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Biodegradable mulch from renewables for vineyard weed control: effects on yield and quality

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ABSTRACT

Effective weed control in the under-vine area is essential for vineyard productivity and sustainability. However, conventional chemical and mechanical methods can damage soil health and ecosystem functions. In this field experiment, a novel biodegradable-sprayable mulch made from renewable resources was evaluated in two separate two-year field trials (2021–2022 and 2023–2024) conducted in Bavaria, Germany. Treatments included an untreated control, mechanical weeding and three mulch applications: early applications of 2.5 L m^{-2} and 5.0 L m^{-2} (SM-2.5E, SM-5.0E) and late application of 5.0 L m^{-2} (SM-5.0L). Each year, data were collected on aboveground weed biomass, standard soil parameters, grape yield (kg $vine^{-1}$), pruning weight, and must quality parameters (°Brix, pH, and titratable acidity). The results show that SM-5.0L consistently achieved the lowest late-season weed biomass, which can be attributed to both the greater mulch thickness and the later application time. The combination of these two factors likely enhanced mulch persistence and weed suppression during the late season. No significant differences were observed between treatments in terms of grape yield, vegetative growth of vine, or must quality, and soil parameters remained largely unaffected. These findings suggest that the biodegradable-sprayable mulch from renewable materials is as effective as mechanical weeding and offers yield-neutral under-vine weed control without compromising vine performance or soil chemical properties within the observation period. Further research across diverse soil types, climatic regions, and water-limited conditions is recommended to evaluate and optimise long-term efficacy, ensuring sustainable and practical integration into vineyard management.

KEYWORDS: under-vine weed control, biodegradable-sprayable mulch, grape yield, must quality, sustainable viticulture, renewable resources, soil cultivation

INTRODUCTION

Weed management is a crucial aspect of viticulture, particularly in under-vine areas where competition for resources must be minimised (Ingels *et al.*, 2005). In recent decades, herbicides and mechanical soil management have been the main approaches to controlling weeds in the inter-row and the under-vine area in vineyards (Kudsk & Mathiassen, 2020). However, the use of herbicides containing glyphosate has become increasingly controversial (Kudsk & Mathiassen, 2020) due to associated environmental concerns, such as groundwater contamination (Louchart *et al.*, 2001), residues in food (Ying & Williams, 1999), the emergence of herbicide-resistant weed populations (Doğan *et al.*, 2022), and negative effects on soil organisms (Gaupp-Berghausen *et al.*, 2015). Although the active ingredient glyphosate (N-(phosphonomethyl) glycine) remains legally permitted under stricter regulations (Bundesministerium für Ernährung und Landwirtschaft, 2024), the rising demand for sustainable agro-ecosystems has led wine growers to reevaluate their management practices.

Mechanical weed control, the most common alternative to herbicides, is effective in flat vineyards but presents challenges on sloped terrains. Recent advancements in soil management tools have nonetheless significantly improved the effectiveness of under-vine management (Sozzi *et al.*, 2021; Moysiadis *et al.*, 2022; Gagliardi *et al.*, 2023). However, the use of cultivation equipment often damages vine roots and trunks (Pergher *et al.*, 2019), increases the risk of soil erosion (Ruiz-Colmenero *et al.*, 2011), and degrades soil structure (Ruiz-Colmenero *et al.*, 2013). Additionally, repeated mechanical cultivation can reduce soil organic matter and release carbon (Mordhorst *et al.*, 2017), alter microbial dynamics (Virto *et al.*, 2012), and bring weed seeds to the surface, leading to increased weed pressure (Bàrberi, 2002). Reliance on any single method, whether chemical or mechanical, risks a shift in weed flora towards more tolerant species (MacLaren *et al.*, 2020; Doğan *et al.*, 2022). These issues are exacerbated in steep-slope vineyards, where slope inclination limits the feasibility of conventional mechanical methods and increases fuel consumption due to repeated passes (Jradi *et al.*, 2018).

To address these limitations, alternative weed management strategies that protect soil quality while maintaining vineyard productivity are needed. Mulching has been identified as a potential solution for both weed control (Rathore *et al.*, 1998) and soil improvement (Ngouajio & McGiffen, 2004). Over time, various materials have been used as mulch, including organic substances like straw, wood chips, and crop residues, as well as biodegradable film-based mulches made from renewable materials, such as paper or plant fibres (Ahmad *et al.*, 2024; Zhang *et al.*, 2019; Hayes *et al.*, 2019; Madrid *et al.*, 2022). Loose organic mulches offer benefits such as improved soil structure and decreased soil compaction (Némethy *et al.*, 2006), increased abundance of soil fauna, such as earthworms (Sauvage, 1995; Thomson & Hoffmann, 2007), reduced erosion (Granatstein & Mullinix, 2008), and weed control (Fredrikson *et al.*, 2011). However, applying them is labour intensive, which may not be cost-effective for large-scale vineyards, and their effects are often not long-lasting (Sauvage, 1995).

Biodegradable film-based mulches, such as those made from plant fibres, fully decompose into the soil, improving soil conditions and supporting sustainable agricultural practices (Zhang *et al.*, 2019; Follak *et al.*, 2024). Although these mulches involve high raw-material costs, they produce no waste and they can be fully incorporated into the soil (Madrid *et al.*, 2022). In contrast to loose organic mulches, biodegradable film-based materials require less manual labour, ensure more uniform soil coverage, and maintain their weed-suppressive and moisture-conserving effects (Zhang *et al.*, 2019; Hayes *et al.*, 2019). They also minimise nutrient immobilisation and reduce the risk of introducing weed seeds or pathogens that can occur as a result of unprocessed organic residues (Hayes *et al.*, 2019; Follak *et al.*, 2024).

