620 nm. A standard glucose curve was plotted, and the soluble sugar and glucose concentrations were interpolated from it. The crude protein content of the kernel samples was determined with the Kjeldahl method. The protein content was calculated using a factor of 6.25 for the N content [24]. The total fat content was obtained using the Soxhlet extraction method [24]. The crude fat content was calculated by dividing the dried extracted oil mass by the dried powder sample mass.

To describe the main morphological characteristics of nuts, some physical parameters were calculated according to Equations [23]:

$$V = \frac{\pi LWT}{6},\ D = (LWT)^{\frac{1}{3}},\ \varnothing = \frac{D}{L},\ PK = \frac{KM}{NM} \times 100,\ NSI = \frac{W + T}{2L}$$

where V is the volume of nuts (cm^3), π is the circumference ratio (≈3.14), L is the length of the nut (mm), W is the width of the nut (mm), T is the thickness of the nut (mm), D is the geometric mean diameter of the nut (mm), $\varnothing$ is the sphericity of the nut, PK is the kernel percentage, KM is the kernel mass (g), NM is the nut mass (g), and NSI is the nut shape index.

2.5. Statistical Analysis

Each determination was performed in triplicate, and the data are reported as means ± standard deviations. The data variables from this study were subjected to an analysis of variance using SPSS statistical software package version 18.0 (SPSS Inc., Chicago, IL, USA), which was also used to carry out Duncan's multiple comparisons test to analyze the differences in various parameters in different experimental treatments. For all statistical analyses, $p \leq 0.05$ was considered significant and $p \leq 0.01$ was deemed to be very significant. All figures in this manuscript were drawn with Excel 2010.

3. Results

3.1. Effect of the Mulching Thickness on Soil Physico-Chemical and Biological Properties

3.1.1. Soil Temperature

There were significant differences in the monthly variation of the soil temperature at different soil depths for each treatment (Table 2). During the field experiment period, for each treatment, the soil temperature at different soil depths showed a trend of first rising and then falling, reaching a peak in August and a valley in December. The average topsoil temperature of CK was 0.77, 1.32, and 1.81 °C higher than that of MT1, MT2, and MT3 in the growth period (from May to October), respectively. However, in the dormancy period (from November to December), the average topsoil temperature of CK was 0.32, 0.75, and 1.17 °C lower than that of MT1, MT2, and MT3, respectively. There were significant differences in the topsoil temperature between the MT2, MT3, and CK treatments throughout the study period.

The average soil temperature during the mulching treatments was significantly lower than that of CK in the growth period at a depth of 10 cm with magnitudes of 16.64 ± 0.14, 16.28 ± 0.16, and 15.86 ± 0.13 °C for MT1, MT2, and MT3, respectively. During the dormancy period, the average soil temperature of CK was 0.42, 1.02, and 1.56 °C lower than that of MT1, MT2, and MT3, respectively. There were significant differences in the soil temperature of at a depth of 10 cm between the mulching and non-mulching treatments.

Compared with CK, at a depth of 20 cm, MT1, MT2, and MT3 decreased the soil temperature by an average of 0.30, 0.51, and 0.83 °C in the growth period and increased the soil temperature by 0.26, 0.71, and 1.05 °C in the dormancy period. There were significant differences in the soil temperature between the MT3 and CK treatments during the study period at a depth of 20 cm.

3.1.2. Soil Water

In this study, the soil water content was investigated at depths of 15, 30, and 45 cm because the fine-roots of *C. heterophylla* × *C. avellana* are mainly distributed in the depth range of 0–50 cm [25]. The soil water content was significantly affected by the mulching practices, and it varied spatially and temporally (Table 3).

Table 2. Monthly average soil temperature (°C) at different soil depths during the field experiment period for the mulch treatments.

Soil Temperature	Mulch Treatments	May	June	July	August	September	October	November	December
0 cm depth	MT1	15.46 ± 0.16 aA	18.37 ± 0.52 bA	22.76 ± 0.50 cA	27.47 ± 0.44 dA	17.51 ± 0.36 eA	4.31 ± 0.37 fA	0.45 ± 0.04 gA	−6.69 ± 0.49 hA
	MT2	14.86 ± 0.24 aB	17.62 ± 0.47 bB	22.13 ± 0.33 cB	26.19 ± 0.44 dB	16.94 ± 0.47 eA	4.87 ± 0.15 fB	0.62 ± 0.05 gB	−5.99 ± 0.21 hB
	MT3	14.31 ± 0.18 aC	16.77 ± 0.38 bC	21.24 ± 0.31 cC	25.00 ± 0.28 dC	16.82 ± 0.63 bA	5.51 ± 0.16 eC	0.70 ± 0.04 fC	−5.24 ± 0.33 gC
	CK	15.98 ± 0.20 aD	19.09 ± 0.47 bD	23.85 ± 0.43 cD	29.32 ± 0.29 dD	18.42 ± 0.33 eB	3.85 ± 0.39 fD	0.33 ± 0.06 gD	−7.21 ± 0.39 hA
10 cm depth	MT1	14.61 ± 0.18 aA	17.31 ± 0.31 bA	20.56 ± 0.28 cA	25.23 ± 0.43 dA	17.01 ± 0.22 bA	5.09 ± 0.23 eA	0.56 ± 0.08 fA	−5.12 ± 0.39 gA
	MT2	14.15 ± 0.24 aB	16.85 ± 0.43 bA	19.99 ± 0.17 cB	24.61 ± 0.38 dB	16.46 ± 0.19 bB	5.60 ± 0.20 eB	0.86 ± 0.13 fB	−4.21 ± 0.30 gB
	MT3	13.93 ± 0.20 aB	16.00 ± 0.35 bB	19.03 ± 0.22 cC	23.91 ± 0.42 dC	16.21 ± 0.25 bB	6.06 ± 0.18 eC	1.15 ± 0.12 fC	−3.42 ± 0.18 gC
	CK	15.04 ± 0.30 aC	17.90 ± 0.31 bC	21.20 ± 0.30 cD	26.49 ± 0.25 dD	17.53 ± 0.27 bC	4.49 ± 0.21 eD	0.38 ± 0.07 fD	−5.77 ± 0.44 gD
20 cm depth	MT1	13.95 ± 0.28 aAB	16.67 ± 0.39 bA	19.99 ± 0.24 cAB	24.56 ± 0.27 dA	16.80 ± 0.16 bA	6.34 ± 0.35 eAB	1.28 ± 0.19 fAB	−4.46 ± 0.35 gA
	MT2	13.64 ± 0.14 aAC	16.42 ± 0.26 bA	19.78 ± 0.21 cA	23.97 ± 0.35 dB	16.58 ± 0.21 bAB	6.68 ± 0.20 eAC	1.56 ± 0.21 fAC	−3.85 ± 0.19 gB
	MT3	13.42 ± 0.26 aC	15.65 ± 0.48 bB	19.14 ± 0.33 cC	23.60 ± 0.22 dB	16.36 ± 0.25 eB	6.95 ± 0.28 fC	1.77 ± 0.28 gC	−3.37 ± 0.07 hC
	CK	14.28 ± 0.31 aB	16.99 ± 0.26 bA	20.37 ± 0.22 cB	25.22 ± 0.26 dC	17.19 ± 0.21 bC	6.06 ± 0.42 eB	1.16 ± 0.24 fB	−4.85 ± 0.36 gA

Note: Lowercase letters represent significant differences ($p < 0.05$) among different months for the same treatment; capital letters represent significant difference ($p < 0.05$) among different treatments in same month.

