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Rice Straw Mulch Installation in a Vineyard Improves Weed Control and Modifies Soil Characteristics

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Abstract: After harvesting rice paddy fields, rice straw is a significant problem due to uncontrolled CO_2 emissions when the straw is burned. One solution to this problem is to use this rice by-product for mulching planting lines of fruit trees or vineyards with the purpose of controlling weeds and improving soil characteristics. A 3-year experiment was conducted at the Polytechnic University of Valencia (Spain) demonstration vineyard, where rice-straw mulch was installed at three rates in 2021, 24.0, 43.1, and 63.1 t ha^{-1}, and in 2022, 25.0, 37.5, and 50.0 t ha^{-1}. Weeds were mainly controlled with the highest treatment rate (50.0–63.1 t ha^{-1}), as the time of the year for mulch installation is decisive for achieving different weed control rates. On average, mulch decreased soil bulk density (5.4%), and increased the soil organic carbon (24.3%) and water-soluble organic carbon (24.3%) compared to bare soil. Soil temperature changes were observed due to the mulch treatment, with soil temperature lower in bare soil than in mulched soil during the cold season, and higher during the warm season. This effect was highly dependent on the mulch application rate. Soil moisture content was also higher under the mulch treatment, showing a mulch-rate response during the four seasons of the year. The changes in the physical and biological soil properties induced a higher soil respiration rate when mulched soil was compared to bare soil. This study concludes that the use of rice straw as a mulch had positive effects on weed control and soil properties, although three factors concerning mulch management were paramount: rate, the timing of installation, and replacement rate.

Keywords: soil organic matter; soil moisture; soil temperature; soil respiration; agriculture by-products; weed management

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1. Introduction

Spain has the largest surface area dedicated to grapevines in the world. Around 1 million ha of grapes are cultivated in the rain-fed semi-arid plain in the central plateau region of Spain. Due to the limited water availability, soil properties like organic matter or moisture content are important, and its improvement is recommended. Cover crops are a relatively inexpensive method of augmenting carbon and organic matter content in the soil, which increases soil biological activity and water-holding capacity [1]. Mulching has been an important agricultural practice for long time [2], and many materials have been used including living plants, plastic films, and other agricultural by-products, such as straw. An important advantage of dead mulches over living ones is the potential of living mulches to compete with the crop [3]. Non-living mulches do not compete with the crop and can minimize weed competition. Several authors have reported the effect of straw mulches providing some measure of weed control in different crop systems, such as winter cereals [4], maize [5], watermelon and potato [6], and fruit-tree orchards [7]. Rice straw mulching has a significant effect on weed suppression in crops like no-till wheat [8], groundnut [9], tomato [10], mandarin [11], or direct seeded rice [12]. Rice straw is the major by-product in the environmentally rich flooded rice area (15,000 ha) of the Natural Park of the Albufera of Valencia (Spain). After harvesting, rice straw is traditionally burned to reduce aboveground weed seeds and the presence of other pathogens [13], but this practice is prohibited due to uncontrolled CO_2 emissions. Alternatives to burning are under research, and using the straw as a mulch in the surrounding fruit-tree or vineyard orchards could be one of the solutions. Mulch can help in conserving soil moisture and hence increase water use efficiency, moderate soil temperature, and improve the physical, chemical, and biological properties of soil [14]. In addition, mulch can protect the soil against erosive processes, preventing crust formation, improving soil aggregate stability [15] and reducing soil cracking and soil penetration resistance [16]. Finally, mulch can also modify microbial populations and their activity, influencing the dynamics of carbon and other nutrients in the soil [17–19].

We hypothesize that the use of rice straw as a mulch in the vineyard lines can prevent weed emergence and improve important soil characteristics. Therefore, the objective of this research was to determine the dose–response effect of a rice straw mulch installation in a vineyard for weed control and its influence on soil properties such as bulk density (BD), temperature, volumetric water content (VWC), organic carbon (SOC), water-soluble organic carbon (WSOC), and respiration rate.

2. Materials and Methods

2.1. Experimental Site

This research was conducted in a demonstration vineyard (*Vitis vinifera* L., 4 m × 1.5 m spacing) from November 2019 to July 2023. Most of the data were collected during the last 2 years (May 2021 to July 2023). The vineyard is located at the Polytechnic University of Valencia (UPV) experimental farm (39°29′3″ N, 0°20′11″ W; 5 m asl), in Valencia, eastern Spain (Figure 1).

