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Article

Mulching with Municipal Solid Waste (MSW) Compost Has Beneficial Side Effects on Vineyard Soil Compared to Mulching with Synthetic Films

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Abstract: Municipal solid waste (MSW) compost represents a sustainable alternative to plastic film for mulching in viticulture. This study investigated the effects of MSW compost on vineyard soil properties, specifically focusing on side effects such as soil temperature and microbial decomposition activity, independently from its role in weed control. The experiment was conducted in a vineyard located in the Mediterranean region (Southern Italy), with six different mulching treatments: black polyethylene (PE) film, black and white biodegradable film, three different amounts of MSW compost (8, 15, and 22 kg plant^{-1}), and a control without mulching. Weed growth was monitored to determine the optimal compost application amount. The 15 kg plant^{-1} treatment was selected for further analyses, as it did not significantly impact weed growth compared to the control. Results indicated that MSW compost mulching maintained lower soil temperatures compared to other treatments (up to 5 °C in the warmest hours) and reduced the amplitude of the thermal wave up to 50% compared to the non-mulched soil and even more compared to black film mulched soil, particularly during the warmest periods. This suggests that MSW compost can mitigate heat stress on plant roots, potentially enhancing plant resilience and preserving crop production also in stressful growing conditions. Microbial decomposition activity, assessed using the tea bag index, was higher in the MSW compost treatment during spring compared to the control, indicating temperature as a key driver for organic matter decomposition, but this effect disappeared during summer. These findings highlight the potential of MSW compost to support sustainable viticulture by reducing reliance on synthetic mulching materials and promoting environmental sustainability through the recycling of organic municipal waste.

Keywords: mediterranean region; organic fraction of municipal solid waste; agricultural plastic films; microbial decomposition activity; tea bag index (TBI); soil temperature; weed control

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1. Introduction

Mulching is a key soil management practice based on the application of a layer of material on top of the soil surface [1]. It effectively controls weeds, enhances soil moisture retention [2], and regulates soil temperature [3]. Additionally, it prevents soil erosion caused by abiotic factors [4] and reduces soil compaction from heavy agricultural machinery [5].

Several studies have highlighted the role of mulching in viticulture. Steinmaus et al. [6] and Mairata et al. [7] reported mulching as an alternative method to conventional weed control methods that include mechanical cultivation, herbicide application, and manual control [8]. Mechanical cultivation involves using machinery to till the soil and remove weeds, which can be labor-intensive and potentially harmful to soil structure. Herbicide application involves the use of chemical substances to kill or inhibit weed growth, which can raise environmental and health concerns. Manual control, while effective, is time consuming and not always feasible for large-scale operations [9]. Various authors discussed the contribution of mulching to improving the water use efficiency of grapevine [10] in semi-arid conditions [11–13]. Prosdocimi et al. [14] focused on the role of mulching in reducing soil erodibility and surface runoff. Ferrara et al. [15] observed positive impacts on grapevine physiology and soil fertility using exhausted olive pomace as an organic mulch. Alternative organic mulches, such as compost, not only improve grapevine health and soil texture but also contribute to soil fertility, and are particularly beneficial in the context of circular economy and sustainable practices [16]. Their relevance is even more pronounced in arid climates, where challenges include both soil salinization and the limited availability of organic matter [17].

Various materials can serve as mulch, including vegetative residues, plastic films, biological geotextiles, gravel, and crushed stones [18]. Therefore, mulches are generally categorized into inorganic, organic, and special-type materials. Inorganic mulches include plastic film, with or without holes—widely used in agriculture—landscape fabric—used alone or below other mulches—and biodegradable or photodegradable plastic film [19]. Polyethylene (PE) mulch films, produced using non-renewable petroleum-based polymers, can have negative effects on the environment if not properly recovered and disposed of after use [20]. Thus, considerable research efforts have been expended in developing and investigating biodegradable mulch alternatives to PE mulching film in the last decades [21] and in investigating the use of organic mulch like MSW compost as a sustainable alternative [18]. Biodegradable and photodegradable plastic films were developed to address the environmental issues caused by low-density PE accumulation and plastic waste in soil and further problems resulting from improper disposal [22]. Biodegradable mulches, now widely available, consist of various polymers or additives like starch, cellulose, polyhydroxyalkanoates (PHA), and polylactic acid (PLA) [4]. The functionality of bio-based films employed in agriculture is still a matter of major concern [23]. Organic mulches, which should be weed-free, easy to apply, and readily available, often consist of on-site or off-site plant residues left on the soil surface after cropping [19]. Further organic materials like shredded grass, litter, compost, and small branches can also be utilized. In particular, MSW compost enhances soil carbon and nitrogen content and enzyme activities, providing a cost-effective alternative to expensive chemical amendments [24,25]. However, ensuring the safe use of MSW compost in agriculture requires careful monitoring for potential contaminants and heavy metals [26]. Special mulches include living mulch, reflective mulch, or biodegradable mulch [18,27]. Each type of mulch meets different needs and suits different environments. Organic mulches improve soil health and fertility over time as they get decomposed, but this decomposition requires a regular replenishment. In contrast, inorganic and specialized mulches are more durable and require less maintenance; however, they are typically more costly and often impractical for large-scale agricultural use due to both their higher initial investment and potential environmental impact [28]. The choice of mulch depends on factors such as crop specific needs, local climate conditions, the availability of materials, and the farmers' goals [29].