Table 3. Monthly average soil water content (%) at different soil depths during the field experiment period for the mulch treatments.

Soil Water	Mulch Treatments	May	June	July	August	September	October	November	December
15 cm depth	MT1	19.64 ± 1.06 aA	22.47 ± 1.23 bcA	23.35 ± 1.43 bA	20.11 ± 1.02 adA	21.11 ± 1.05 acdA	21.36 ± 1.02 cdA	19.78 ± 0.97 adA	9.25 ± 0.46 eA
	MT2	20.01 ± 1.09 aA	25.54 ± 1.53 bB	26.31 ± 0.89 bB	22.32 ± 0.96 cdB	22.69 ± 1.10 cA	22.27 ± 1.00 cdA	20.84 ± 0.66 adAB	10.34 ± 0.38 eB
	MT3	20.90 ± 3.37 aA	21.73 ± 1.16 aA	22.38 ± 1.10 aAC	20.89 ± 1.27 aAB	21.05 ± 1.31 aA	21.63 ± 1.17 aA	21.46 ± 0.47 aB	13.86 ± 0.47 bC
	CK	15.87 ± 1.25 aB	20.32 ± 1.77 bA	20.51 ± 1.37 bC	19.64 ± 1.32 bcA	20.84 ± 1.11 bA	21.01 ± 0.74 bA	18.33 ± 0.99 cC	8.78 ± 0.46 dA
30 cm depth	MT1	20.90 ± 0.50 aAB	24.54 ± 1.42 bAB	24.71 ± 1.01 bAB	21.87 ± 1.24 acAB	22.35 ± 1.07 acAB	23.27 ± 0.76 bcAB	21.24 ± 0.86 aA	12.26 ± 0.33 dA
	MT2	22.66 ± 1.28 abB	26.05 ± 1.40 cA	25.58 ± 1.06 cA	23.34 ± 0.91 aA	23.56 ± 0.90 aA	23.86 ± 1.04 aA	21.59 ± 0.67 bA	14.52 ± 0.35 dB
	MT3	22.13 ± 1.88 abB	22.15 ± 1.18 abC	23.51 ± 0.87 aBC	21.54 ± 0.64 bB	21.75 ± 1.04 bB	22.38 ± 0.97 abB	21.77 ± 0.30 bA	18.44 ± 0.38 cC
	CK	18.99 ± 1.09 aA	22.76 ± 0.83 bBC	22.82 ± 0.90 bC	21.14 ± 1.19 cdB	22.18 ± 0.79 bcAB	22.04 ± 0.82 bcdB	20.83 ± 0.63 dA	10.28 ± 0.27 eD
45 cm depth	MT1	24.23 ± 1.95 abA	25.45 ± 1.64 aAB	25.81 ± 0.93 aA	23.66 ± 0.52 bA	23.67 ± 0.49 bA	23.52 ± 0.61 bAB	21.76 ± 0.45 cAB	19.46 ± 0.41 dA
	MT2	24.77 ± 0.68 aA	26.86 ± 0.72 bA	27.35 ± 0.50 bB	23.81 ± 0.72 cA	23.72 ± 0.66 cA	23.79 ± 0.84 cA	22.06 ± 0.39 dA	20.87 ± 0.40 eB
	MT3	24.90 ± 1.81 aA	24.14 ± 1.35 abB	24.51 ± 1.01 abAC	23.08 ± 0.55 bcAB	23.78 ± 0.35 abcA	23.25 ± 0.62 bcAB	22.36 ± 0.35 cdA	21.19 ± 0.33 dB
	CK	21.62 ± 1.76 aB	23.69 ± 1.22 bB	23.57 ± 1.06 bC	22.24 ± 0.67 abB	22.57 ± 0.93 abB	22.36 ± 0.85 abB	21.25 ± 0.47 aB	17.31 ± 0.50 cC

Note: Lowercase letters represent significant differences ($p < 0.05$) among the different months for a given treatment; capital letters represent significant differences ($p < 0.05$) among different treatments in the same month.

The average soil water content of CK showed a monthly fluctuation and was strongly affected by rainfall and evaporation. The average soil water content of the mulch treatments showed a dynamic rising–stable–declining trend during the field experiment period. The soil water content of MT1, MT2, and MT3 was 8.13%, 17.23%, and 12.81% higher than that of CK, respectively, at a depth of 15 cm. At a depth of 30 cm, the soil water content of MT1, MT2 and MT3 was 6.27%, 12.48%, and 7.84% higher than that of CK, respectively. The soil water content of CK was 7.41%, 10.66%, and 7.20% lower than that of MT1, MT2, and MT3, respectively, at a soil depth of 45 cm. In this study, the average soil water content increased as the soil depth increased. The soil water content first increased and then decreased as the mulching thickness increased (from 0 to 15 cm), and the 10 cm mulching thickness treatment had a better water holding capacity. The SMS mulching not only had a positive effect by improving the soil water content, but it also effectively alleviated the soil moisture variation.

3.1.3. Soil Bulk Density and Porosity

The monthly dynamics of the soil bulk density and porosity under the different mulching thickness treatments are shown in Figure 2.

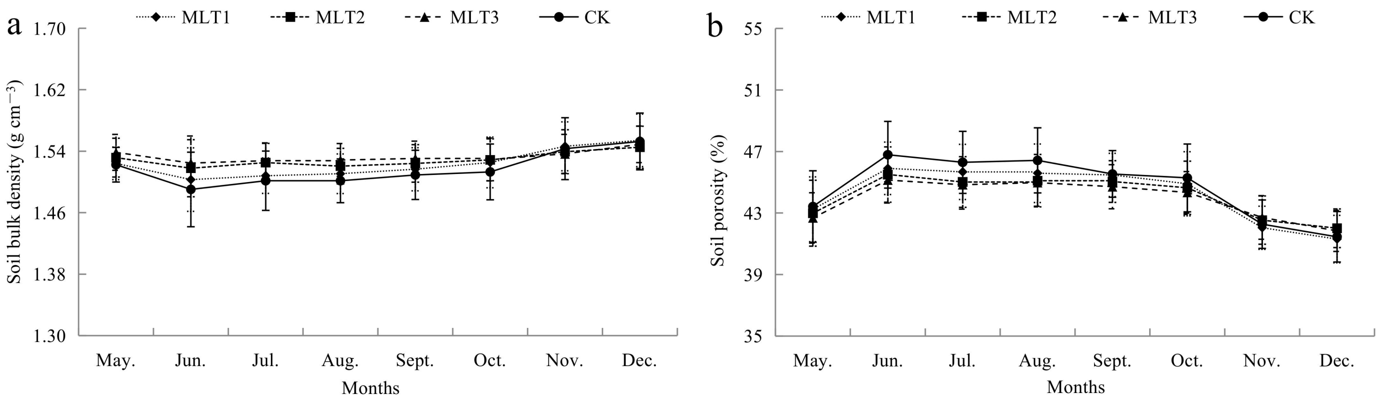

Figure 2. Variation in the soil physical properties among different treatment groups during the field experiment period: (**a**) soil bulk density and (**b**) soil porosity.