Biodegradable-sprayable mulches are a novel approach, as the material can be applied as a liquid mixture directly onto the soil surface using a tractor-mounted application device. The system allows adjustment of both the application width and the material rate, offering high flexibility in practical use under different soil and management conditions, and can reduce the manual workload compared with the distribution of loose organic mulches. Materials derived from renewable resources, such as sodium alginate, cellulose, and chitosan, create a physical barrier that suppresses weeds and regulates soil temperature and moisture (Immirzi *et al.*, 2009; Giaccone *et al.*, 2018; Borrowman *et al.*, 2020; Follak *et al.*, 2024).

In recent studies, several types of sprayable and biodegradable mulch systems have been explored. These include polysaccharide-based emulsions, such as alginate–oil blends, which were investigated by Immirzi *et al.* (2009) and Kirchinger *et al.* (2024), fibre slurries made from materials such as paper pulp or straw, as studied by Mas *et al.* (2021), Weiss *et al.* (2025) and Ahmad *et al.* (2024), as well as film-forming biopolymer suspensions, described by Vox *et al.* (2013). Applied to a narrow strip in the under-vine area in the vineyard, biodegradable-sprayable mulches could be integrated into inter-row management techniques, like mowing or tillage, thus providing a sustainable weed control for permanent crops.

However, there are still gaps in key knowledge regarding their long-term weed suppression efficacy, optimal application methods and effects on soil and vine performance under varying environmental conditions, as well as their potential to reduce soil evaporation. While most vineyards in Europe are dry-farmed (van Leeuwen *et al.*, 2019) and mulch can reduce soil evaporation (Zhang *et al.*, 2019; Hayes *et al.*, 2019), the current study focuses on the capacity of mulch for weed suppression.

Therefore, the present study investigates a newly developed biodegradable-sprayable mulch made from renewable raw materials (Kirchinger *et al.*, 2023b; Kirchinger *et al.*, 2024; Follak *et al.*, 2024) to determine its effectiveness in controlling under-vine weeds and its influence on grape yield and must quality, as well as to assess its practical applicability in vineyards.

MATERIALS AND METHODS

1. Field and experimental design

The experiments were conducted in two field trials at Thüngersheimer Ravensburg, Bavaria, Germany (49° 51' 17.3" N 9° 51' 49.8" E). Before starting the field trials, several mulch treatments with different application times and layer thicknesses were tested under field-like conditions in 2020. Based on these results, three mulch treatments were selected for the experiments from 2021 to 2024 (Table 1). Both trials were conducted on clay-loam soil with similar texture, and the under-vine area was covered with natural weed vegetation and was not tilled prior to mulch application.

The vineyard used in field trial A had been planted in 2016 and managed for the cultivation of cv. 'Sylvaner' (*Vitis vinifera* L.) grafted on rootstock SO4. The vines had been planted at a spacing of 1.20 m × 2.00 m and trained using a Vertical Shoot Positioning (VSP) system. The row orientation was south-west. From planting until the start of the field trial in 2021, no chemical herbicides such as glyphosate had been applied. Under-vine weed control had been carried out using mechanical methods, including disc cultivators, dished ploughshares, or rotary star hoes. The experiment followed a randomised design, where each vine row represented an individual experimental unit (replicate). Each replicate consisted of 20 vines used for data collection, flanked by four border vines on each side of the row that were not included in the assessment. The experiment comprised four replicates per treatment.

In field trial B (49° 51' 17.3" N 9° 51' 49.8" E), the experiment was carried out on the cv. 'Sylvaner' grape variety that had been grafted onto rootstock SO4 and planted in 2013 with identical spacing (1.20 m × 2.00 m) and using a VSP system. The vine rows are similarly oriented in a south-west direction, and the inter-rows had been managed in the same way as in field trial A. In contrast to field trial A, field trial B followed a block design in which three adjacent vine rows formed one block, with three randomised replications. Each replicate consisted of 12 vines, with four vines on each side of the row serving as border plants. Identical treatments had been applied to both field trials in the years preceding the study, neither glyphosate nor any other chemical herbicides had been used. The treatments in both field trials comprised an untreated control (UC), a weed-free control by mechanical weeding (MW), and three different biodegradable-sprayable mulch treatments (SM-). The latter comprised the application of a mulch in a 2.5 L m^{-2}-thick layer and a 5.0 L m^{-2}-thick layer, referred to as SM-2.5E and SM-5.0E, respectively, where "E" stands for an early application before seeds emerged (Table 1). In addition, another biodegradable-sprayable mulch treatment (SM-5.0L), where "L" denotes a late application with weeds already reaching approximately 25 cm in height, was included (Table 1). Mechanical weeding (MW) was carried out according to standard practical methods using a Dished Ploughshare Cultivator round-the-vine weeder (LUV Perfekt®, Braun Maschinenbau GmbH, Landau/Pfalz, Germany) in the under-vine area when weeds covered about 60–75 % and were approximately 25 cm tall. In most seasons, mechanical weeding was performed twice, and in one year three times, depending on weed pressure.

2. Weather data

The region's climate is classified as humid temperate, with an annual average temperature of 10.4 °C and total annual precipitation of 649 mm (Deutscher Wetterdienst, 2021). Weather data for the experimental field were collected using the Adcon Telemetry AddVantage weather station system (Adcon Telemetry, Klosterneuburg, Austria), which was installed in the centre of the experimental area in both field trial A (36 rows with 2 m spacing, weather station placed ~35 m from edge) and field trial B (21 rows with 2 m spacing, weather station placed ~20 m from edge). Measurements included temperature and precipitation, which are summarised in Table 2 and Figure 2.