In agriculture, a variety of application techniques are utilized for mulching, each with distinct benefits. For example, traditional flat mulching involves covering with organic, inorganic, or a combination of materials to maintain a specific thickness. Plastic mulching with holes, a variation of flat mulching, partially covers the soil to improve rainfall infiltration and aeration [4,18]. Another technique, ridge-shaped mulching, involves covering ridges with plastic to direct rainwater into furrows, thus reducing surface runoff and improving water use efficiency. This method is especially effective in rainwater harvesting and reducing evaporation. Additionally, the ridge-furrow system, utilizing both plastic film and organic mulches, optimizes water availability for crops and increases soil productivity, demonstrating significant environmental benefits in semi-arid regions [30].

To assess the effectiveness of mulching practices, weed suppression is generally assessed by analyzing the percentage of weed coverage in a selected area, for instance, using smartphone applications [31]. Furthermore, several other parameters could be monitored in order to evaluate the additional beneficial effects of mulching. For example, soil moisture monitoring is useful to assess water conservation [18,32]; soil and atmospheric temperature allow evaluating the insulative effects of mulching against temperature fluctuations [18]. A further critical parameter is the soil decomposition activity, which provides insights into the contribution of mulching to soil fertility and ecosystem health by influencing the microbial degradative functions [33]. Decomposition of organic matter (OM) is one of the most important soil functions in agroecosystems; therefore, it has been studied extensively, and one of the most useful techniques is the litterbag method [34]. Among these methods, the "tea bag index" uses readily available green tea and red rooibos [33] to estimate OM weight loss due to microbial decomposition.

The aim of the present study was to evaluate the effects of MSW compost mulching on vineyard soil properties, specifically focusing on soil temperature and microbial decomposition activity. Additionally, the research attempted to identify the optimal compost application amount for effective weed control. By using MSW compost as a mulch material, the study aims to support sustainable agricultural practices by reducing reliance on synthetic mulching materials, aligning with circular economy principles, and promoting environmental sustainability through the recycling of organic municipal waste.

2. Materials and Methods

2.1. Vineyard Localization and Climatic Conditions

The 5-year-old experimental vineyard (*Vitis vinifera* cv. 'Primitivo', rootstock M4) is located in Salento (Apulia region, Southern Italy), 40°27′50.6′′ N–17°58′18.7′′ E, and belongs to the company "Cantina Due Palme" (Cellino San Marco-BR-, Italy) (Figure S1A,B).

Soil physico-chemical analyses were performed by the winery "Cantina Due Palme" in 2020. The soil had about 55 g kg^{-1} of skeleton, 61% of sand, 26% of silt and 13% of clay. The pH was 7.6, and the soil conductibility was 0.194 dS m^{-1}. Ca, Mg, K, and Na concentrations were 2367 g kg^{-1}, 158 g kg^{-1}, 404 g kg^{-1}, and 20 g kg^{-1}, respectively. Total limestone was 41 g kg^{-1}. The soil was poor in organic matter (1%), as well as in nitrogen (0.5 g kg^{-1}).

The site is on flat land, 50–60 m a.s.l, with a typically Mediterranean climate, hot and dry in summer and mild and humid in winter, belonging to the class Csa in the Köppen-Geiger classification [35]. During summertime, intense heat waves are prevalent over the Salento peninsula due to the dominance of a subtropical high-pressure system for several days. In contrast, mild and wet winters exhibit moderate and variable temperatures [36]. In the Salento peninsula, the average annual precipitation amounts are approximately 650 mm [37], primarily occurring from January to March and throughout the autumn season [38]. Summers are typically characterized by dry conditions, where short and intense convective rainstorms generate mostly low rainfall. The average annual temperature is around 16–17 °C [39].

Table 1 shows an overview of the main weather parameters observed throughout the year 2023 in the territory of the experimental study. Data was obtained from a weather station (iMetos 3.3, Pessl Instruments GmbH, Weiz, Austria) positioned at ~4 km from the experimental site. The climatic parameters were measured with a frequency of 5 min, averaged, and recorded by the data logger every 60 min. Air relative humidity was measured by a Hygromer® IN-1 sensor (Rotronic, Zurich, Switzerland). Air temperature was measured by a PT1000 sensor and precipitation by a double-tipping bucket rain gauge (Pessl Instruments GmbH, Weiz, Austria). The maximum and minimum temperature values (T_{max} and T_{min}, respectively) were calculated on a daily basis, and averaged over the month (T_{avg}). Precipitation is represented as a monthly cumulative value. During the winter season, T_{avg} ranged from 8.1 °C to 11.5 °C, with the lowest daily minimum temperature recorded in February (7.6 °C). Relative humidity consistently remained high during this period, fluctuating between 78.9% and 81.9%, indicative of humid conditions. By May, T_{avg} rose to 18.4 °C, while relative humidity remained relatively stable (83.7%). During the summer season, T_{avg} peaked at 27.5 °C in July and 26.3 °C in August, coinciding with a noticeable drop in relative humidity, which fell to 63.8%. The precipitation pattern remained relatively consistent until May, experiencing a significant spike in April with 155.6 mm of rainfall. A transition to a drier period occurred from June onwards, resulting in no precipitation in August, before returning to higher values for the remaining months.

Table 1. Overview of the main weather parameters during the test year 2023.