Figure 2a depicts the dynamic variation in the soil bulk density during these mulch treatments throughout the field experiment period. The lowest and highest bulk densities of these treatments appeared in June and December, respectively. All treatments had similar dynamic trends, that is, the density first decreased (from May to June), then stabilized (from July to October), and finally increased (in November and December). In a field experiment period of one year, the bulk density tended to increase as the mulching thickness increased. The MT3 treatment had the highest average bulk density (1.533 g cm^{-3}), followed by MT2 (1.529 g cm^{-3}), MT1 (1.524 g cm^{-3}), and CK (1.517 g cm^{-3}).

In this study, different mulch treatments reduced the soil porosity. The general dynamic variation in the soil porosity was in contrast to that of the bulk density, showing a trend of first rising and then decreasing (Figure 2b). There were no significant differences in soil porosity among these treatments throughout the field experiment period. The highest and lowest total porosities recorded for these treatment groups all appeared in June and December, respectively. The MT3 treatment was associated with the lowest average total porosity (43.9 %), followed by MT2 (44.1 %), MT1 (44.3 %), and CK (44.7 %).

3.1.4. Soil Nutrients

Figure 3a presents the monthly dynamics of the SOM content under different mulching thicknesses. The change trend for the SOM content in MT1, MT2, and MT3 was an initial increase and then a decrease. In the CK treatment, the trend was a continuous decrease at first, followed by a stable period. There were no significant differences in the SOM content among MT1, MT2, and MT3. However, the SOM concentration of the mulched plots was significantly higher than that of the plots, with no mulch from July to October. With an increase in the mulching thickness, the SOM concentration tended to increase. During the field experiment period, MT3 had the highest average SOM concentration (16.10 ± 1.29 g kg^{-1}), slightly higher than that of MT2 (15.89 ± 1.33 g kg^{-1}) and MT1 (15.35 ± 1.66 g kg^{-1}), while the lowest average SOM content, which was only 13.65 ± 1.85 g kg^{-1}, occurred in CK.

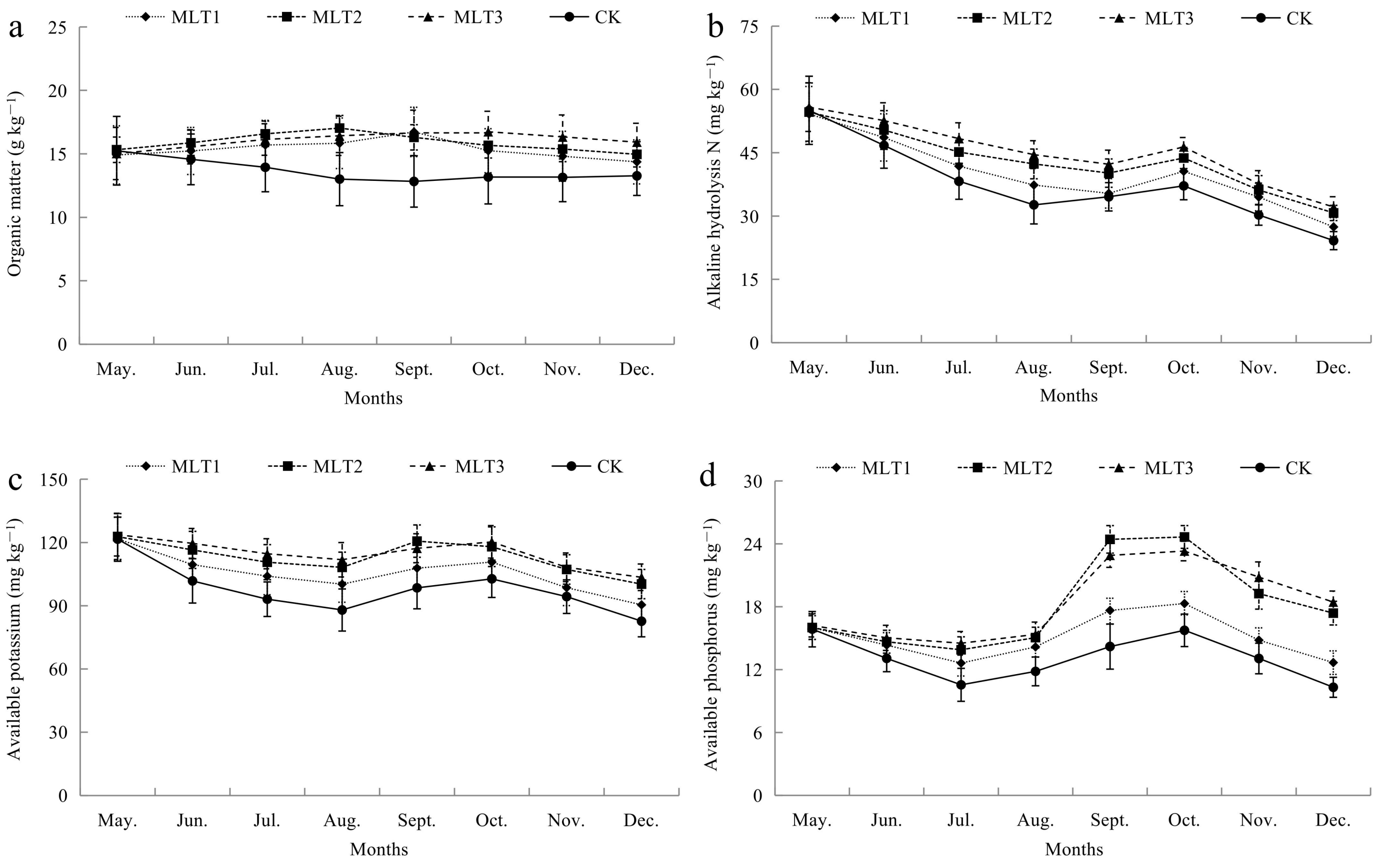

Figure 3. Variation in soil nutrient contents among different treatments during the field experiment period: (**a**) organic matter; (**b**) alkaline hydrolyzable nitrogen; (**c**) available potassium; (**d**) available phosphorus.

Figure 3b depicts the monthly dynamics of the AH-N content with different mulch treatments. The dynamic changes in the AH-N content in these treatments were similar; that is, there was an initial rapid decrease, followed by a slight increase and, finally, an obvious decrease. The highest AH-N content of each treatment appeared in May, and the lowest value appeared in December. There were significant differences in the AH-N content not only in different months, but also for different treatments. The average AH-N content in soil exposed to the MT3 treatment was 20.39%, 12.46%, and 4.77% higher than that for CK, MT1, and MT2, respectively.

The monthly dynamics of the AK content in soil exposed to the mulch treatments are shown in Figure 3c. The change trend for the AK content in soil exposed to these treatments was similar among groups, with all of them showing a decline–rise–decline fluctuation during the study period. The AK contents of MT2 and MT3 were significantly higher than that of CK. MT3 had the highest average AK concentration (114.89 ± 4.97 mg kg^{-1}), followed by MT2 (113.04 ± 4.77 mg kg^{-1}), MT1 (105.37 ± 4.58 mg kg^{-1}), and CK (97.85 ± 6.26 mg kg^{-1}).