TABLE 1. Overview of treatments, details and application dates from 2021 to 2024 in two different experimental vineyards (field trial A and field trial B). UC = untreated control, MW = mechanical weeding, SM-2.5E = 2.5 L m^{-2} of mulch applied early, SM-5.0E = 5.0 L m^{-2} of mulch applied early, and SM-5.0L = 5.0 L m^{-2} of mulch applied late).

Treatment	Details	Field trial A		Field trial B	
		2021	2022	2023	2024
UC	Untreated control	included	included	included	included
MW	Mechanical weeding using dished ploughshare	27/04/2021 27/07/2021	03/05/2022 27/06/2022	15/05/2023 10/08/2023	20/03/2024 24/06/2024 28/08/2024
SM-2.5E	Mulch 2.5 L m^{-2} applied early	08/03/2021	17/03/2022	07/03/2023	12/03/2024
SM-5.0E	Mulch 5.0 L m^{-2} applied early	08/03/2021	17/03/2022	07/03/2023	12/03/2024
SM-5.0L	Mulch 5.0 L m^{-2} applied late	28/04/2021	20/04/2022	25/04/2023	23/04/2024

3. Composition of the biodegradable-sprayable mulch

The development, composition and characteristics of the biodegradable-sprayable mulch are described in detail in the European patent *EP 4 189 034 A1* by Kirchinger *et al.* (2023a) and by Kirchinger *et al.* (2024). It consists of two components: an oil-based component (A) and an aqueous starch-based component (B). The oil-based component contains ingredients such as fillers and the gelling agent sodium alginate. The aqueous component contains starch, as well as additional auxiliaries, including preservatives. Both components were mixed during application directly in the field, causing the substance to solidify immediately upon contact with the soil (Figure 1B). This process is essential for creating a relatively uniform mulch layer, even on coarsely structured topsoils. The composition of both components is shown in Table 3.

4. Application of the biodegradable-sprayable mulch

An application device (Figure 1A) was developed for the field trials, as described by Kirchinger *et al.* (2024). The device was attached directly to the tractor's three-point hitch. It consisted of two separate tanks for components A and B of the mulch, two independently controlled peristaltic pumps, each equipped with a pressure sensor, and one control unit. The two components were applied via a set of flat spray jet nozzles (3 mm diameter). Due to the mixing ratio, one nozzle was used for the oil-based phase, while two nozzles were used for the water-based phase. Two sets of the nozzle system were used, aligned at a precisely tuned angle to each other to prevent gaps in the mulch layer due to the rough texture of the ground. The pump flow and thus the mixing ratio of the two components was set using control software programmed using LabVIEW, which was developed by National Instruments (NI, Austin, TX, USA).

5. Soil sampling and analysis

Soil samples were taken from the under-vine area to a depth of 0–30 cm. For each treatment replicate, a composite sample was formed from four randomly collected soil cores. Sampling was carried out in field trial A on 8 March 2021 (before treatment application) and 17 October 2022 (after two growing seasons), and in field trial B on 20 February 2023 and 23 October 2024. Soil analyses were carried out to determine pH, available nutrients (P_2O_5, K_2O, Mg^{2+}), mineral nitrogen ($N–NH_4^+$, $N–NO_3^-$, N_{min}), organic carbon (C_{org}), humus content, and the C/N ratio. Measurements were performed according to VDLUFA (1991).

6. Weed suppression effectiveness

The effectiveness of weed suppression was evaluated by measuring aboveground weed biomass in the under-vine treatment area. For standardisation of the sampling area, a frame measuring 0.15 m^2 was randomly positioned four times within the 40 cm-wide treatment zone of each replicate. Above-ground vegetation within the frame was cut at ground level using scissors, ensuring that roots were not included, and all present weeds were manually harvested. For each treatment, 12 samples were collected on two different dates and in different places during the growing season in May/June and in September. The biomass was then dried in an oven at 90 °C for three days until a constant weight was achieved. The dry matter of the samples was determined and expressed as grams per square meter (DW_{weed} (g m^{-2})).

TABLE 2. Annual weather data of the experimental site, annual mean air temperature (°C), seasonal mean air temperature (°C, April to October), annual total precipitation (mm), and seasonal total precipitation (mm, April to October) calculated for 2021 to 2024.

Year	Annual total precipitation (mm)	Seasonal total precipitation (mm)	Annual mean air temperature (°C)	Seasonal mean air temperature (°C)
2021	571	357	10.2	14.3
2022	492	296	10.4	16.4
2023	537	308	10.8	16.2
2024	611	405	11.0	16.0

TABLE 3. Composition of component A (oil-based phase) and component B (water-based phase) of the mulch in mass percent.

Ingredients of component A (mass %)		Ingredients of component B (mass %)	
Rapeseed oil	30.1	Water	44.6
Cellulose fibres	2.3	Starch	12.3
Calcium sulphate	1.5	Glycerine	4.5
Sodium alginate	1.2	Sorbitol	2.2
		Sodium benzoate	1.1
		Sodium phosphate	0.3

FIGURE 1. A) Application of the biodegradable-sprayable mulch in the field trial B in spring using the prototype developed by the project partner Technology and Support Centre (TFZ) Straubing; B) and C) The biodegradable-sprayable mulch forms a uniform, gel-like layer directly on the soil in the under-vine area, which later solidifies to ensure stability; B) 2.5 L m^{-2} of mulch was applied early in March 2024 (SM-2.5E) and C) 5.0 L m^{-2} of mulch was applied early in March 2024 (SM-5.0E); D) Application using the prototype tractor-mounted device.