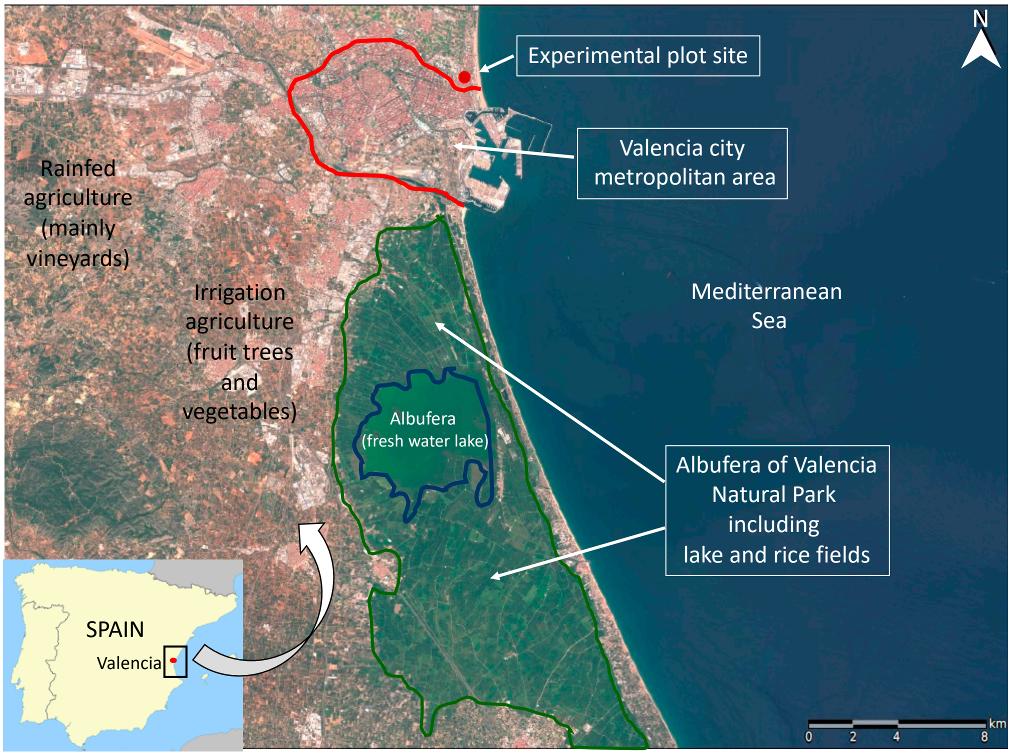

Figure 1. Experimental plot location with respect to the rice cropping area in the Albufera of Valencia Natural Park (Image source: Institut Cartogràfic Valencià. Modified by the authors).

The average annual temperature is 18.3 °C, and the annual precipitation is 475 mm (1981–2010 period), although during the experimental period, the average temperature was slightly higher (19.4 °C), and the cumulated rainfall was lower (736 mm for the

27 months). The soil in the experimental area was an alluvial soil (Calcaric Fluvisol, according to the World Reference Base [20]). At the beginning of the experiment, a soil analysis was performed in a surface composite sample (0–20 cm). The soil is sandy loam (76.7% sand, 13.3% silt, and 10.0% clay), not stony (3% of coarse elements), alkaline (pH 8.52, 1:2.5 soil/water suspension), non-saline (EC 0.167 dS m^{-1}, 1:5 soil/water suspension), low in organic matter (24.9 g kg^{-1}), and had a medium content of carbonates (29.6% $CaCO_3$).

2.2. Treatments and Determinations

In each of three plantation lines, four subplots were considered, each 4.5 m in length and 1 m in width, and included three vine stocks. On 27 November 2019, after removing all weeds, four different amounts of rice straw were distributed over the subplots, T0 (0 t ha^{-1}), T1 (24.0 t ha^{-1}), T2 (43.1 t ha^{-1}), and T3 (63.1 t ha^{-1}), and randomly replicated on the other two adjacent lines. The same procedure was repeated 2 more times on the same subplots on 13 May 2021 with the same straw rates and on 4 October 2022 with similar straw rates: T0 (0 t ha^{-1}), T1 (25.0 t ha^{-1}), T2 (37.5 t ha^{-1}), and T3 (50.0 t ha^{-1}). Mulch height ranged between 10 and 20 cm at the installation time depending on the mulch rate, although that difference decreased over the time. After the second and third mulch application the following determinations were conducted in each subplot: (i) total and specific weed coverage (%) visually determined in a 1–3 month frequency basis depending on the season; (ii) total fresh and dry weed biomass after 12 and 10 months following the straw application in 2021 and 2022, respectively; (iii) weekly soil respiration using an EGM-4 environmental gas monitor device (PP System Company, Amesbury, MA, USA); (iv) weekly soil VWC and soil temperature at 7 cm depth using a WET-2 sensor (HH2 Moisture Meter; Delta-T Devices, Burwell, UK); and (v) BD, SOC, and WSOC which were determined 5 times throughout the experiment in a 4–8 month frequency interval. These last three determinations (BD, SOC, and WSOC) were performed by collecting undisturbed soil from the upper layer (0–12 cm) in each subplot, using a cylindrical auger (5.35 cm diameter and 12.77 cm high). Soil samples were air-dried and sieved through a 2 mm mesh. The BD was determined using a gravimetric method with the ratio of the mass of soil dried at 105 °C to the soil sample volume. The SOC was determined after sieving through a 0.5 mm mesh by wet oxidation with 1 N potassium dichromate in acidic medium and evaluating the excess of dichromate with 0.5 N ferrous ammonium sulfate, as described by Walkley and Black [21]. The WSOC was determined in the 1:2.5 aqueous soil extract obtained after 30 min of mechanical shaking and centrifugation at 2500 rpm for 5 min. The WSOC in the extract was determined by 0.033M $K_2Cr_2O_7$ oxidation in concentrated 13.4 M H_2SO_4 [22]. Measurements of respiration, temperature, and soil moisture were always taken at the same time interval within a day (8:00 am to 10:00 am). A total of 93 measurements were taken between 13 May 2021 and 24 July 2023, of which 26 were taken in summer, 23 in fall, 21 in winter and 23 in spring.