Month	Air Temperature (°C)			Air Relative Humidity (%)	Precipitation (mm)
	T_{avg}	T_{max}	T_{min}		
Jan-23	9.6	10.2	9.1	90.4	77.4
Feb-23	8.1	8.7	7.6	78.9	13.4
Mar-23	11.5	12.1	10.9	81.9	50.2
Apr-23	12.9	13.5	12.3	83.4	155.6
May-23	18.4	18.9	18.0	83.7	60.6
Jun-23	22.8	23.4	22.1	77.9	29.0
Jul-23	27.5	28.1	26.9	63.8	0.0
Aug-23	26.3	26.8	25.8	67.7	1.2
Sep-23	24.0	24.5	23.4	73.8	7.4
Oct-23	19.9	20.5	19.3	83.2	49.4
Nov-23	14.5	15.1	14.2	84.5	154.2
Dec-23	10.2	10.8	9.4	89.5	113.8

2.2. Experimental Plan

The vineyard implantation consists of rows, with a spacing of 1 m intra-row and 2.2 m inter-row between the plants, a density of around 4500 plants per hectare, and a vertical shoot positioning with Guyot pruning. Five rows were included in the experiment (Figure 1): the first and last row (rows 1 and 5, respectively) were considered borders and were neither treated nor monitored. In the three middle rows (rows 2, 3 and 4), grapevine plants were divided into eight blocks of six plants each; the first and last blocks (blocks A and H) were also considered borders and were neither treated nor monitored. Each of the six internal blocks (blocks B to G) of rows 2, 3, and 4 was then subjected to one of the following treatments:

1. Film-black: mulching with a traditional black PE film;
2. Film-b/w: mulching with a black and white biodegradable film;
3. Compost (8): mulching with municipal solid waste compost (MSW compost)—8 kg plant^{-1}, 4 cm thick;
4. Compost (15): mulching with MSW compost—15 kg plant^{-1}, 6.5 cm thick;
5. Compost (22): mulching with MSW compost—22 kg plant^{-1}, 10 cm thick;
6. Control (no mulching).

Compost quantities were selected based on the previous experience of the authors. The mulch films, black plastic film (Film-black) and biodegradable and bi-color film (Film-b/w), were chosen as conventional mulching techniques, for comparison to the MSW compost treatments. In particular, the innovative Film-b/w was chosen with the purpose of assessing the feasibility of its application in vineyards.

Therefore, each treated row contained one block per treatment, and the treatments were applied according to a completely randomized design to finally obtain three replicates per treatment randomly positioned within each row (Figures 1 and S1C). During the experiment, inter-row spaces were left untreated and were neither tilled nor unweeded.

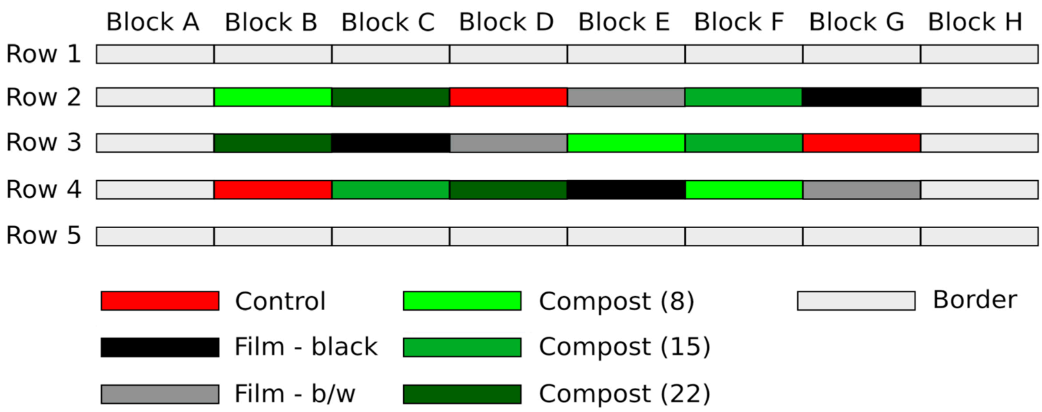

Figure 1. Experimental design. Three randomized replicates per each treatment were created, one in each treated row (rows 2, 3, and 4). Each block contained six *Vitis vinifera* cv. "Primitivo" plants. Rows 1 and 5, and blocks A and H were considered as borders.

Immediately after an initial tillage, common to all treatments, mulching was applied on 24 March 2023 and the trial was monitored until September 2023, to include the complete grapevine vegetative season. The compost used in this work as mulching was produced and provided by the company Heracle S.r.l. (Erchie-BR, Italy); it consists of a composted mixture of green residues and the organic fraction of municipal solid waste (MSW) (Table S1), collected through separate waste collection at source and subjected to strictly controlled biological processes. The compost was weighed in a bucket, and the same amount (8, 15, or 22 kg, according to the treatment) was distributed around each grapevine plant by keeping a width of ~50 cm (~25 cm to both sides of the vine line). Thus, keeping the treatment width constant, the thickness of the compost layer changed accordingly to the amount of compost used.

As a comparison with MSW compost mulching, soil was covered with black mulching film in UV-stabilized PE, hereafter "Film-black" (Tenax Black Cover, Tenax SpA, Lecco, Italy; technical data from manufacturer: thickness 60 micron, weight 37 g m^{-2}) or with black/white biodegradable mulching film made with the bioplastic ecovio® (BASF), hereafter "Film-b/w" (Ecotelo, Filnova S.r.l., Milano, Italy; technical data from manufacturer: thickness 18 micron, weight 24.84 g m^{-2}). The same wideness of the coverage made with MSW compost mulching (~50 cm) was maintained.

2.3. Canopy Cover/Weed Control

To identify the mulching strategy most suitable for the experimental purpose, weed growth was measured during springtime. In 18 April, 29 May and 23 June 2023, the percentage of grass cover was measured using the smartphone application "Canopy Cover Free" [40]. In detail, the application calculates the percentage of green area in a photo of the soil (as shown in Figure S2). In each block, 3 photos were collected (between the 2nd and 3rd plants; between the 3rd and 4th plants; and between the 4th and the 5th plants). Thus, on each date, 9 measurements were collected for each treatment. As explained in the next paragraphs, the treatment "Compost (15)" (mulching with MSW compost—15 kg $plant^{-1}$, 6.5 cm thick) was selected for further analyses (soil temperature and decomposition of organic matter) due to the similarity to the control treatment in the weed growth dynamics.