Figure 3d illustrates the monthly dynamics of the AP content in soil exposed to different mulch treatments. The dynamic change trend in the AP content was similar to that of the AH-N and AK contents. There were significant differences in the AP content among these treatments. The AP contents of MT2 and MT3 were much higher than those of CK and MT1 from September to December. MT3 had the highest average AP concentration (18.32 ± 0.62 mg kg^{-1}), which was 40.11%, 21.59%, and 0.85% higher than that of CK, MT1, and MT2, respectively.

3.1.5. Soil Enzymatic Activities

Soil enzymes are some of the most active components in various biochemical processes and nutrient cycles. They play an important role in the degradation of SOM and nutrient mineralization [26,27]. The dynamics of three soil enzymatic activities under different mulch treatments are shown in Figure 4.

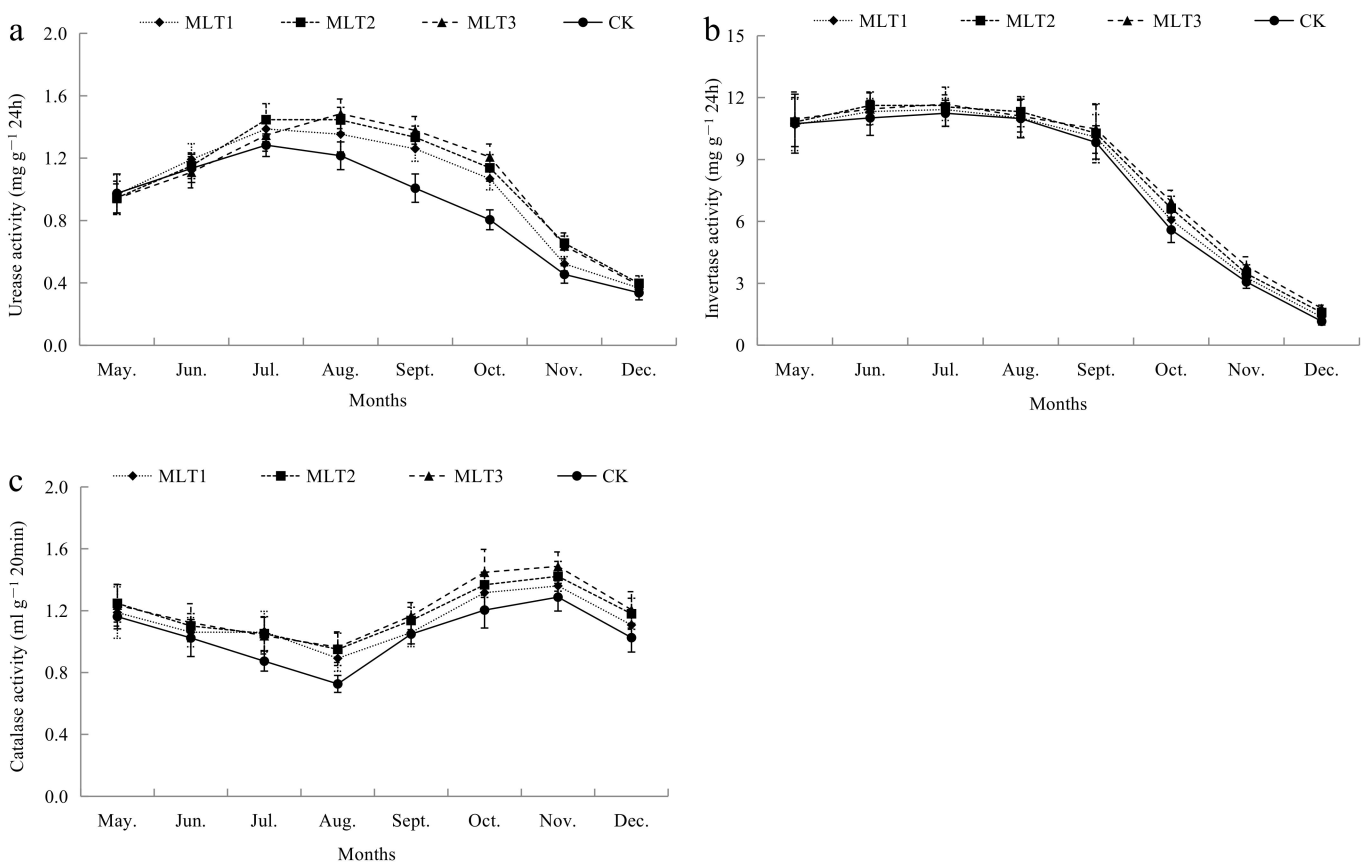

Figure 4. Variation in soil enzymatic activities among different treatment groups during the field experiment period: (**a**) urease activity; (**b**) invertase activity; (**c**) catalase activity.

The urease activity varied significantly across the sampling period and with different mulching thickness gradients (Figure 4a). In MT1, MT2, and MT3, the urease activity went through a rising period and was maintained at a high level before sharply decreasing over time. However, the urease activity decreased in CK after the rising period. The urease activity was higher in summer and lower in winter. The average urease activity of MT1, MT2, and MT3 increased by 12.56%, 18.04%, and 17.74%, respectively, compared with that of CK.

The invertase activity dynamics of the four treatments all showed a similar trend: a slight increase at first and then a rapid decrease (Figure 4b). The invertase activity of these four treatments was higher in summer, while lower invertase activity occurred in winter. MT3 had the highest average invertase activity (8.53 ± 0.46 mg g^{-1}·24 h^{-1}), followed by MT2 (8.41 ± 0.37 mg g^{-1}·24 h^{-1}), MT1 (8.16 ± 0.36 mg g^{-1}·24 h^{-1}), and CK (7.95 ± 0.47 mg g^{-1}·24 h^{-1}).

Figure 4c shows the monthly dynamics of catalase activity in soil exposed to these mulch treatments. The catalase activity showed a similar trend in these treatment groups with a decline–rise–decline fluctuation during the sampling period. The catalase activity differed significantly among sample sets from different months and with different mulching thickness gradients. The catalase activity of each treatment group was higher in autumn and lower in late summer. The average catalase activity of MT1, MT2, and MT3 was 8.35%, 13.24%, and 15.76% higher, respectively, than that of CK.

3.2. Effect of Mulching Thickness on Weed Suppression

The investigation of weeds was carried out in June, August, and October. In total, 18 weed species belonging to nine families were identified from these treatments (Table 4). Weed biomass and control efficiency are presented in Table 4.

In June, there were 8, 5, 3, and 14 weed species in MT1, MT2, MT3, and CK, respectively. The dominant weed species in CK were *Cephalanoplos segetum* (Willd.) MB., *Conyza canadensis* (L.) Cronq., *Equisetum hyemale* L., *Ixeris sonchifolia* (Bunge) Hance, and *Taraxacum mongolicum* Hand.-Mazz. *Chenopodium album* L., *Eleusine indica* (L.) Gaertn., and *Ixeris sonchifolia* (Bunge) Hance were found in all treatment groups. In August, the number of weed species decreased in MT1 (7 species) and CK (10 species). The major weeds found in CK changed to *Amaranthus retroflexus* L., *Chenopodium album* L., *Eleusine indica* (L.) Gaertn., and *Equisetum hyemale* L.. *Amaranthus retroflexus* L., *Chenopodium album* L. and *Ixeris sonchifolia* (Bunge) Hance appeared in all treatments. In October, the number of weed species in MT1 (4 species), MT2 (4 species), MT3 (1 species), and CK (7 species) reduced obviously. *Ixeris sonchifolia* (Bunge) Hance, *Equisetum hyemale* L., and *Xanthium sibiricum* Patrin ex Widder became the dominant weed species. *Ixeris sonchifolia* (Bunge) Hance was found in all plots.