2.3. Experimental Design and Statistical Analysis

The experimental design was a randomized complete block design with one factor at four levels (rice-straw rate) with three replicates. The statistical analysis was carried out with the statistical software Statgraphics Centurion XIX version 18.1.13 (StatPoint Technologies, Warrenton, VA, USA), and Fisher's protected least significant difference (LSD) test was used (p = 0.05) to identify significant differences when using the one-way ANOVA procedure. Multiple regression analyses were used to assess the relative importance of the soil properties over soil respiration in the different treatments, using the stepwise procedure (p = 0.05).

3. Results

3.1. Influence on Weed Control

Weed coverage on the vineyard experimental plot before the second mulch application (13 May 2021) was 81.3% with no differences among different treatments (Table 1). The weed species present were *Bromus madritensis* L. (around 40%), *Malva parviflora* L. (around 40%), and some isolated specimens of *Sonchus oleraceous* L., *Sonchus tenerrimus* L., and *Urtica urens* L. On 13 May 2021, all weeds were removed, and the rice straw mulch was installed at four different rates (0, 24.0, 43.1, and 63.1 t ha^{-1}). During the following two months climate conditions were appropriate for weed growing (average temperature of 23.5 °C and 37 mm of precipitation). The first weed coverage difference among treatments was detected on 22 July. The T0 subplots had 21.7% weed coverage, while the mulched subplots (T1, T2, and T3) averaged a weed coverage of 1.6%. From the 22 July until the end of winter 2022, differences in weed coverage were greater between the T0 treatment (88.3 to 98.3% of weed coverage during this period) and mulched ones (0.1 to 33.3% of weed coverage), but no differences were detected among mulched treatments. As temperatures began to increase at the end of winter 2022, weed coverage in the T1 treatment increased to 61.7% on 19 May 2022, one year after mulch installation, while the T2 and T3 treatment weed coverage remained around 25%. However, no significant differences were detected.

Table 1. Weed coverage (%) during the experiment. T0, 0 t ha^{-1}); T1, 24.0 and 25.0 t ha^{-1} in 2021 and 2022; T2, 43.1 and 37.5 t ha^{-1} in 2021 and 2022; T3, 63.1 and 50.0 ha^{-1} in 2021 and 2022; LSD, least significant differences. The same letters on each evaluation date indicate non-significant differences according to Fisher's protected least significant difference test ($p < 0.05$) to identify significant differences among means for treatment effect.

Date	Weed Coverage (%)				LSD	*p*-Value
	T0	T1	T2	T3		
19 April 2021	86.7	90.0	80.0	68.3	25.34	0.3271
13 May 2021	Mulch application				–	–
22 July 2021	21.7 a	4.0 b	0.7 b	0.1 b	5.75	0.0001
20 September 2021	95.0 a	10.0 b	5.1 b	0.4 b	13.25	0.0000
9 November 2021	98.3 a	33.3 b	21.7 b	15.7 b	33.90	0.0017
15 December 2021	93.3 a	14.0 b	10.0 b	9.0 b	19.05	0.0000
13 January 2022	88.3 a	10.7 b	6.9 b	1.7 b	22.59	0.0001
4 March 2022	93.3 a	26.7 b	14.0 b	5.7 b	21.39	0.0000
19 May 2022	96.7 a	61.7 ab	26.7 b	23.3 b	49.22	0.0277
31 May 2022	Weed harvesting				–	–
26 July 2022	8.3	5.3	3.7	2.0	6.29	0.1995
3 October 2022	21.7	12.3	9.3	9.0	16.95	0.3407
4 October 2022	Mulch application				–	–
27 December 2022	88.3 a	61.7 b	38.3 c	10.0 d	21.57	0.0002
24 March 2023	86.7 a	80.0 ab	61.7 b	33.3 c	22.57	0.0026
26 April 2023	80.0 a	66.7 a	46.7 ab	25.0 b	37.26	0.0413
25 July 2023	78.3 a	61.7 a	60.0 a	16.7 b	33.94	0.0161
25 July 2023	Weed harvesting				–	–

On 31 May 2021, weeds were removed again and weighed for the first time (Figure 2), with similar results obtained as when weed coverage was determined 2 weeks before, that is, one year after mulch installation. T2 and T3 treatments reduced the weed biomass by 75.5 and 72.1%, respectively, in comparison to T0 subplots.

On 4 October 2022, rice straw mulch was applied again on the same subplots at a very similar rate (0, 25.0, 37.5, and 50.0 t ha^{-1}) to the previous application. The first sampling date was 3 months later, and in this case, all treatments induced different weed coverages. T1 and T2 treatments did not result in an acceptable weed control rate, 30.2 and 56.6%, respectively, in comparison with T0 subplots, while the T3 treatment weed control was 88.7% (Table 1). At this time, T0 subplots had an 88.3% of weed coverage (mainly *B. madritensis* and *Diplotaxis erucoides* L.). On the following sampling dates (24 March, 26 April, and 25 July 2023), T1 and T2 treatments were losing effectiveness, while the T3 treatment maintained an efficacy level of 61.5, 68.8, and 78.7% for weed control on those 3 dates, respectively. Weeds were removed and weighed again on 25 July, and the results are shown in Figure 2, confirming the previous weed coverage visual estimation. Only the T3 treatment, controlled weeds (74.1%) in comparison to T0 subplots, with only *Cyperus rotundus* L. specimens passing through the rice straw mulch. This is because *C. rotundus*, unlike annual weeds, presents a very vigorous emergency as it sprouts from a tuber with large carbohydrates and nutrient reserves, thus, not even a dense straw mulch can prevent it from growing. In fact, *C. rotundus* is capable of piercing even plastic films [23].