2.4. Soil Temperature

The soil and the atmospheric temperature were logged continuously in the period July–September 2023 by using portable WatchDog 1000 Series Micro Stations (Spectrum Technologies Instruments, Aurora, IL, USA) placed at 170 cm height inside the vineyard at the top of the support poles (Figure S3). The atmospheric temperature measurement was carried out using the internal sensor of one of the micro-stations. The station was adequately shielded from solar radiation (Figure S3). The soil temperature was detected by the SMEC 300 sensor (Spectrum Technologies Instruments, Aurora, IL, USA) placed at 20 cm soil depth under the treatments Film-black, compost (15), and control. One soil temperature sensor was used for each treatment. The stations stored the values with a 10 min measurement interval.

The thermal performance of the different treatments was assessed by the temperature mean values of the soil under the black film (T_{Fb}), under the compost layer (T_{C15}), and of the untreated soil used as a control (T_{Ctrl}). Air temperature (T_{air}) was also recorded.

2.5. Decomposition of Organic Matter (Tea Bag Index)

The tea bag index (TBI) method is a special litterbag method that was used to assess the soil microbial activity through the estimation of the organic matter decomposition rate [33]. The green tea used was the Lipton green tea (EAN: 8711327515765); the red tea used was the Lipton rooibos tea (EAN: 8711327514348). Both of them were purchased at Dutchsupermarket (Gelderland, NL; article codes: THEE049 and THEE056, respectively). Despite the changes in tea bag net manufacturers that occurred in the last ten years, the method was proven to still be valid [41]. The content of green tea comprises a higher fraction of easily degradable organic compounds, while rooibos tea contains a higher fraction of more recalcitrant organic compounds. Tea bags were weighed and then buried at a depth of ~12 cm, one green and one red tea bag per block of the treatments Film-black, compost (15), and control, halfway between two vines. According to the original protocol [33], after a burial time of 3 months, tea bags were recovered, dried at 65 °C for 48 h, and then re-weighted to calculate the mass loss (excluding the weight of the bag, the cord and the label). The measure was repeated twice, in the periods April–June (spring) and July–September (summer). This method was already applied in vineyards [42–44]. Green tea and red tea mass loss were used as a reliable and intuitive proxy to estimate the degradation of labile organic matter fraction and recalcitrant organic matter fraction, respectively [45–47].

2.6. Statistical Analyses

Data were analyzed using SPSS v.20 software (IBM Corporation, Armonk, NY, USA) or MATLAB v.2023b (The MathWorks Inc., Natick, USA). For weed control and tea bag analysis (Sections 2.3 and 2.5, respectively), one-way ANOVA was used to compare means between treatments for each measurement date. For soil temperatures (Section 2.4), one-way analysis of variance (ANOVA) was carried out to identify significant differences between T_{Fb}, $T_{C1}5$, T_{Ctrl}, and T_{air}. One-way ANOVA analyses were also performed for comparing the mean temperature difference between the soil (under the black film, the compost layer, and the control soil) and the air (ΔT_{Fb}, ΔT_{C15}, ΔT_{Ctrl}, respectively); the analyses were carried out for every value of the air temperature (1 °C intervals) in the studied summer period. Additionally, to evaluate the effects of treatments across the whole monitored period, a repeated-measures ANOVA was used. All ANOVAs were followed by a post hoc test (Tukey HSD or Duncan's) at $p \leq 0.05$.

3. Results

3.1. Weed Control and Treatment Selection

The trend of weed growth during the first 3 months of the experiment is reported in Figure 2. To inhibit weed growth, with an effect similar to the one obtained using mulching films, a high quantity of compost was necessary (22 kg plant^{-1}). However, this effect lasted less than that obtained with the mulching films. In fact, the compost mulching (22 kg plant^{-1}) favored weed growth later on. On the contrary, a thin compost layer (8 kg plant^{-1}) stimulated the weed growth earlier, inducing a significant increase in the covered surface already 2 months after the application. It is worth noting that, three months after the application, any of the compost mulching produced significant differences from the non-mulched control.