The highest weed dry biomass content was recorded in June for CK (1563.86 ± 116.33 g m^{-2}), whereas the lowest weed biomass was recorded in October (318.46 ± 20.13 g m^{-2}). In early summer (June), the weed biomass of mulched plots was much less than that of plots with no mulch, and the weed control efficiency ranged from 79.01% to 97.90%. In August, the weed biomass of MT1, MT2, and MT3 increased by 37.84%, 250.46%, and 687.52%, respectively, compared with that in June, while the weed control efficiencies decreased to 48.25%, 55.66%, and 70.43%, respectively. The weed biomass of the mulched plots decreased significantly in October, and the weed control efficiency improved greatly, ranging from 80.42% to 96.63%. The highest level of weed suppression, 70.43–97.90%, was obtained with MT3, followed by MT2 (55.66–92.93%), and the lowest level was found in the MT1 plots (48.25–80.42%).

With an increase of mulching thickness, the number of weed species decreased obviously and the weed control efficiency increased. SMS mulching was better able to control the growth of *Conyza canadensis* (L.) Cronq., *Cephalanoplos segetum* (Willd.) MB., *Humulus scandens* (Lour.) Merr., *Portulaca oleracea* L., and *Artemisia lavandulaefolia* DC.

Table 4. Comparison of weed species exposed to different mulch treatments.

Months	Mulch Treatments	Weed Species	The Number of Weed Species	Weed Biomass (g m^{-2})	Weed Control Efficiency (%)
June	MT1	*Taraxacum mongolicum* Hand.-Mazz., *Amaranthus retroflexus* L., *Chenopodium album* L., *Ixeris sonchifolia* (Bunge) Hance, *Equisetum hyemale* L., *Conyza canadensis* (L.) Cronq., *Tagetes erecta* L., *Eleusine indica* (L.) Gaertn.	8	328.32 ± 24.46	79.01
	MT2	*Taraxacum mongolicum* Hand.-Mazz., *Chenopodium album* L., *Ixeris sonchifolia* (Bunge) Hance, *Eleusine indica* (L.) Gaertn., *Amaranthus retroflexus* L.	5	110.63 ± 10.32	92.93
	MT3	*Taraxacum mongolicum* Hand.-Mazz., *Ixeris sonchifolia* (Bunge) Hance, *Eleusine indica* (L.) Gaertn.	3	32.84 ± 3.26	97.90
	CK	*Taraxacum mongolicum* Hand.-Mazz., *Amaranthus retroflexus* L., *Chenopodium album* L., *Ixeris sonchifolia* (Bunge) Hance, *Conyza canadensis* (L.) Cronq., *Cirsium setosum* (Willld.) MB., *Tagetes erecta* L., *Eleusine indica* (L.) Gaertn., *Descurainia sophia* (L.)Webb. ex Prantl, *Equisetum hyemale* L., *Artemisia lavandulaefolia* DC., *Xanthium strumarium* L., *Mentha haplocalyx* Linnaeus, *Hemisteptia lyrata* (Bunge) Bunge	14	1563.86 ± 116.33	–
August	MT1	*Amaranthus retroflexus* L., *Ixeris sonchifolia* (Bunge) Hance, *Eleusine indica* (L.) Gaertn., *Equisetum hyemale* L., *Tagetes erecta* L., *Mentha haplocalyx* Linnaeus, *Chenopodium album* L.	7	452.57 ± 28.63	48.25
	MT2	*Amaranthus retroflexus* L., *Eleusine indica* (L.) Gaertn., *Chenopodium album* L., *Mentha haplocalyx* Linnaeus, *Ixeris sonchifolia* (Bunge) Hance	5	387.71 ± 20.54	55.66
	MT3	*Amaranthus retroflexus* L., *Eleusine indica* (L.) Gaertn., *Chenopodium album* L., *Ixeris sonchifolia* (Bunge) Hance	4	258.62 ± 16.71	70.43
	CK	*Amaranthus retroflexus* L., *Ixeris sonchifolia* (Bunge) Hance, *Artemisia lavandulaefolia* DC., *Eleusine indica* (L.) Gaertn., *Mentha haplocalyx* Linnaeus, *Equisetum hyemale* L., *Chenopodium album* L., *Tagetes erecta* L., *Cirsium setosum* (Willld.) MB., *Humulus scandens* L.	10	874.48 ± 60.56	–
October	MT1	*Ixeris sonchifolia* (Bunge) Hance, *Geranium carolinianum* L., *Equisetum hyemale* L., *Chenopodium album* L.	4	62.36 ± 8.27	80.42
	MT2	*Geranium carolinianum* L., *Xanthium strumarium* L., *Chenopodium album* L., *Ixeris sonchifolia* (Bunge) Hance	4	38.55 ± 4.62	87.89
	MT3	*Ixeris sonchifolia* (Bunge) Hance	1	10.73 ± 3.39	96.63
	CK	*Equisetum hyemale* L., *Chenopodium album* L., *Ixeris sonchifolia* (Bunge) Hance, *Artemisia lavandulaefolia* DC., *Portulaca oleracea* L., *Cirsium setosum* (Willld.) MB., *Xanthium strumarium* L.	7	318.46 ± 20.13	–

3.3. Effect of Mulching Thickness on Leaf Nutrients and Chlorophyll Content

The monthly dynamics of the leaf N content in soil exposed to different mulch treatments are shown in Figure 5a. In CK, the leaf N content first decreased in June, then increased from July to August, and finally decreased sharply in September and October. The dynamic trend for the leaf N content in the other treatment groups was an initial increase followed by a decrease. The monthly variation in the leaf N content in all treatments was significant. There were also significant differences in the leaf N content among different treatments from June to October. The average leaf N content of MT3, MT2, and MT1 was 14.03%, 12.28%, and 8.39% higher, respectively, than that of CK.