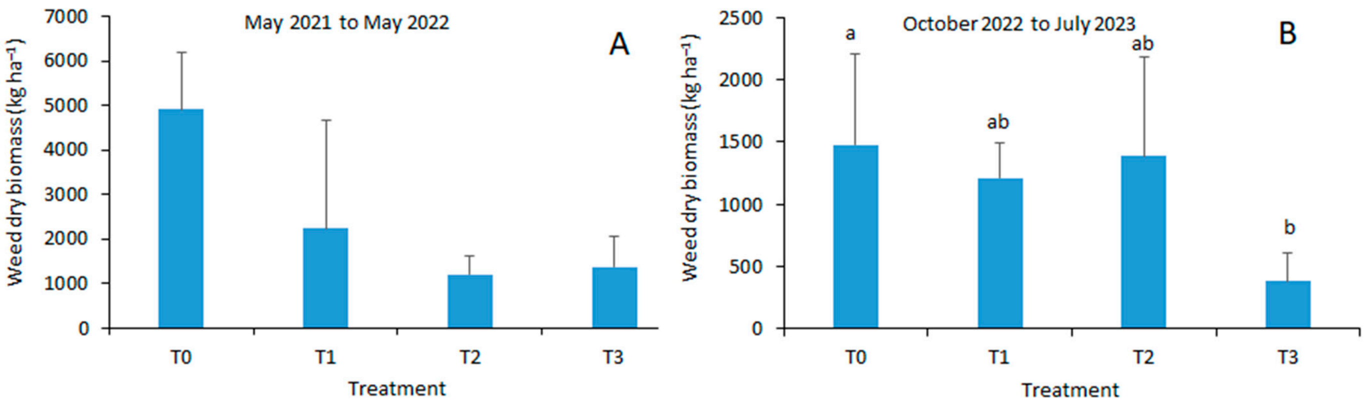

Figure 2. Total dry weed biomass after the first experimental year (**A**) and second year (**B**). T0, 0 t ha^{-1}; T1, 24.0 and 25.0 t ha^{-1} in 2021 and 2022; T2, 43.1 and 37.5 t ha^{-1} in 2021 and 2022; T3, 63.1 and 50.0 ha^{-1} in 2021 and 2022. Same letters above bars indicate non-significant differences according to Fisher's protected least significant difference test ($p < 0.05$) to identify significant differences among means for treatment effect.

3.2. Influence on Physical Soil Properties

To study the influence of rice straw mulch on physical properties, bulk density, soil temperature, and soil moisture were measured in the different treatments. BD values throughout the experiment ranged from 1.204 to 1.389 g cm^{-3}. The average of the five soil samplings performed over time was lower under mulch than under bare soil (T0), regardless of the straw rate (Table 2), although there was no difference among mulched treatments. The percentages of reduction in BD with respect to the bare soil were 5.2%, 4.4%, and 6.7% for the T1, T2, and T3 treatment, respectively.

Table 2. Mean values (±standard deviation) of bulk density (BD), soil organic carbon (SOC), water-soluble organic carbon (WSOC), and ratio of water-soluble organic carbon to soil organic carbon throughout the experiment (n = 15). Same letters within columns indicate non-significant differences according to Fisher's protected least significant difference test ($p < 0.05$) to identify significant differences among means for treatment effect.

Treatment	BD (g cm^{-3})	SOC (g C kg^{-1})	WSOC (g C kg^{-1})	WSOC/SOC (%)
T0	1.36 ± 0.04 a	10.15 ± 0.97 a	0.119 ± 0.045 a	1.19 ± 0.48
T1	1.29 ± 0.08 b	11.87 ± 1.99 b	0.143 ± 0.044 ab	1.22 ± 0.38
T2	1.30 ± 0.09 b	12.62 ± 1.84 bc	0.160 ± 0.048 bc	1.29 ± 0.42
T3	1.27 ± 0.08 b	13.39 ± 2.87 c	0.188 ± 0.062 c	1.45 ± 0.60
p-value	0.0101	0.0004	0.0037	0.4373

Soil temperature measurements (0–7 cm) were also different when comparing bare to mulched subplots, with a difference that ranged between −4.63 °C and 4.95 °C depending on the season of the year. The variation in soil temperature throughout the year in the different treatments (Figure 3) shows how mulch moderates temperature extremes compared to the bare ground plots, as this effect is more pronounced when the mulch rate is increased. This is more evident during the first and last summer (2021 and 2023) since in the summer of 2022, the straw degradation together with a slight weed coverage in T0 minimized the mulch effect on the soil temperature, causing no differences among treatments.