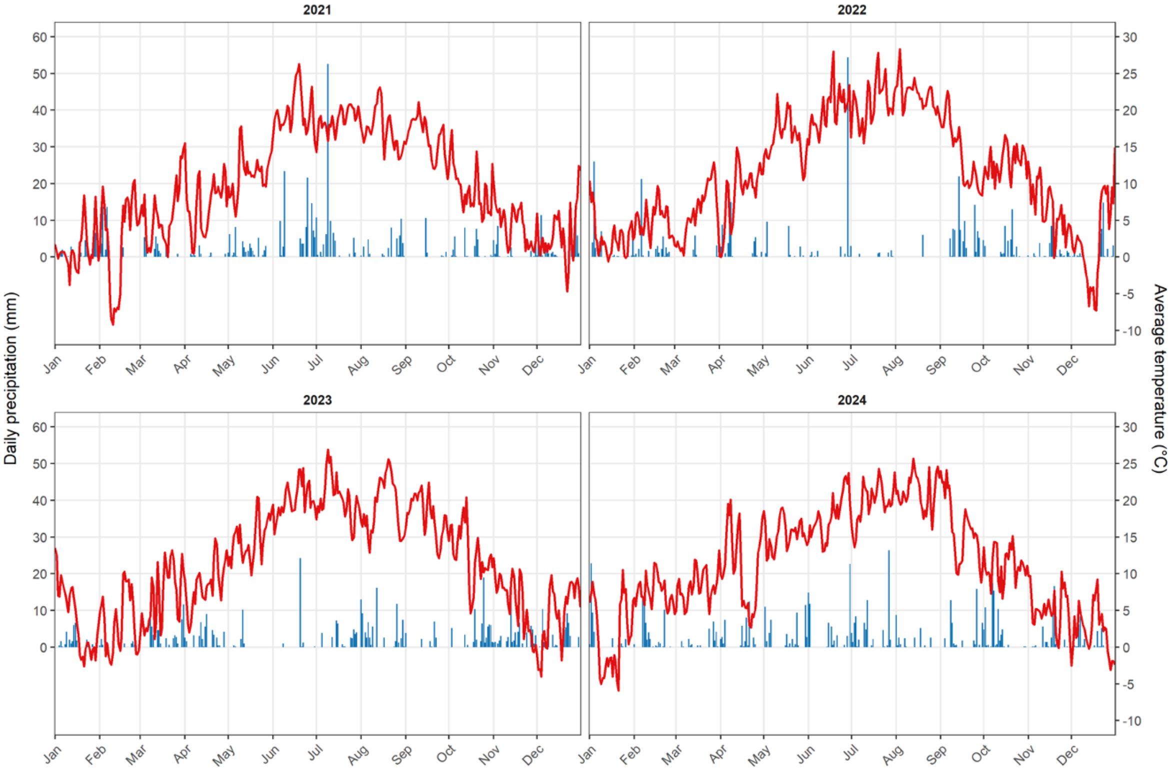

FIGURE 2. Daily total precipitation (mm, blue bars) and daily average air temperature (°C, red line) from January 2021 to December 2024.

7. Pruning weight

Pruning weight of grapevines was determined during winter dormancy as an indicator of vegetative growth. For each treatment, 10 grapevines per replicate were assessed. Shoots of each vine were manually chopped, weighed fresh and then dried in an oven at 90 °C until constant weight was achieved before being weighed.

8. Yield and must quality

In each year at harvest, grape yield was determined by weighing the grapes harvested from each vine (kg vine^{-1}) individually, with 10 vines per replicate. Grape quality was assessed by measuring total soluble solids (°Brix), total acidity (g L^{-1}), and pH in must samples obtained from the harvested grapes of 10 vines per replicate. The analyses were performed using Fourier-transform infrared spectroscopy (FTIR; FOSS, Denmark) to identify and quantify chemical components based on infrared absorbance as well as an enzymatic determinations with a Gallery Analyzer (Thermo Fisher Scientific, USA).

9. Statistical analysis

To assess the effects of treatment on yield and quality parameters, an Analysis of Variance (ANOVA) was conducted, followed by post-hoc Tukey's HSD test for pairwise comparisons among treatment means. Differences were considered significant at a significance level of $\alpha = 0.05$. In the cases where the data did not meet the assumptions for ANOVA (Shapiro–Wilk and Brown–Forsythe tests, $p < 0.05$), a Kruskal–Wallis test was applied, with subsequent post-hoc analyses, using pairwise Wilcoxon rank-sum tests with Bonferroni correction ($\alpha = 0.05$) to identify significant differences between the treatments. Soil chemical properties were analysed using ANOVA with Tukey's HSD or, when assumptions were violated, Kruskal–Wallis tests were carried out, followed by Dunn's tests with Holm correction ($\alpha = 0.05$). Statistical analyses were performed using SigmaPlot version 14.0 (Systat Software Inc., San Jose, California, USA).

RESULTS

1. Weather

The weather conditions during the growing season (April–October) and the entire year are summarised in Table 2. From April to October 2022, total precipitation was 492 mm, which is substantially lower than in the other experimental years (571 mm in 2021; 537 mm in 2023; 611 mm in 2024), and all experimental years received less precipitation than the 1991–2020 long-term average of approximately 649 mm (Deutscher Wetterdienst, 2021). During the same period, mean air temperatures averaged 10.4 °C in 2022, which is slightly higher than 10.2 °C in 2021, but is lower than the 10.8 °C and 11.0 °C recorded in 2023 and 2024, respectively. Notably, 2022 featured a 20-day rain-free interval between August and September, whereas 2021 experienced a 14-day dry period and 2023 an even longer 26-day dry period in early summer. In spring 2024, five post-budbreak frost nights were recorded, the coldest of which reached –1.4 °C (on 7 April). By comparison, the preceding years recorded only two frost events of comparable risk damage, with a temperature of around –1 °C. Figure 2 shows the climatic developments during the growing seasons and each year – notably the daily course of total precipitation and the daily average air temperature from 2021 to 2024.