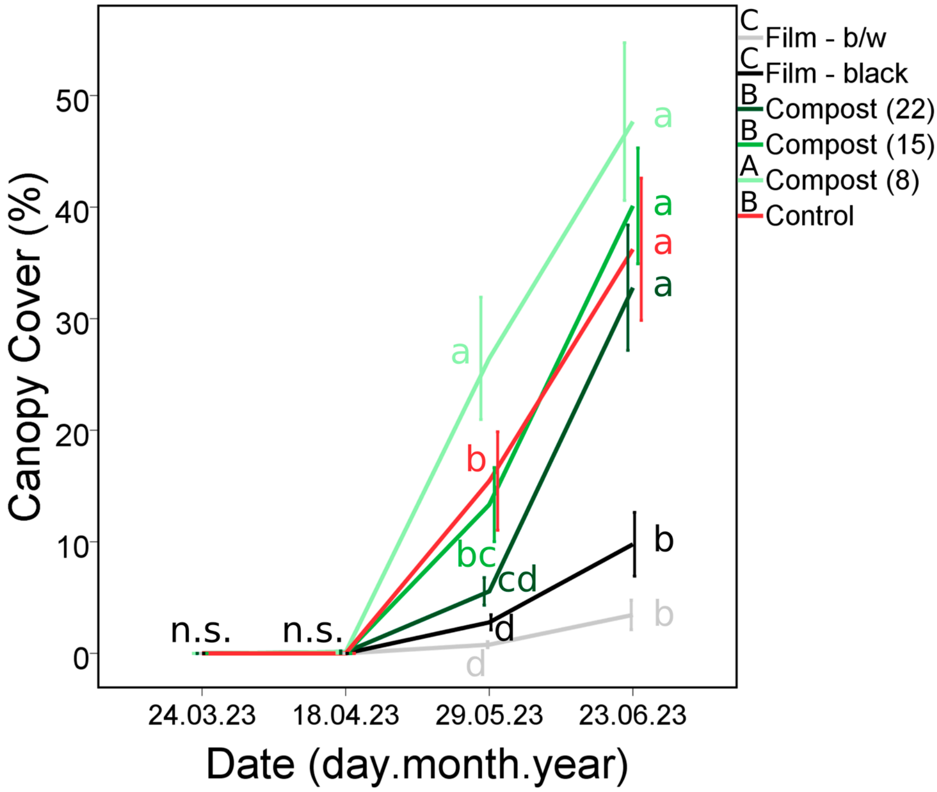

Figure 2. Trend in weed growth, expressed as percentage of the soil covered by green canopies. The whisker indicates the standard error. Different lowercase letters indicate significantly different means between the treatments for each date (Duncan post hoc test, $p < 0.05$). Different capital letters indicate significantly different means between the treatments with repeated measures for the entire duration of the surveys (Duncan post hoc test, $p < 0.05$). n.s.= not significant.

The intermediate quantity of compost (15 kg plant^{-1}) did not produce any significant effect on the percentage of surface covered by weeds with respect to the non-mulched control during the springtime. Thus, this treatment was selected to highlight the effects of compost mulching on the soil properties, excluding weed interference.

Both mulching films were able to significantly reduce weed growth, but differences among them were not significant. Thus, the most commonly used PE black film was selected as a conventional reference mulching film product.

3.2. Soil Temperature

Statistically significant differences were always found when comparing the values of T_{Fb}, T_{C15}, T_{Ctrl}, and T_{air} in each month and over the entire period of July–September 2023 (Figure 3). The average soil temperature followed the trend of the air temperature related to the advancement of the months. Interestingly, the lowest average soil temperature was recorded in each month as well as in the whole period in the compost treatment, followed by the control, and then the Film-black. Regardless of the different weather conditions, the adoption of the compost layer allowed for maintaining the average soil temperature at values lower than T_{Ctrl}, demonstrating the cooling effect of the MSW compost during the analyzed summer period. The lowest mean soil temperature (27.5 °C) was recorded in the compost treatment in September, while the black film kept the soil temperature over 29.1 °C. During July, the month with the highest mean air temperature (28.6 °C), the compost layer allowed for maintaining the mean T_{C15} under 31.1 °C, significantly lower than the mean T_{Ctrl} (31.7 °C) and T_{Bf} (32.4 °C).

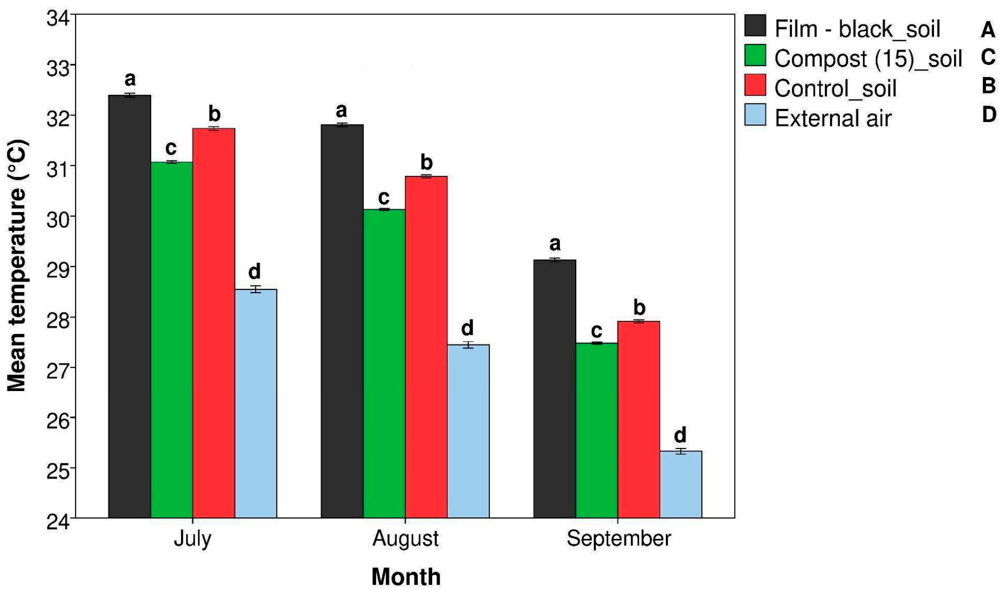

Figure 3. Mean values ± standard errors (whiskers) of the temperature of the soil treated with the black film (T_{Fb}) and the compost layer (T_{C15}), of the control soil (T_{Ctrl}) and of the air (T_{air}), during July–September 2023. Different lowercase letters indicate significant differences between the means for each month (Duncan post hoc test, $p < 0.05$). Different capital letters indicate significant differences between the means for the entire duration of the surveys (Duncan post hoc test, $p < 0.05$).

Figure 4 shows the mean daily patterns of air and soil temperature from July to September 2023. As expected, minimum temperatures were typically observed for both air and ground temperatures during the early morning hours. The air temperature exceeded all ground temperatures from 09:00 until 14:00; the pattern reversed from 18:00 to 09:00. In comparison to the temperature of the control soil, the Film-black showed significantly higher values at all times. This difference notably increased between 11:00 and 17:00. In contrast, the soil temperature under the compost was higher than the control between 05:00 and 11:00 and was lower between 13:00 and 01:00; it was not different from control between 02:00 and 04:00. Note that the flexure between 13:00 and 14:00 is due to the shading of the vineyard.