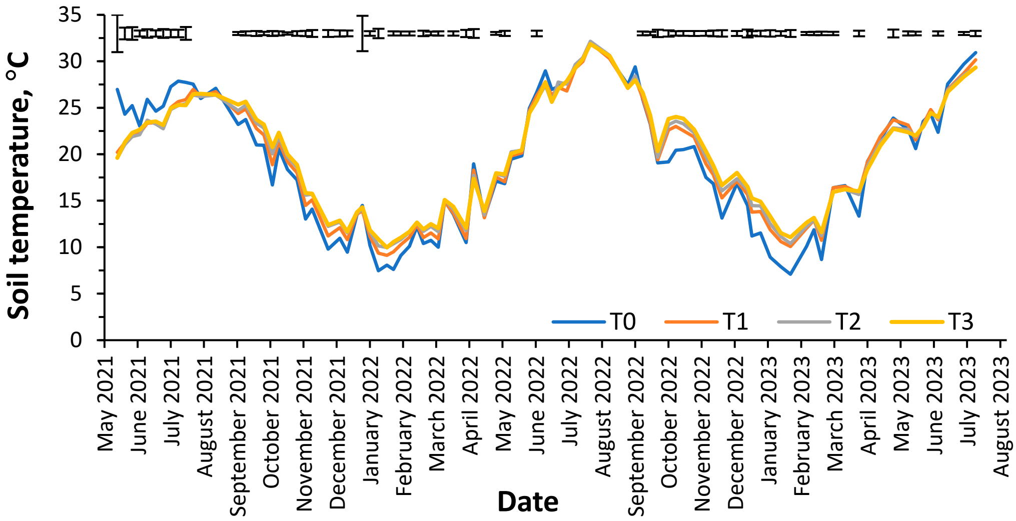

Figure 3. Soil temperature (0–7 cm) during the experiment. Legend: T0, 0 t ha^{-1}; T1, 24.0 and 25.0 t ha^{-1} in 2021 and 2022; T2, 43.1 and 37.5 t ha^{-1} in 2021 and 2022; T3, 63.1 and 50.0 ha^{-1} in 2021 and 2022. Vertical bars represent the least significant differences (p = 0.05) for comparing means (n = 3).

The average season soil temperature (Table 3) showed differences among treatments in autumn and winter. Soil temperature differences in autumn between bare soil and the T1, T2, and T3 treatments were 1.36, 1.86, and 2.19 °C, respectively, although there were only significant differences between the T2 and T3 rates, and the bare soil. In winter, a significant difference was only observed between the highest straw rate (T3) and the bare soil (2.20 °C). The average soil temperature during spring and summer did not show any differences among treatments, although in both situations, soil temperature was numerically lower in mulched treatments than in bare soil.

Table 3. Average seasonal values of soil temperature (°C) and soil volumetric water content (%) (n = 78 for summer; n = 69 for autumn and spring, n = 63 for winter). Same letters within columns indicate non-significant differences according to Fisher's protected least significant difference test (p < 0.05) to identify significant differences among means for treatment effect.

Treatment	Soil Temperature (°C)				Volumetric Water Content (%)			
	Summer	Autumn	Winter	Spring	Summer	Autumn	Winter	Spring
T0	27.2	19.7 a	10.6 a	17.6	4.5 a	7.9 a	6.7 a	10.1 a
T1	26.5	20.8 ab	12.0 b	17.4	6.8 b	11.3 b	10.4 b	12.5 a
T2	26.4	21.4 b	12.5 bc	17.4	8.7 c	14.6 c	14.3 c	16.7 b
T3	26.4	21.8 b	12.8 c	17.5	9.9 c	17.1 d	16.5 d	18.4 b
p-value	0.149	0.026	0.000	0.994	0.000	0.000	0.000	0.000

Mulch installation affected the soil moisture content (0–7 cm) as well. Figure 4 shows differences among treatments throughout the whole experimental period except for summer 2022, again coinciding with the straw degradation as it was placed one year ago. A straw-rate response effect was also observed considering the whole experimental period; the T0 (bare soil) treatment averaged a VWC of 7.2% that increased with the straw rate by 10.1, 13.4, and 15.3% for T1, T2, and T3, respectively.