2. Soil nutrient and chemical properties

In field trial A, no significant differences between treatments were observed at the beginning of the experiment (February 2021), except for the C/N ratio, for N_{min} and for K_2O. At the end of the trial experiment (October 2022), significant differences were found for nitrogen-related parameters. The mulch treatments showed lower $N\text{-}NO_3^-$ and N_{min} contents compared to the control (UC) and the mechanical treatment (MW). In addition, treatments with mulch exhibited increased values of C_{org} and humus content. Meanwhile, in field trial B, no significant differences were found between treatments at the beginning (February 2023), but after two seasons (October 2024), significant differences were detected in both soil pH and nitrate contents. The pH was higher in treatment SM-5.0E. Moreover, the $N\text{–}NO_3^-$ values in the mulch treatments were lower compared to UC and MW (mechanical weeding). All other soil parameters remained statistically unchanged. The results of the soil analyses are presented in Tables S1–S4.

3. Under-vine above-ground weed biomass

In field trial A (2021–2022), the untreated control (UC) consistently showed the highest biomass, measuring 227.2 g m^{-2} in May 2021 ($p < 0.05$), whereas mechanical weeding (MW) and mulching application (SM-2.5E, SM-5.0E, SM-5.0L) resulted in significantly lower values. In September 2021, all treatments showed reduced biomass (SM-5.0L at 11.3 g m^{-2}) that was significantly lower than UC (209.7 g m^{-2}). In May 2022, UC reached 333.0 g m^{-2}, while the lowest values were recorded for SM-2.5E and SM-5.0E (3.0 g m^{-2} and 2.2 g m^{-2}), which were significantly different to both UC and MW. In September 2022, SM-5.0L had the lowest biomass (1.6 g m^{-2}), but was only significantly different from UC (112.3 g m^{-2}). In field trial B (2023–2024), UC also consistently showed the highest biomass. In June 2023, UC had a biomass of 106.9 g m^{-2}, while MW and SM-5.0E tended to show lower values. No significant differences were observed in June 2023. In September 2023, biomass was 154.0 g m^{-2} for UC and 13.2 g m^{-2} for SM-5.0E. All mulch treatments were significantly different from UC. Furthermore, SM-5.0E was significantly different from MW (91.8 g m^{-2}). In May 2024, UC measured 111.0 g m^{-2}, while SM-5.0E biomass growth remained low (10.3 g m^{-2}). Furthermore, SM-5.0E was significantly different to MW (33.5 g m^{-2}). In September 2024, UC measured 103.3 g m^{-2}, while MW and all mulch treatments showed significantly lower values.

The production of biomass in SM-5.0E was the lowest (6.0 g m^{-2}) and was significantly different from MW. The late treatment of SM-5.0L also showed a low value of 11.1 g m^{-2}, but it was not significantly different from MW. Overall, the biodegradable-sprayable mulch treatments were effective in controlling under-vine weeds throughout the growing season. In particular, SM-5.0L reduced weed biomass consistently across both field trials and study years, except in June 2023, when no treatment differed significantly from the control. The aboveground weed biomass results are summarised in Table 4.

4. Grape yield and vine pruning weight

In field trial A (2021–2022), grape yield did not differ significantly between the treatments in 2021. However, in 2022, both SM-5.0E and SM-5.0L showed significantly higher yields than UC and performed comparably to MW (Table 5).

In field trial B (2023–2024), no significant differences in grape yield were observed between the treatments in either year (Table 5).

Vine pruning weights were highest under MW in 2021 and 2022. However, in 2021, mulch treatments had significantly increased pruning weights compared to UC and reached values similar to MW. Treatment comparison in 2022 showed that MW resulted in significantly greater vine pruning weights than UC and SM-2.5E. However, vine pruning weights under SM-5.0E and SM-5.0L were not significantly different from MW (Table 5).

In 2023, there were no significant differences between the treatments. By contrast, in 2024, SM-2.5E showed the highest vine pruning weights, slightly above MW, whereas SM-5.0L had significantly lower values (Table 5).

5. Grape must quality parameters

In 2021, no significant differences between the treatments were observed in terms of total soluble solids (TSS) and pH. However, total acidity (TA) differed significantly, with SM-5.0E showing significantly lower values compared to UC. In 2022, none of the measured grape must quality parameters (TSS, pH, TA) differed significantly between the treatments. In field trial B (2023–2024), no significant differences were detected between the treatments for any of the must quality parameters in either year. The results are summarised in Table 6.

TABLE 4. Effects of vineyard treatments (UC = untreated control; MW = mechanical weeding; SM-2.5E = 2.5 L m^{-2} of mulch applied early; SM-5.0E = 5.0 L m^{-2} of mulch applied early; SM-5.0L = 5.0 L m^{-2} of mulch applied late) on under-vine aboveground biomass (dry matter in g m^{-2}) in 2021 and 2022 in field trial A (*n* = 16), and 2023 and 2024 in field trial B (*n* = 12). Values are means ± standard deviation. Different letters in columns indicate significant differences among treatments (Kruskal–Wallis test followed by pairwise Wilcoxon tests with Bonferroni correction, $p < 0.05$).