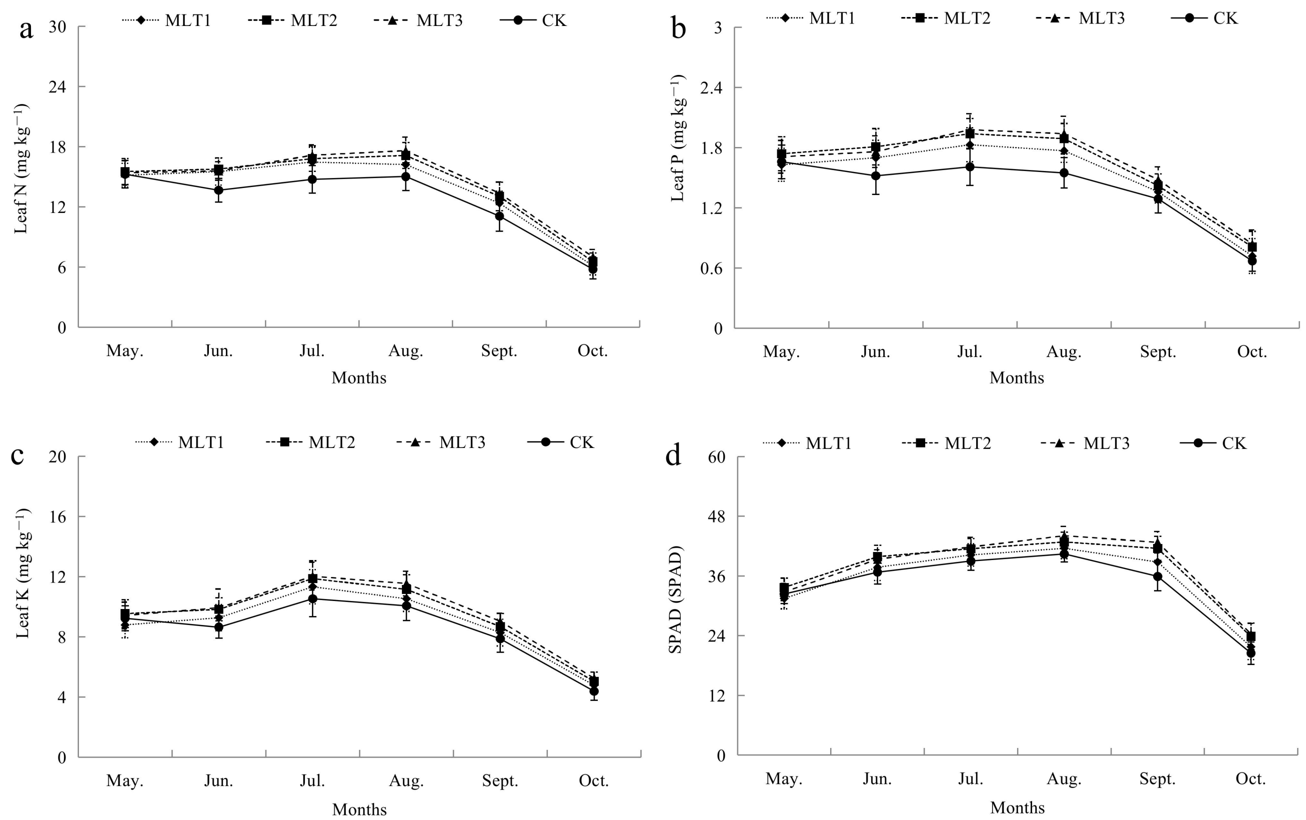

Figure 5. Variation in leaf nutrient contents among different treatment groups during the growth period: (**a**) leaf N; (**b**) leaf P; (**c**) leaf K; (**d**) SPAD.

Figure 5b shows the monthly dynamics of the leaf P content with different mulch treatments. The dynamic trend for the leaf P content in MT1, MT2, and MT3 was similar; that is, an initial slight increase from May to July and then a decrease from August to October. In CK, the trend was a decrease from May to June, then a stable period from July to August, and finally a rapid decrease in September and October. The highest leaf P content appeared in July for MT1, MT2, and MT3, while for CK, it appeared in May, and the lowest leaf P content was in October for all groups. The average leaf P content of MT3, MT2, and MT1 was 16.99%, 15.78%, and 8.55% higher, respectively, than that of CK.

Figure 5c shows the monthly dynamics of the leaf K content in soil exposed to different mulch treatments. There were significant differences in the leaf K content not only in different months, but also with different treatments. The highest leaf K content appeared in July for MT1, MT2, MT3, and CK: 11.33 ± 1.14, 11.87 ± 1.18, 12.02 ± 1.25, and 10.53 ± 1.20 mg g^{-1}, respectively. The minimum leaf K content occurred in October for MT1, MT2, MT3, and CK: 4.78 ± 0.49, 5.03 ± 0.62, 5.24 ± 0.54, and 4.37 ± 0.59 mg g^{-1}, respectively. The average leaf K content of the MT3, MT2, and MT1 treatments was 12.79%, 10.61%, and 4.45% higher, respectively, than that of CK.

Figure 5d presents the monthly dynamics of SPAD in soil exposed to these mulch treatments. There were significant differences in SPAD both in different months and with different treatments. The four treatments showed similar dynamic trends; that is, an initial increase from May to August and then a decrease from September to October. The average value of SPAD in MT3, MT2, and MT1 was 9.87%, 8.96%, and 3.24% higher, respectively, than that in CK.

3.4. Effect of Mulching Thickness on the Nut Yield and Quality Traits

The nut yield and quality traits varied in soil exposed to different mulch treatments. The values of these parameters are shown in Table 5.

Table 5. Comparison of weed species exposed to different mulch treatments.

Nut Traits	MT1	MT2	MT3	CK
Individual-plant yield (g/tree)	1027.06 ± 151.71 A	1045.26 ± 146.41 A	1019.50 ± 144.15 A	1001.40 ± 144.54 A
L (mm)	19.92 ± 2.87 AB	20.47 ± 2.23 A	20.71 ± 3.07 A	19.22 ± 2.28 B
W (mm)	17.96 ± 2.34 A	18.18 ± 2.11 A	17.78 ± 1.93 AB	16.97 ± 1.90 B
T (mm)	16.77 ± 2.29 AB	16.97 ± 1.95 A	16.53 ± 2.08 AB	16.05 ± 1.70 B
D (mm)	18.13 ± 2.15 A	18.45 ± 1.76 A	18.23 ± 2.13 A	17.34 ± 1.70 B
V (cm^3)	3.25 ± 1.11 A	3.38 ± 0.93 A	3.29 ± 1.01 A	2.81 ± 0.82 B
∅	0.92 ± 0.08 A	0.91 ± 0.07 AB	0.89 ± 0.06 B	0.91 ± 0.06 AB
NSI	0.88 ± 0.12 A	0.86 ± 0.11 AB	0.84 ± 0.09 B	0.87 ± 0.09 AB
NM (g)	2.40 ± 0.78 A	2.56 ± 0.73 A	2.45 ± 0.69 A	2.08 ± 0.63 B
KM (g)	0.95 ± 0.29 A	1.00 ± 0.30 A	0.95 ± 0.29 A	0.82 ± 0.21 B
PK (%)	40.28 ± 6.43 A	40.02 ± 9.93 A	38.96 ± 7.69 A	39.69 ± 5.43 A
CPC (%)	21.16 ± 1.15 A	22.18 ± 1.15 A	21.70 ± 1.00 A	20.89 ± 1.45 A
SSC (%)	4.11 ± 0.18 A	4.23 ± 0.15 A	4.18 ± 0.11 A	4.05 ± 0.24 A
CFC (%)	60.29 ± 1.68 AB	61.87 ± 1.41 A	60.63 ± 1.25 AB	59.82 ± 1.89 B

Note: Capital letters represent significant differences ($p < 0.05$) among treatments.