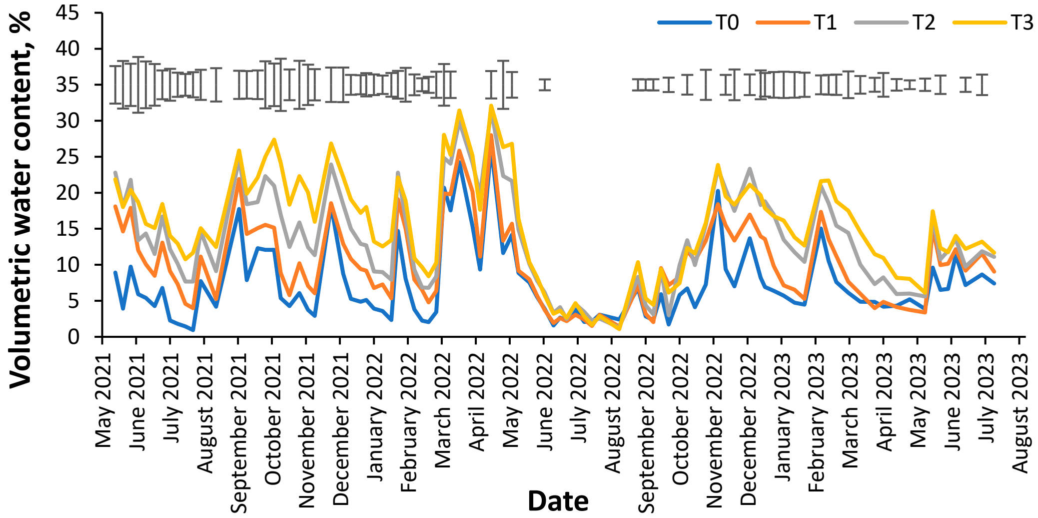

Figure 4. Volumetric water content (0–7 cm) from 2021 to 2023 in Valencia, Spain. Legend: T0, 0 t ha^{-1}; T1, 24.0 and 25.0 t ha^{-1} in 2021 and 2022; T2, (43.1 and 37.5 t ha^{-1} in 2021 and 2022; T3, 63.1 and 50.0 ha^{-1} in 2021 and 2022. Vertical bars represent the least significant differences (p = 0.05) for comparing means (n = 3).

Changes in soil moisture were related to precipitation and evapotranspiration, as there was no irrigation system in the field. Both meteorological factors are highly variable in the Mediterranean area, and in order to elucidate the effect of mulch and its application rate on the soil VWC, a comparison for each climatic season is shown in Table 3. There were differences among treatments in soil VWC in summer, autumn and winter according to the following pattern: T3 > T2 > T1 > T0. In spring, there were just differences between the highest straw-rate treatments (T2 and T3) and the lowest ones (T0 and T1). Taking into account only the T0 and T3 treatments, there was a soil VWC increase of 120% in summer, 116% in autumn, 146% in winter, and 82% in spring for T3 in relation to T0.

3.3. Influence on Biological Soil Properties

Soil monitoring throughout the experiment shows variations in SOC associated with the application of rice straw mulch. The SOC ranged from 8.76 to 12.11 g C kg^{-1} for the T0 treatment, 8.39 to 14.72 g C kg^{-1} for T1, 9.60 to 15.61 g C kg^{-1} for T2, and 10.39 to 19.04 g C kg^{-1} for T3. However, as the SOC is a soil property that changes slowly over time, data from the five sampling dates were averaged and are shown in Table 2. It can be observed how the rice straw mulch application increases the SOC and that the increase is also dependent on the mulch rate. Bare soil averaged an SOC of 10.15 g C kg^{-1}, while the mulched plots averaged 11.77, 12.62, and 13.39 g C kg^{-1} for T1, T2, and T3, respectively. This represents an increase in SOC of 17, 24 and 32% compared to bare soil.

When analyzing the water-soluble fraction of organic carbon of the soil (WSOC), differences among treatments only appeared after the second mulch application. The biggest differences were observed at the end of the experiment when the T0 treatment averaged 0.078 g C kg^{-1}, T1 averaged 0.109 g C kg^{-1}, T2 averaged 0.143 g C kg^{-1}, and the T3 treatment averaged 0.207 g C kg^{-1}. The WSOC has a high temporal variability, as it is dependent on soil VWC and leaching during the previous days of sampling dates, therefore data from the five sampling dates were averaged over the time (Table 2). Those treatments with the highest straw rates (T2 and T3) averaged a higher WSOC (0.160 and 0.188 g C kg^{-1}, respectively) than the T0 treatment (0.119 g C kg^{-1}). It represents a 35 and 58% increase in WSOC from the T0 treatment. The observed OM and WSOC changes during the experiment caused variations in the WSOC/SOC rate. The average of the five sampling dates of the aforementioned ratio increased with the mulch rate increment, although no significant differences were observed (Table 2).

The soil respiration rate was influenced by the presence of straw, with marked differences among treatments following mulch installation, from May to November 2021 and from October 2022 to February 2023 (Figure 5). In these periods soil respiration was higher in the T3 treatment and decreased as the mulch rate was lower. During the period of March to September (2021), the aforementioned differences were smaller and non-statistically significant, coinciding with the fact that there were also no differences in soil temperature and VWC.

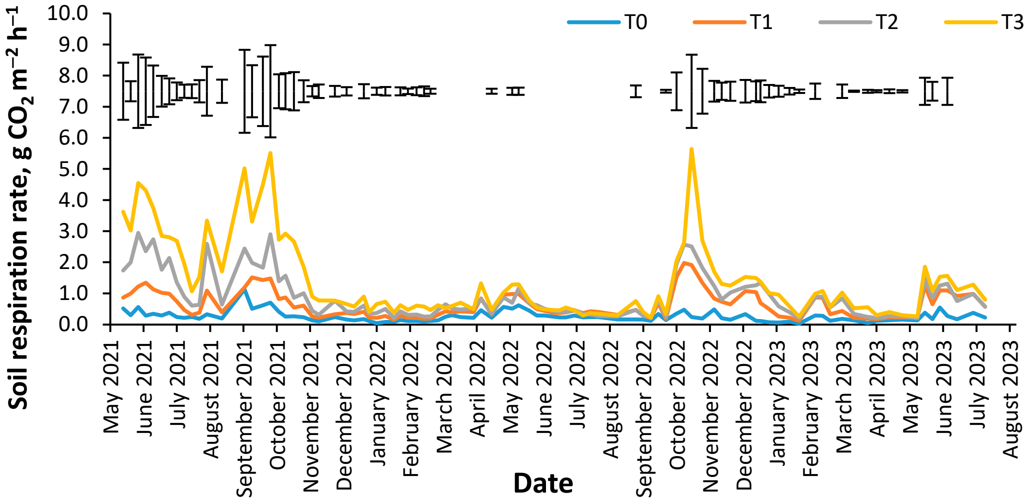

Figure 5. Soil respiration rate (g CO_2 m^{-2} h^{-1}) evolution during the experiment. Legend: T0, 0 t ha^{-1}; T1, 24.0 and 25.0 t ha^{-1} in 2021 and 2022; T2, 43.1 and 37.5 t ha^{-1} in 2021 and 2022; T3, 63.1 and 50.0 ha^{-1} in 2021 and 2022. Vertical bars represent the least significant differences (p = 0.05) for comparing means (n = 3).