Significant differences were shown for the three treatments over the entire monitored period; in particular, the Film-black showed the highest values, the control intermediate values, and the compost the lowest values (Figure 4). Significant differences between the treatments at almost all times, except between Film-black and compost from 05:00 to 09:00 and between compost and control from 02:00 to 04:00, were also revealed.

The damping of thermal waves at 20 cm was on average higher in compost mulched soil with a mean amplitude of 3.1 °C than in the control and black film mulched soil with mean amplitude values of 6.0 °C and 7.4 °C, respectively, during the whole summer period (Figure 4). Monthly mean amplitudes in the soil covered with the compost were lower than about 47–49% of those calculated for the control soil, while increments of 9–35% were associated with the black film treatment. The compost allowed for a reduction in the daily fluctuation of soil temperature, due to the relevant lowering of the daily maximum temperature value. It is worth considering that temperature peaks are not detected through the analysis of average data.

A more in-depth analysis of the mean temperature difference between the soil under the different treatments and the air (ΔT_{Fb}, ΔT_{C15}, ΔT_{Ctrl}) was carried out (Figure 5). The results showed that, for air temperature values above 23.0 °C, the compost on average allowed for maintaining the soil temperature slightly cooler than the control and fairly cooler than the black film, with a more pronounced effect for air temperature values above 28.1 °C.

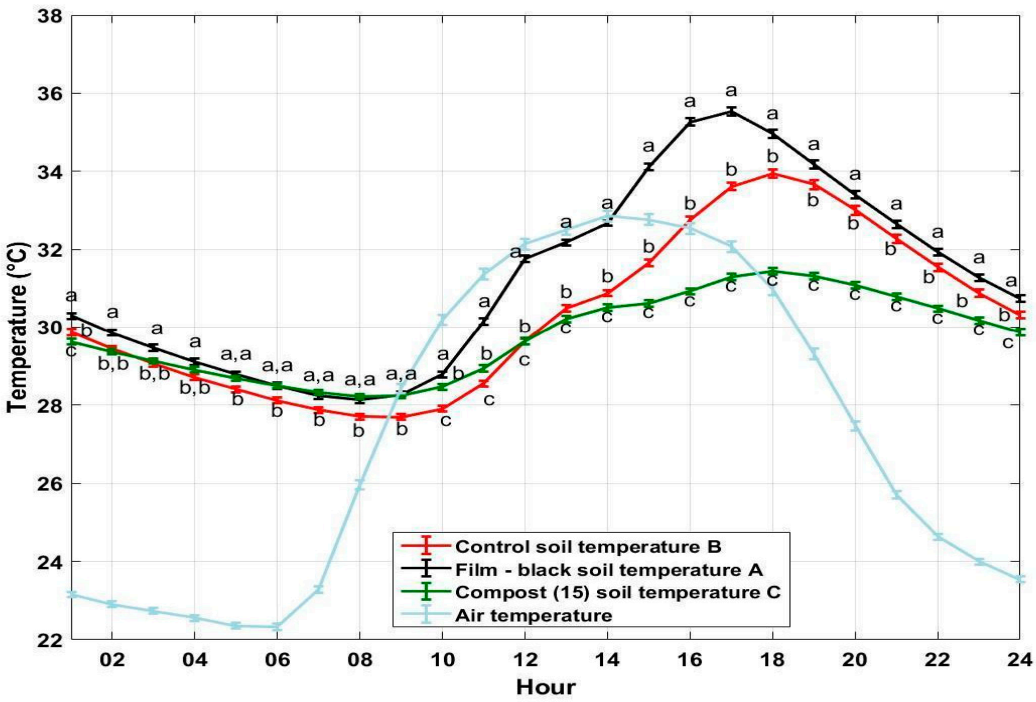

Figure 4. Diurnal pattern of the soil and air temperature. The whisker indicates the standard error. Different lowercase letters indicate significant differences between the three selected treatments for each hour (hsd post hoc test, $p < 0.05$). Different capital letters indicate significant differences between treatments with repeated measures for the entire monitored period (hsd post hoc test, $p < 0.05$). The air temperature pattern is shown for reference only.