Under-vine aboveground biomass [dry matter in g m^{-2}]								
	Field trial A				Field trial B			
Treatment	May 2021	September 2021	May 2022	September 2022	June 2023	September 2023	May 2024	September 2024
UC	227.2 ± 105.1 a	209.7 ± 174.3 a	333.0 ± 151.5 a	112.3 ± 156.0 a	106.9 ± 137.3 a	154.0 ± 92.7 a	111.0 ± 80.8 a	103.3 ± 67.5 a
MW	23.5 ± 23.5 b	72.7 ± 90.0 b	99.7 ± 92.7 b	9.4 ± 10.9 b	14.7 ± 23.3 a	91.8 ± 66.3 ab	33.5 ± 24.7 b	2.1 ± 5.6 b
SM-2.5E	55.9 ± 33.7 b	48.1 ± 69.0 bc	3.0 ± 6.9 c	10.6 ± 13.3 b	23.6 ± 34.1 a	24.9 ± 15.7 b	14.3 ± 10.2 bc	16.4 ± 27.4 c
SM-5.0E	74.5 ± 71.5 b	49.5 ± 24.8 bc	2.2 ± 4.6 c	65.2 ± 119.2 ab	15.8 ± 11.7 a	13.2 ± 13.2 b	10.3 ± 8.1 c	6.0 ± 7.8 bc
SM-5.0L	28.5 ± 57.0 b	11.3 ± 21.5 c	42.2 ± 58.0 b	1.6 ± 4.8 b	21.3 ± 26.2 a	23.8 ± 38.1 b	12.1 ± 12.0 bc	11.1 ± 21.1 c

TABLE 5. Grape yield (kg $vine^{-1}$) and vine pruning weight (g $vine^{-1}$) under different vineyard treatments (UC = untreated control; MW = mechanical weeding; SM-2.5E = 2.5 L m^{-2} of mulch applied early; SM-5.0E = 5.0 L m^{-2} of mulch applied early; SM-5.0L = 5.0 L m^{-2} of mulch applied late) in field trial A (2021, 2022) and field trial B (2023, 2024). Values are means ± standard deviation (*n* = 40 for 2021–2022 and *n* = 30 for 2023–2024, respectively). Different letters in columns indicate significant differences between treatments (Tukey's HSD, 5 % level; 95 % confidence).

	Field trial A				Field trial B			
	Grape yield (kg $vine^{-1}$)		Vine pruning weight (g $vine^{-1}$)		Grape yield (kg $vine^{-1}$)		Vine pruning weight (g $vine^{-1}$)	
Treatment	2021	2022	2021	2022	2023	2024	2023	2024
UC	1.5 ± 0.1 a	1.7 ± 0.9 a	70.7 ± 52.9 a	185.1 ± 114.0 a	3.1 ± 0.7 a	3.2 ± 0.9 a	227.3 ± 70.5 a	356.7 ± 179.2 ab
MW	2.0 ± 0.3 a	2.2 ± 1.0 ab	124.0 ± 39.4 b	226.7 ± 62.6 c	3.1 ± 0.8 a	3.6 ± 1.0 a	261.0 ± 103.3 a	325.0 ± 128.5 ab
SM-2.5E	1.7 ± 0.4 a	2.3 ± 1.1 ab	112.0 ± 58.4 b	179.1 ± 71.0 ab	3.1 ± 0.8 a	3.4 ± 1.3 a	246.9 ± 87.1 a	384.3 ± 139.3 a
SM-5.0E	1.7 ± 0.3 a	2.5 ± 0.8 b	112.93 ± 50.2 b	204.6 ± 67.8 abc	3.5 ± 0.8 a	3.4 ± 1.1 a	240.6 ± 75.6 a	304.8 ± 106.1 ab
SM-5.0L	1.9 ± 0.4 a	2.8 ± 0.9 b	106.14 ± 55.3 b	211.1 ± 67.7 abc	3.4 ± 0.8 a	3.0 ± 1.1 a	208.1 ± 83.1 a	295.9 ± 123.4 b

TABLE 6. Grape must quality parameters of cv. 'Sylvaner' under different vineyard treatments (UC = untreated control; MW = mechanical weeding; SM-2.5E = 2.5 L m^{-2} of mulch applied early; SM-5.0E = 5.0 L m^{-2} of mulch applied early; SM-5.0L = 5.0 L m^{-2} of mulch applied late) in field trial A (2021, 2022) and field trial B (2023, 2024). Values are means ± standard deviation (n = 4 in 2021–2022; n = 3 in 2023–2024) for total soluble solids (TSS; °Brix), pH, and total acidity (TA; g L^{-1}). Different letters within columns indicate significant differences between treatments (Tukey's HSD, 5 % level; 95 % confidence).