A multiple regression analysis considering all measurements was performed to evaluate the influence of temperature and VWC on the soil respiration rate. The fitted model explains 32% of the variability of the respiration rate (Table 4). This analysis shows a higher incidence of soil temperature and VWC over the respiration rate for the extreme treatments, with an r^2 of 0.352 and 0.334 for T0 and T3, respectively. The inclusion of the other variables in the regression analysis (for those dates when this information is available) improved the model (r^2 = 0.632, SR = −0.48 + 0.50 × logT + 0.03 × Straw rate − 0.07 × SOC), which highlights the fact that the mulch and its rate, and soil organic carbon, have a significant influence on the soil respiration rate.

Table 4. Summary of the regression analyses carried out to investigate the influence of soil temperature (T) and soil moisture (VWC) on soil respiration (SR).

Treatment	Model	R-Squared	F Ratio	df *	*p*-Value
T0	SR = −0.48 + 0.02 × VWC + 0.21 × logT	0.3524	75.11	278	0.000
T1	SR = −1.68 + 0.04 × VWC + 0.66 × logT	0.2917	56.84	278	0.000
T2	SR = −3.16 + 0.06 × VWC + 1.14 × logT	0.3011	59.45	278	0.000
T3	SR = −7.33 + 0.11 × VWC + 2.41 × logT	0.3343	69.32	278	0.000
All treatments	SR = −3.05 + 0.07 × VWC + 1.04 × logT	0.3164	257.65	1115	0.000

* df: Degrees of freedom.

Given the importance of the soil temperature dependency on soil respiration rate, and to a lesser extent the soil VWC, the effect of the rice straw treatment was evaluated for each climatic season of the year (Figure 6). The average seasonal soil respiration shows differences among treatments with the same sequence (T3 > T2 > T1 > T0) in all climatic seasons except in spring, when no differences in soil respiration rate were observed in the intermediate treatments (T1 and T2). The highest soil respiration rates were obtained in autumn, with average values ranging from 0.33 to 2.21 g CO_2 g^{-1} h^{-1} and the lowest in winter ranging from 0.13 and 0.78 g CO_2 g^{-1} h^{-1}.

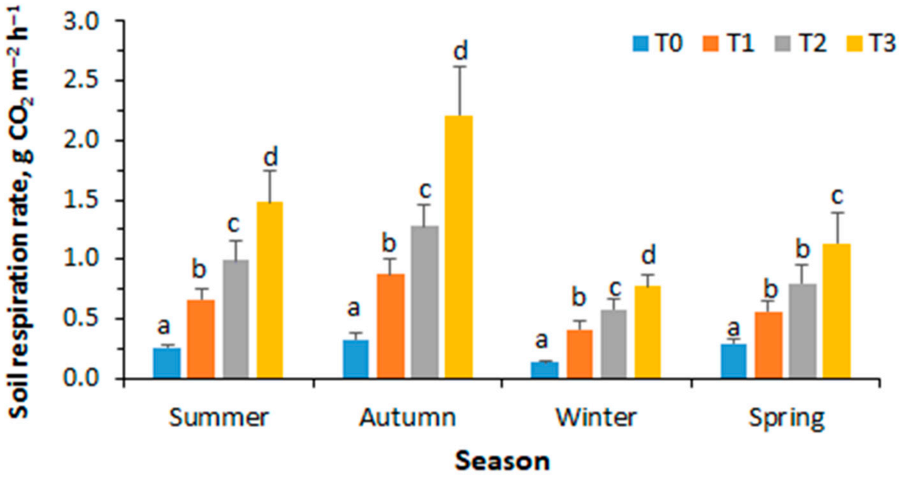

Figure 6. Seasonal values of soil respiration rate (g CO_2 m^{-2} h^{-1}). Legend: T0, 0 t ha^{-1}; T1, 24.0 and 25.0 t ha^{-1} in 2021 and 2022; T2, 43.1 and 37.5 t ha^{-1} in 2021 and 2022 T3, 63.1 and 50.0 ha^{-1} in 2021 and 2022. Same letters over bars indicate non-significant differences according to Fisher's protected least significant difference test ($p < 0.05$) to identify significant differences among means for treatment effect ($n = 78$ for summer; $n = 69$ for autumn and spring; $n = 63$ for winter).