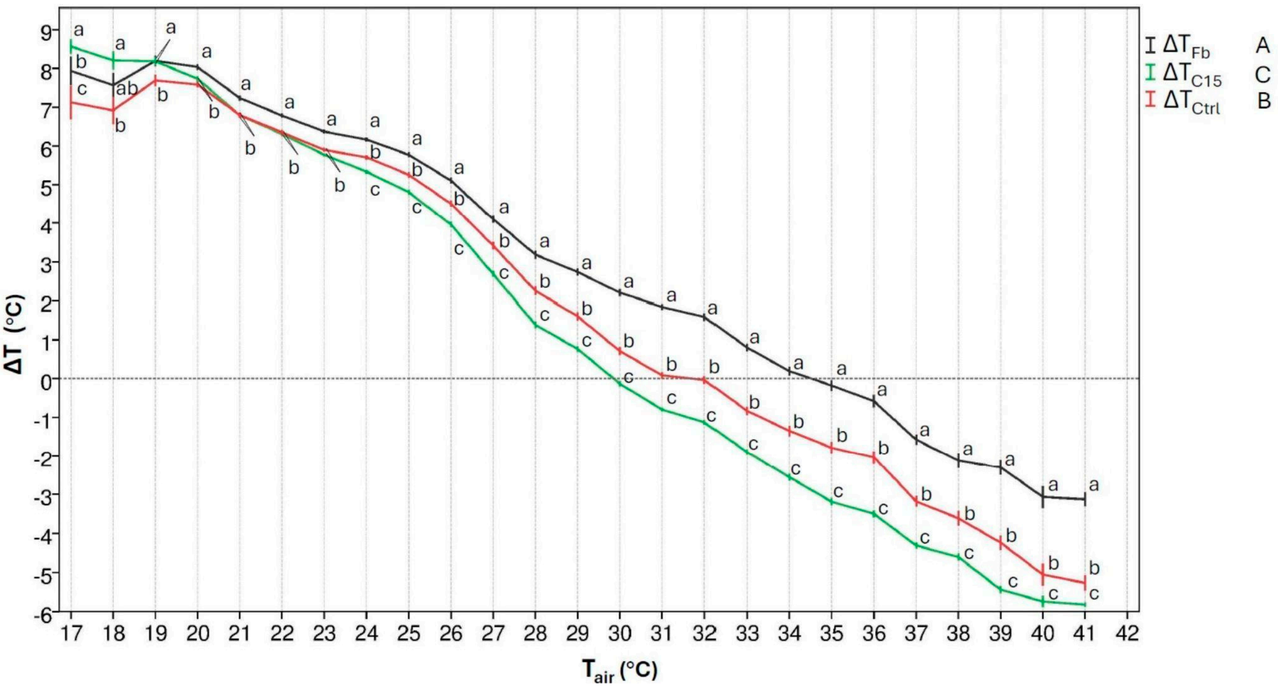

Figure 5. Mean values ± standard errors (whiskers) of the temperature difference between the soil under the black film, the compost layer and the control treatments and the air temperature, in relation to T_{air} (1 °C intervals). Different lowercase letters indicate significant differences between ΔT_{Fb}, ΔT_{C15} and ΔT_{Ctrl} means for each T_{air} value (Duncan post hoc test, $p < 0.05$). Different capital letters indicate significant differences between ΔT_{Fb}, ΔT_{C15} and ΔT_{Ctrl} means for the entire range of T_{air} values (Duncan post hoc test, $p < 0.05$).

3.3. Decomposition of Organic Matter (Tea Bag Index)

Tea bag index, a method used as a proxy for microbial decomposition activity in soil, was measured for the treatments "Compost (15)", "Film-black" and "Control" in two consecutive 90-day periods (spring and summer); it showed that percentages of mass losses due to microbial decomposition ranged between 40% and 60% for the labile organic fraction (green tea) and between 18% and 40% for the recalcitrant organic fraction (rooibos red tea) (Figure 6A,B). The decomposition of recalcitrant organic fraction (red tea) was higher in spring (April–June) than in summer (July–September) (*t*-test, $p = 0.007$), while labile organic fraction (green tea) did not show significant differences between the two periods. MSW compost acted similarly to the Film-black in spring, stimulating the microbial degradation activity of the labile organic fraction (green tea) of the soil (Figure 6A), while in summer this effect disappeared and the MSW compost values were similar to the untreated control (Figure 6B). The same trend was observed for the recalcitrant organic fraction (rooibos red tea), although no statistical significance was observed in this case due to a higher variability between the three replicates (Figure 6A,B). Over the two periods (ANOVA repeated measures), the mulching treatment significantly affected the weight loss of green tea ($p = 0.016$), while no significance was found for red tea ($p > 0.05$) (Figure 6).

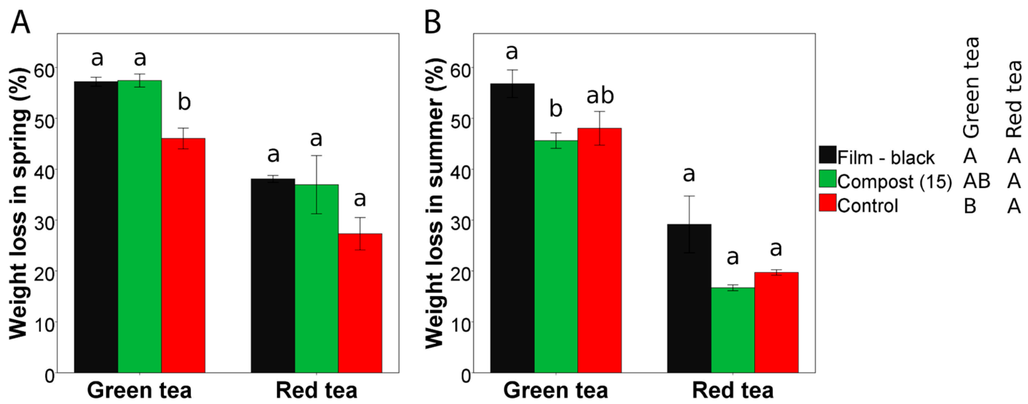

Figure 6. Means ± standard errors (whiskers) of the tea bag index, measured in two periods: April–June (panel (**A**)) and July–September (panel (**B**)), for the treatments "Film-black", "Compost" (15) and "Control". Different lowercase letters indicate significantly different means between treatments for each type of tea (Duncan post hoc test, $p < 0.05$). Different capital letters indicate significantly different means between treatments with repeated measures over the two periods for each type of tea separately (Duncan post hoc test, $p < 0.05$).

4. Discussion

It is well known that MSW compost could be used in viticulture as a fertilizer and that its application as organic mulch on the vine row could inhibit weed growth, modulating the competition among plants. However, other "side-effects" could be exploited: application of MSW compost can maintain a lower soil temperature than the soil under the black PE mulch film and also be compared to uncovered soil, which is beneficial for the plant root system. Furthermore, besides chemical nutrition, soil biological fertility could play an important role in plant resilience. In this work, we explored these side effects of compost mulching using MSW-derived compost.