The average values of *D*, *V*, *NM*, and *KM* were significantly lower in CK in soil exposed to mulch treatments. The highest average *L* value appeared in MT3, and this was 7.75% higher than that of CK. The highest average *D*, average *V*, average *NM*, and average *KM* values all appeared in MT2. These were 6.40%, 20.28%, 23.08%, and 21.95% higher than the values in CK, respectively. Although there were significant differences in *NM* and *KM* between soil exposed or not to mulch treatments, the difference in *PK* was not significant. MT1 treatment had the highest *PK*, followed by MT2, CK, and MT3. Sphericity and shape index are the main indicators of nut shape, and these variables are determined by nut dimensions. According to Milošević and Milošević [28], an *NSI* value of 0.84 indicates that the hazelnut shape is conical, and an *NSI* value above 0.86 indicates that the hazelnut shape is globular. In this study, the average nut sphericity and nut shape index values were highest in MT1, which means that the nuts in MT1 were rounder than in other treatments. There were no significant differences in the plant yield, *CPC*, or *SSC* among these treatment groups. The individual plant yield, *CPC*, and *SSC* were the highest in MT2, 4.38%, 6.18%, and 4.44% higher than the values in CK, respectively. The *CFC* of MT2 was significantly higher than that of CK.

4. Discussion

4.1. Effect of Mulching on Soil Physico-Chemical and Biological Properties

Soil temperature is a key environmental factor that has an impact on crop growth and development by regulating water absorption and nutrient uptake in root zones [29]. Mulches alter the soil temperature, which affects the thermal regime of a soil [30]. However, the effect of mulches on the soil temperature varies depending on the capacity of the mulching materials to reflect and transmit solar energy [31]. Organic mulches can reduce the maximum soil temperature, but increase the minimum soil temperature, while they significantly reduce the soil temperature [8]. The results of a mulching study conducted on the Loess Plateau showed that daily mean soil temperatures in soil treated with mulch at a depth of 10 cm were lower in warmer periods by 0–4 °C and higher in colder periods by 0–2 °C compared with non-mulched soil [32]. Similarly, in our study, SMS mulching measures can efficiently regulate the soil temperature by reducing it in warm weather and increasing it in cold weather. However, the regulation ability of SMS varies with the mulching thickness and soil depth. SMS forms a temperature isolation layer on the soil surface owing to its high reflectivity and low thermal diffusivity, which can effectively reduce fluctuations in the soil temperature.

Soil moisture is also considered to be an important factor affecting plant growth and development, and even a small change in soil water storage could affect crop productivity [33]. A large number of previous studies have confirmed that mulching can effectively conserve soil water by reducing soil evaporation [29]. Mulching has a positive impact on the soil water content that depends on the type of mulching materials and thickness of mulching used [34]. Some studies have shown that the mulch thickness is more important than the texture of the mulch for evaporation suppression, and thicker mulch prevents soil water evaporation more effectively. Moreover, studies have shown that mineral or organic mulches must have a critical thickness to effectively reduce soil evaporation, and the crop yield and water use efficiency can be reduced if the mulching thickness is excessive [35]. McMillen [36] compared the soil water retention capacity of three organic mulching materials with different mulching thickness. The results showed that treatment with 10 cm thick mulch increased the soil moisture by over 10% compared with bare soil, while 15 cm thick mulching treatment did not significantly reduce soil evaporation further. The results of this study are consistent with the previous research conclusion, that is, 10 cm thick mulch had a strong water holding capacity throughout the field experiment period. The soil moisture content of MT2 was significantly higher than that of CK in all three soil depths during the rainy season. Evaporation and drainage were the main factors that reduced the soil moisture content in the soil profile of 0–30 cm in the rainy season, and mulching can conserve the soil moisture for longer periods than bare soil [37]. With an increase in the soil depth, the difference in soil moisture among different treatments decreased.

The effect of mulching on the soil bulk density varies depending on the soil properties, mulch material used, climatic conditions, and land use. Mulching increases the soil bulk density when conventional tillage is used, but can also reduce it by adding organic matter to the soil. Whether there is an increase or decrease in the soil bulk density depends on the specific situation [8]. Massaccesi et al. [38] supports the idea that the soil bulk density tends to increase with the application of organic mulch combined with no-tillage practices. In 2015, Kader et al. showed that the soil bulk density following straw mulching was lower than at a depth of 0–30 cm compared with that of bare soil; however, the reverse trend was found in 2016 [37]. Ni et al. [39] reported non-significant results for the effects of mulching on the soil bulk density at a depth of 0–10 cm. The results of this study demonstrate that the soil bulk density tended to increase as the mulching thickness increased, but there was no significant difference between mulching and non-mulch treatments. Soil porosity is influenced by the agronomic practices implemented, and it decreases with the soil depth [40,41]. Nzeyimana et al. [42] conducted a two-year mulching experiment to quantify the effects of different organic mulches on soil properties, and the results showed that the application of mulch had a positive impact on the soil porosity. However, the effects of the interactions between the type of mulch and type of soil were site-specific. In our study, there was no significant difference in soil porosity among the different mulch treatments. SMS usually required a long time to completely mineralize [43], thus it may take a longer time to improve soil structure when SMS is used as a mulching material.

A significant loss in soil nutrients occurs within 1–2 years of plastic mulching, probably owing to temperature-induced accelerated biodegradation [44], which is closely linked and entangled with an increasing C/N metabolism [45]. However, when the soil carbon pool is maintained by organic matter input, the SOM content remains stable [8]. A study by

Pal and Mahajan [46] revealed that higher soil nutrient contents can be achieved through the application of an optimal level of organic mulch (pine-needle mulch). Similarly, our study showed that the use of SMS mulch can significantly increase the soil nutrient content compared with soil not treated with mulch. Although the highest average values of SOM, AH-N, AK, and AP were observed in MT3, there were no significant difference in soil nutrient contents between MT2 and MT3. This may be owing to the fact that nutrient release by mineralization requires an appropriate quantity of SMS mulch. The monthly dynamics of soil nutrients are strongly affected by both the mineralization rate and plant uptake and utilization. In this experiment, higher contents of AK and AP were found in soil exposed to mulch treatment. Similar results were also reported in straw mulch by Xia [47] and Zhao [48]. The high AK content found in MT2 and MT3 may be due to the fact that K exists in SMS (plant tissue) in the free ionic form and is easily leached into the soil. However, the high content of AP in MT2 and MT3 may be related to the accumulation of P in the soil. The demand for P decreases in the nut maturity stage, while soil microorganisms accelerate the mineralization process and release a large amount of AP into the soil with mulch treatments. Microbial communities are closely associated with soil nutrients and strongly influence the soil quality.

Soil enzymes mainly come from the process of microbial metabolism and are closely related to the composition, abundance, and activity of soil microbial communities. Soil enzymes are also regulated by the demand for substrates as well as by the substrate availability [49]. Qu and Feng [50] found that straw mulching increased the activity levels of soil urease, invertase, and acid phosphatase. Similarly, this study showed that SMS mulch can effectively increase soil enzyme activities compared with soil not treated with mulch. The increase in soil enzyme activities following SMS mulching treatment might owing to the increased carbon sources and the improved soil quality. Soil enzymatic activity levels followed the order MT3 ≈ MT2 > MT1 > CK. Sufficient, but not excessive application of SMS was beneficial for the carbon source utilization of fast-growing microorganisms [51]. In this study, the use of a moderate mulching thickness may be a better way to improve soil enzymatic activity from a cost perspective.