4. Discussion

In this study, rice straw reduced the occurrence of weeds and improved soil properties. The big success in weed control of the straw mulch during the first year of the experimental period was probably due to the fact that weed removal plus mulch installation was performed on a key date (13 May), when summer weeds had already emerged. On the contrary, the third mulch installation was performed in early October, at a time of the year with low weed pressure, and when next spring arrived, the mulch coverage over the plot was not satisfactory after 7 months from installation. Johnson et al. [6], also reported that mulch application management was important for controlling weeds, they obtained better results when mulching just at potato and melon planting time rather than 4 weeks later. They also achieved good weed control results by applying 10 to 16 t ha^{-1} of chopped wheat straw, smaller rates than the ones used in this study, but again, the straw was previously chopped and an additional 1 t ha^{-1} of straw was added 1 month after the first application to compensate for the straw's decomposition over time, which indicated that the straw management matters. The straw installation rate is paramount as demonstrated in this research, but Devasinghe et al. [12] reported good weed control when using just 4 t ha^{-1} of rice straw mulch, about one-fifth of our lowest mulching rate. In this study, the high straw dose treatments (T2 and T3) effectively reduced in the first year the weed coverage and biomass, contrasting with the second experimental period where only the highest mulch rate (T3) was effective in weed control.

Mulching in the vineyard also had a positive impact on soil properties. All mulch rates reduced BD an increased SOC, as the increment was proportional to the applied mulch rate. The rice straw mulch acts as a natural cover to protect the soil surface against solar radiation and the erosive impacts of raindrops, protecting the soil surface from compaction and reducing the dispersion of soil aggregates. In this research, a BD decrease in all mulched treatments has been observed, which could be related to the observed SOC increase, but also to an increase in soil aggregation. Although there are bibliographical discrepancies on the mulching effect over the soil BD due to the different soil texture classes, types of mulch, and mulch management [24,25], most of the research reported a decrease in BD. Mulumba et al. [24] reported a second-order polynomial relation to describe the BD variation with the straw rate, and they just observed a BD decrease when using high mulching rates

(15 t ha^{-1}). After three years of rice straw mulching, Ram et al. [26] observed a BD decrease with BD ranging from 2.7 to 7.3% depending on the rate. The last-mentioned authors also found an increase in SOC between 5 and 28% in the first soil layer (0–15 cm) depending on the straw application rate (2–6 t ha^{-1}). In our case, the observed SOC increase compared to the bare soil ranged between 17 and 32% when using 25 to 57 t ha^{-1} of mulch, and in addition, an increase in the WSOC was also observed. The observed BD decrease could also be explained by an increase in soil aggregation under mulch treatments. One year after the second mulch implantation there was an increase in the soil aggregation percentage as the mulch rate increased [27]. This could be attributed to a greater microbial activity, which could be corroborated the obtained respiration measurements. In our trial, the observed higher respiration rate found in the mulched treatments compared to bare soil, would indicate that greater microbial activity reported by Hadas et al. [28].

Since mulch was installed, the observed differences in soil properties among treatments decreased as time progressed, one year after the second mulch installation such differences were minimal due to the straw degradation. This would indicate that the straw decreases soil compaction by providing physical protection against the impact of rain and the wind. This effect was evident in the BD measurement, but also during the evaluation of the soil temperature and VWC, with no differences among treatments being observed one year after the second mulch application.

The soil temperature and VWC variation pattern throughout the experiment was similar to that found in similar research using straw as a mulch, which modifies the energy balance at the soil surface by intercepting part of the solar radiation and hindering the emission of long-wave radiation by the soil. As a result, the temperature of mulched soil is cooler than bare soil during the day and warmer at night [29]. In this work, soil temperature was only measured at a fixed time of the day, so it was not possible to evaluate the daily variation, but the seasonal or annual variation could be evaluated. In summer, the soil under mulch was cooler than the bare soil, and in winter, the opposite occurred; this pattern was more pronounced at higher straw rates. Since soil temperature has an important influence on numerous physical, chemical, and biological processes in the soil, the observed changes could affect water storage, microbial activity, and nutrient availability, which have an important impact on crop growth and development. The observed increase in soil VWC under the mulch treatment could be due to an evaporation rate reduction. Ramakrishna et al. [9] found VWC differences ranging from 10%, a few days after rainfall, to 22% in periods without rainfall. In our case, the variations were greater, although the used mulch rates were also higher. The aforementioned increase in soil VWC from mulch treatments could also be due to an improvement in the water retention capacity, which could be explained by an increase in porosity (low BD) and soil aggregation (high SOC). This would result in a greater water availability for cultivation and crop yield improvement [30].

These changes in the soil temperature and VWC together with the observed changes in BD and SOC could explain the observed differences in the respiration rate between mulched subplots and bare soil. However, our multiple regression model indicates that soil temperature, mulch rate and soil organic carbon were the major factors affecting the soil respiration rate. The high respiration rate values observed in the highest straw mulching could be conditioned by a low gaseous diffusion through the dense layer of mulch, an aspect to be investigated in future works.

5. Conclusions

In summary, rice straw mulch can minimize most weed emergence and improve soil physical and biological properties. These agronomic improvements directly impact water availability, microbiological activity, and soil temperature, decrease the use of herbicides, and promote recycling a rice waste by-product. Future research is warranted to determine three important factors concerning mulch management: (i) mulch rate, which should be at least around 40 t ha^{-1}; (ii) the time of the year for mulch installation, which should be in mid-Spring; and (iii) the mulch replacement rate, which should be around 7–9 months.

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