The most widely used mulch in commercial agricultural systems is PE plastic film [48], because of its relatively modest cost, availability, and physical and mechanical properties that enable achieving several benefits [49]. MSW compost, during the summer, kept on average lower soil temperature values than in the control and Film-black treatments, particularly with lower peak values experienced as a consequence of high levels of solar radiation intensity. An analogous effect on soil temperature was observed by Chan et al. [50] regarding the use of composted mulch in vineyards in Australia; the application of composted mulch significantly changed the soil temperature at 10 cm depth, leading to a shorter daily temperature range, lowering daily maximum temperatures, and rising daily minimums. Similar results on soil temperature were evaluated in vineyards with organic mulch under Mediterranean conditions during the summer months, where the monthly maximum soil temperature, at a depth of 7 cm, was found to be lower in mulched soil [51]. By maintaining lower soil temperatures during summertime, compost can mitigate heat stress on plant roots, enhancing their health and overall function. This is crucial, as extreme temperatures can reduce root activity, hinder water and nutrient uptake, and ultimately affect plant growth and resilience. Maintaining root zone temperatures below 30 °C is recommended to ensure normal growth and functionality. A study carried out in China on grapevines showed that temperatures above 30 °C can reduce root and shoot growth, decrease chlorophyll content in leaves, and increase lignin in roots and shoots; additionally, high root zone temperatures can shift root respiration to cyanide-resistant respiration, releasing more heat to alleviate stress damage [52]. Thus, using compost to stabilize soil temperature can be very useful for maintaining healthy root systems during the hottest part of the day. In fact, as shown in Figure 5, the cooling effect of the compost mulching has a higher magnitude at higher, thus more stressful, temperatures (>28 °C).

The values of weight loss for both green and red tea observed in our work are coherent with those reported previously in vineyards [45–47]. The effect of MSW compost on microbial decomposition activity was different in the two different periods investigated (spring and summer): in spring, the compost enhanced the soil decomposition activity with respect to the untreated control, showing values similar to those of the treatment with Film-black, while in summer this effect disappeared. Soil microbial decomposition activity is mainly dependent on humidity and temperature [53]; thus, our results can be explained by observing the temperature trend, which was significantly affected by the mulching treatments in our experiment. In fact, soil temperature, measured in summer, showed exactly the same trend as soil decomposition activity (compare Figure 3 with Figure 6B). Therefore, temperature appears to be the main driver for the decomposition of organic matter, both labile and recalcitrant, in summer. However, other factors may play a role in this seasonal variation of the decomposition activity. For example, the moisture content obviously reduces in summer, and this negatively influences both the growth rate and the metabolism of microbe cells.

In spring, the compost stimulated soil decomposition activity. Organic matter decomposition is a task performed by soil microbes that depends not only on microbial abundance but also on microbial diversity [54,55]; keeping this in mind, besides soil temperature, a reason for the increase in decomposition activity in spring (Figure 6A) could be a direct "microbial inoculation effect" by the MSW compost applied. In the following period, the microbial community likely undergoes physiological changes, and the initial inoculation effect is expected to reduce. In general, active soil microbes decompose organic matter, releasing essential nutrients that promote robust plant growth. This activity also enhances soil aeration and water retention, supporting better root development and resilience to environmental stresses like salinity, drought, and nutrient deficiency. Additionally, beneficial microbes can increase nutrient mobility and availability in the soil and can also outcompete harmful pathogens, thus reducing disease incidence and improving general plant fitness [56,57]. However, confirming this would require thorough microbiological analyses of both soil and MSW compost used [58], to assess the increment in soil microbial load as well as a shift of the microbiota towards an enrichment of heterotrophic species particularly efficient in decomposition activity.

On the contrary, in summertime, the organic matter decomposition was kept lower with respect to the one observed with plastic films. Soil degradation, resulting in low organic matter contents, is a key problem in hot environments (such as the Mediterranean regions), and it could be worsened by climate change [59,60]. Thus, the soil temperature decreases, and the decomposition activity consequently decelerates. This could be an important advantage in the choice of MSW compost as mulching material, as it determines the conservation of organic matter in the soil in hot climates.

Although in this work we did not collect data about the effects the treatments had on vine nutrition and grape quality, the results obtained (especially with tea bags) indicate that MSW compost increases the turnover of organic matter into the soil. This could benefit the plants in terms of available nutrients, which could in turn impact the quality of the grapes. However, this requires further dedicated research.

Further studies could implement the knowledge, including applications in different environmental conditions (e.g., different sites and different climates). Our analyses did not highlight any negative effects of the MSW compost; however, we cannot exclude that further investigations could find different results.

5. Conclusions

The application of MSW compost maintained lower soil temperature values than the soil under the black PE mulch film and was also compared to the control soil. Thus, using MSW compost to stabilize soil temperature is helpful for maintaining healthy root systems, particularly during the hottest hours of the day. We also found that MSW compost stimulates the soil biological activity in the first period after addition, but it reduces the organic matter lost during the hottest period with respect to the plastic film. However, more studies are needed to disentangle the effects of compost-derived microbes from those of environmental factors.

The application of MSW compost as a mulch material supports sustainable practices in viticulture and, in general, in tree crop management, by recycling municipal waste and reducing the use of synthetic materials like PE films. This aligns with the principles of the circular economy and promotes environmental sustainability in agriculture.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/horticulturae10070769/s1, Table S1: Physico-chemical parameters of MSW compost. Values derived from five subsamples of the municipal solid waste (MSW) compost used in this work, as provided by the producing company; Figure S1: Map and photo of the experimental site. (A) Location of the Apulia region in south-east Italy; (B) zoomed-in area (background map from Google Earth) with the red rectangle indicating the location of the experimental vineyard; (C) detail of the experimental vineyard with the different mulching treatments; Figure S2: Example of the Canopy Cover Free smartphone application. (A) Original photo of weeds. (B) Identification and measurement of the green area (leaves); Figure S3: Micro station localized on the vineyard row connected to sensors for recording both soil and air temperature.

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