	Field trial A						**Field trial B**					
	2021	**2022**	**2021**	**2022**	**2021**	**2022**	**2023**	**2024**	**2023**	**2024**	**2023**	**2024**
Treatment	TSS (°Brix)		pH		TA (g L^{-1})		TSS (°Brix)		pH		TA (g L^{-1})	
UC	22.2 ± 0.5 a	21.1 ± 1.0 a	3.1 ± 0.0 a	3.1 ± 0.0 a	9.1 ± 0.2 a	7.1 ± 1.0 a	22.3 ± 0.6 a	21.5 ± 0.8 a	3.2 ± 0.1 a	3.1 ± 0.0 a	6.9 ± 0.3 a	7.2 ± 0.8 a
MW	22.5 ± 0.7 a	20.5 ± 0.7 a	3.1 ± 0.0 a	3.0 ± 0.1 a	8.6 ± 0.4 ab	7.0 ± 1.1 a	22.7 ± 1.0 a	21.2 ± 1.2 a	3.2 ± 0.0 a	3.2 ± 0.0 a	6.5 ± 0.4 a	7.1 ± 0.2 a
SM-2.5E	21.7 ± 0.5 a	20.6 ± 1.5 a	3.1 ± 0.0 a	3.0 ± 0.1 a	8.8 ± 0.2 ab	6.8 ± 0.8 a	21.9 ± 0.7 a	22.0 ± 0.6 a	3.2 ± 0.0 a	3.1 ± 0.0 a	6.8 ± 0.2 a	7.6 ± 1.1 a
SM-5.0E	21.3 ± 0.8 a	19.7 ± 0.8 a	3.1 ± 0.0 a	3.0 ± 0.1 a	8.3 ± 0.3 b	6.8 ± 1.4 a	22.5 ± 0.4 a	21.1 ± 0.3 a	3.2 ± 0.0 a	3.1 ± 0.0 a	7.0 ± 0.3 a	7.2 ± 0.4 a
SM-5.0L	21.4 ± 0.2 a	20.5 ± 1.3 a	3.1 ± 0.0 a	3.0 ± 0.1 a	8.5 ± 0.4 ab	6.9 ± 0.7 a	22.5 ± 0.6 a	21.1 ± 0.8 a	3.2 ± 0.0 a	3.1 ± 0.0 a	6.9 ± 0.5 a	7.0 ± 0.7 a

DISCUSSION

This study aimed to evaluate a biodegradable-sprayable mulch in vineyards based on two field trials conducted over two years each and focusing on its effectiveness in weed control and its practical applicability under field conditions. Weather conditions varied with study year and likely influenced weed growth dynamics and treatment performance. Overall, average temperature and precipitation during the growing seasons was below the long-term average, with 2022 being the driest year. Prolonged dry periods in 2022 and 2023, as well as several frost events in spring 2024, may have affected both weed emergence and growth, as well as vine development.

The effectiveness in weed control was assessed by measuring the weed biomass in the under-vine area. The analysis of weed biomass from 2021 to 2024, showed that, when applied in spring, the biodegradable-sprayable mulch was in most cases at least as effective as mechanical weed control, and in several instances it was significantly more effective.

This demonstrates that the mulch can provide effective weed management under field conditions. In particular, the higher application rate (5 L m^{-2}) tended to maintain longer-lasting suppression, suggesting that film thickness plays a crucial role in the persistence of the barrier effect. This observation is consistent with Gloeb *et al.* (2023), who demonstrated that higher mulch application rates can prolong weed suppression. Borrowman *et al.* (2020) and Kirchinger *et al.* (2024) showed that thicker mulch layers form a more stable physical barrier, degrade more slowly, and thus maintain longer-lasting protection. Although no significant differences were observed between the mulch treatments in most years, the results suggest that a greater film thickness tends to be associated with longer weed-suppression efficacy.

Overall, the results of the biomass show that the mulch layer remained functional throughout an entire growing season. However, first signs of mulch degradation were observed approximately after two months of application, with cracks and holes in the mulch film (data not shown). From September onwards, the mulch turned grey-black and became very brittle in places. This is an indication of microbial degradation processes that primarily cause discolouration and signal the beginning of progressive material ageing. In a laboratory and a field trial using the same mulch material, Kirchinger *et al.* (2024) reported that initial cracks appeared in the mulch under dry conditions after just two months. After it rained, the cracks got smaller because the sodium alginate in the material soaked up the water, making the material softer and more resistant to cracking.

Previous studies on sprayable mulch systems reported effective durations of approximately two months (Giaccone *et al.*, 2018), three months (Immirzi *et al.*, 2009), and five–six months (Vox *et al.*, 2013) and nine months (Sartore *et al.*, 2013).

Despite these clear treatment effects, some treatments showed high standard deviations. This variability reflects the heterogeneous spatial distribution of weed infestation in the under-vine area, which can result from clustered growth of dominant species such as creeping thistle *(Cirsium arvense)* or localised environmental conditions. While the use of randomised plot selection ensured unbiased sampling, it may have contributed to the observed data spread.

In our field trials, the mulch layer did not always appear uniform, suggesting that local site conditions influenced the quality of coverage. This unevenness was likely caused by soil surface roughness, existing weed cover, and slight variations in spray distribution during application. As suggested by Immirzi *et al.* (2009), Vox *et al.* (2013), and Follak *et al.* (2024), the uniformity of the mulch layer depends heavily on the soil conditions prior to application. On loose, coarse and uneven soils, the liquid material cannot form a homogeneous film, but instead flows into cracks and depressions, significantly reducing its barrier effect against weeds. Conversely, on compacted, smooth surfaces, a more consistent and stable mulch layer can be achieved. According to Follak *et al.* (2024), loose, uneven soil prevents the mulch from forming an effective barrier, as it allows light to penetrate into the soil, thus promoting the germination of photoblastic seeds. In the present study, our visual observations indicated that, with optimal coverage by the biodegradably mulch, parts of the aboveground foliage were severely damaged or necrotic. This can be attributed to impairment of leaf function, particularly through coverage of leaf surfaces and stomata by the mulch film, blocking transpiration and gas exchange (Kirchinger *et al.*, 2024), which can lead to the temporary weakening or even death of individual organs or entire plants. Despite these observations, no significant differences in dry biomass were detected between the late (SM-5.0L) and early (SM-5.0E) applications at the May and September assessments, except for May 2022, when the early mulch applications resulted in significantly lower weed biomass than the late treatment. It can therefore be assumed that the observed stress stimulus was insufficient to permanently suppress established weeds, or that the effect occurred only in competitively weaker species, without substantially affecting total biomass.