4.2. Effect of Mulching on Weed Suppression

Weed control is one of the biggest challenges in the farming system [52]. As the growth of weeds depends on the availability of light and because light can only penetrate soil to a depth of up to a few centimeters, a certain thickness (>5 cm) of organic mulch is considered to effectively suppress weed germination through the exclusion of light or by acting as a physical barrier [53]. In our study, SMS mulching decreased light penetration and inhibited the germination of weed seeds in the early stage. At this stage, the weed control efficiency was as high as 79.01–97.90% for mulch treatment. With the arrival of the rainy season, alien weed seeds emerged easily from thin or damaged parts of the mulch layers, resulting in a weakened inhibition effect of mulching on weeds. The weed control efficiency decreased to 48.25–70.43%. This can largely be explained by the positive effect of soil moisture on weed emergence. In addition, SMS decomposition resulted in a decrease in soil cover during the growing season and may also have positively affected weed emergence [54]. With a continuous decrease in temperature, some annual weeds completed their life cycle, resulting in a significant decrease in weed biomass in October. Additionally, the weed control efficiency increased to 80.42–96.63% in the nut maturity stage.

Previous studies indicated that a certain amount of organic mulch is needed for weed suppression [17,18]. Thankamani et al. [18] suggested that the application of 6 $t \cdot ha^{-1}$ of paddy straw along with 7.5 $t \cdot ha^{-1}$ of green leaf mulch at 45 and 90 days after planting could led to a higher weed control efficiency and a greater yield, as well as economic return. Taak et al. [55] evaluated the effects of mulching and herbicide treatments on weed control and found that straw mulching treatment (15 $t \cdot ha^{-1}$) not only effectively controls weeds, but is also associated with the highest crop yield. Weed emergence and biomass decreased with increasing amounts of organic mulch [54]. The results of our study also support the conclusion that SMS with a thickness of more than 10 cm is associated with a better weed control efficiency.

4.3. Effect of Mulching on the Leaf Nutrient and Chlorophyll Contents

Leaf tissue is most commonly used for nutrient analysis because it is the one of the most active sites of plant metabolism. The leaf nutrient analysis provides an indication of plant nutritional status that can reflect plant health. It is necessary to determine whether or not a plant is well nourished, as having an adequate nutritional state is a determining factor in the productivity/yield of any plant [21]. In our study, all SMS mulch treatments effectively increased the leaf nutrient (N, P, and K) and chlorophyll contents, while the leaf N, P, K, and chlorophyll contents of MT2 and MT3 were significantly improved. In the short-term experiment of one year, the leaf nutrient content decreased twice. The first decrease occurred in June when the nutrients of newborn leaves were easily leached out by rainfall with the arrival of the rainy season. The second decline occurred from September to October when the leaf N, P, and K contents began to be transferred to other vigorous organs (such as fruit), and the leaves entered the senescence stage. The chlorophyll content of leaves showed a trend involving an initial increase, following by a decrease. With leaf senescence, the chlorophyll content also reduced. Although studies about the effect of organic mulching on leaf nutrients are still insufficient, some existing literature supports the idea that organic mulching can improve the leaf nutrient level. Pal and Mahajan [46] found a significantly higher leaf K content in *Stevia rebaudiana* Bertoni following the application of pine-needle mulching at a level of 15 $t{\cdot}ha^{-1}$ compared with other treatments. Namaghi et al. [56] also found higher levels of P and Mg in barley-straw-mulched pistachio leaves. Kader et al. [37] reported that straw mulching significantly improved the leaf chlorophyll content of soybean compared with bare soil. The higher leaf nutrient and chlorophyll contents may have been due to the suitable soil microclimate created by organic mulching, which promoted root growth, and thus increased the absorption of soil nutrients [37]. In addition, the nutrients of organic matter were gradually released into the soil after organic mulching and significantly increased the available soil nutrients [56].

4.4. Effect of Mulching on Fruit Yield and Quality

Although previous studies have reported the effect of organic mulching on the fruit yield and quality, there has been no consistent conclusion in this regard owing to differences in mulching materials, mulching practices, climatic conditions, research objects, and so on. Some studies have shown that organic mulching can markedly increase the fruit yield with no significant effect on fruit quality [57]. Some studies have observed that organic mulching has a significant positive effect on both fruit yield and quality. Ye et al. [58] showed that mulching significantly increased the yield and quality of *Camellia oleifera*, which was consistent with previous results for apple trees [59], peach trees [57], jujube trees [60], and pistachio trees [56]. The present study suggests that all mulch treatments were associated with an increasing trend in nut yield and quality compared with the non-mulching treatment. All mulch treatments were associated with the production of nuts with significantly higher geometric mean diameters and volumes than those produced with CK. A higher variability in growth of individual fruits is mainly due to the fruit-to-fruit competition for nutrients and resources [61]. SMS mulch increased the availability of soil nutrients; therefore, the nuts produced in plots treated with mulch were larger. The larger nut size correspondingly increased the nut mass and kernel mass. These two important parameters of nuts were significantly improved under mulch treatments. The nut sphericity and nut shape index were significantly lower in MT3 than in MT1, which may be due to the rapid growth in the longitudinal diameter when the nutrient supply was relatively sufficient. Variations in fruit size and shape under different mulch treatments were also reported by Ye et al. [58]. Although our research revealed that short-term SMS mulching had no obvious advantage in terms of increasing the individual plant yield, *CPC*, or *SSC*, MT2 did effectively increase the *CFC* of nuts. The non-significant increase in nut yield may have been due to the following factors: (1) organic mulch could improve soil hydro-thermal regimes [62]; (2) organic mulch could increase the soil nutrient content by organic matter decomposition; (3) organic mulch could prevent excessive weed growth; and (4) organic mulch could improve the nutrient status and photosynthetic capacity of leaves [56]. Variations in the *CPC*, *SSC*, and *CFC* of nuts among mulch treatments indicated that the formation of fruit quality is a complex physiological and biochemical process. This process is closely related to the transport, allocation, conversion, and metabolism of carbohydrates, which is strongly influenced not only by biological factors, but also by environmental factors [63]. The soil moisture status is often considered to be a critical factor affecting oil synthesis. When a water deficit occurs, it will lead to a decrease in the crude fat content of fruit [64].

5. Conclusions

SMS mulching was found to influence soil fertility, weed control, leaf quality, and nut traits. The effects varied depending on the mulching thickness used. Although SMS mulching had no significant effect on soil structure in the short-term experiment, it significantly improved the topsoil nutrient availability. SMS mulching also decreased the number of weed species and weed biomass obviously. Short-term SMS mulching had no obvious advantages in terms of increasing the individual plant yield, *CPC*, or *SSC*, but it increased the nut size, nut and kernel mass, as well as *CFC* to a certain extent. The results showed that SMS with a 10 cm thickness could be used for mulching practices.

While SMS mulching is known to improve soil fertility and nut quality in the short term, its long-term effects require further research. In particular, more research is needed to understand the effects of SMS mulching on photosynthetic efficiency and water consumption, which are fundamental factors in the shaping of the characteristics of nuts over an extended period of time.

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