In this study, the timing of mulch application had only a minor effect on weed suppression. Significant differences between early and late treatments were found only in spring 2022, when early applications resulted in lower weed biomass in May. This was likely related to the unusually dry conditions in early spring 2022, which generally reduced weed emergence and biomass due to limited soil moisture.

While previous studies on the efficacy of spray-mulch systems have focused primarily on pre-emergence applications (Braunack *et al.*, 2020; Claramunt *et al.*, 2020; Giaccone *et al.*, 2018; Shen *et al.*, 2019; Warnick *et al.*, 2006), a study by Gloeb *et al.* (2023) has indicated that post-emergence application can also be effective, provided that the plants are still at an early developmental stage (*e.g.*, the cotyledon phase). In this study, however, the weeds in the late application treatment were already approximately 25–30 cm tall, but in most cases, late applications achieved a weed suppression effect comparable to early applications. Such an extended application window could have the practical advantage of allowing mulch treatments to be more flexibly integrated into operational workflows as long as the soil and weather (no wind, frost or rain) conditions are suitable (based on the conditions of this study). The efficacy of the mulch also depends on the weeds present.

This observation is further supported by Mas *et al.* (2021), in which various hydro-mulch formulations based on wheat straw, rice husks, and fungal substrate were tested under controlled environmental conditions in a greenhouse setting. Despite differing compositions, all treatments exhibited a significant reduction in shoots of perennial or pre-germinated rhizomatous weeds, a clear indication of the mulch's mechanical barrier effect. In the present study, all mulch treatments effectively prevented weed growth with a consistent basic barrier effect across application rates. In a few cases, the treatments with a double concentration showed a better effect. However, the field and species observations revealed that some of the perennial species, particularly the creeping thistle *(Cirsium arvense)* and hoary cress *(Lepidium draba)*, are able to penetrate the thicker and intact mulch layers (see Tables S5–S8). This is most likely due to their vigorous regenerative capacity and extensive rhizome reserves. Individuals of *Cirsium arvense* are known to resprout from mechanically damaged root fragments in deeper soil layers (Graglia & Melander, 2005), and *Lepidium draba* exhibits a high vegetative dispersal dynamic (Selleck, 1965).

Similar observations were made by Lososová *et al.* (2004). In this study, competitive species such as *Cirsium arvense* and *Lepidium draba* were observed to persist or even increase in the treatment replicates over the study period, evidencing their ability to penetrate dense mulch layers, particularly where the application was uneven or the mulch started to degrade. While Mas *et al.* (2021) specifically measured the penetration rate of defined rhizome fragments, a differentiated comparison in this field study was not feasible, as the weed vegetation was able to establish itself unhindered over the years. Notably, competitively weaker species, such as *Veronica persica* and *Polygonum aviculare*, were absent from treated areas or occurred at lower relative abundances, while they regularly occurred in the untreated control. In treated areas, these species were observed only where gaps in the mulch film were present or where material degradation had occurred. This pattern indicates a higher sensitivity of these species to the physical barrier formed by the mulch layer. A general trend observed across both field trials was that weed biomass in mulch treatments tended to be lower in the second year compared to the first year. This suggests a cumulative suppression effect, possibly resulting from the residual mulch layer and a gradual depletion of the weed seed bank. Similar findings by Fredrikson *et al.* (2011) and Mas *et al.* (2021) indicate that repeated mulching can reduce weed emergence over time by creating a more highly buffered soil environment that limits germination and seedling establishment. Therefore, the tendency toward reduced weed biomass in the second application year in this study may reflect a combination of residual mulch effects and a diminished weed seed reservoir in the soil. It can be assumed that this trend would continue in subsequent years, potentially leading to a gradual reduction in overall weed diversity and a shift toward more dominant, persistent species. However, this assumption remains speculative and highlights the need for long-term studies to investigate such vegetation dynamics under continued mulch application.

In summary, these findings confirm that the biodegradable-sprayable mulch is a yield-neutral alternative to conventional mechanical cultivation that has the potential to sustain yields under dry conditions.

In our two separate field trials, yield differences were only observed under dry climatic conditions. In 2022, the driest growing season of the entire study period, in which there were several prolonged dry phases, both of the higher mulch application rates resulted in greater mean yields than the control, whereas no significant differences were found in the other more humid years. This suggests that the mulch may have improved soil moisture and may have contributed to yield stabilisation or optimisation under water-limited conditions. In the years with sufficient rainfall, however, the effect on yield appears to have been too small to become statistically significant. Similar observations have been reported in other studies. Several experiments using organic or biodegradable-sprayable mulch materials have shown improved soil-water availability but no consistent yield increases under well-watered conditions (Čížková *et al.*, 2021; Braunack *et al.*, 2020; Warnick *et al.*, 2006). For instance, Čížková *et al.* (2021) found that organic loose mulches increased soil moisture compared with bare soil, while yield responses remained minor in years with adequate rainfall. Similarly, Cabrera-Pérez *et al.* (2022) and El-Wahed *et al.* (2020) observed that when rainfall is sufficient, natural soil moisture already meets crop water demand and mulch therefore provides no additional yield benefit. This indicates that although mulching effectively conserves soil moisture, the effect is generally not strong enough to influence yield when water availability is not limiting. Overall, the results show that biodegradable-sprayable mulch can provide measurable advantages under dry climatic conditions, while remaining yield-neutral in years with sufficient rainfall. Future research should therefore focus on quantifying these water-related effects and the underlying soil processes. Long-term studies will be essential to confirm whether the observed yield improvements under dry conditions can be consistently reproduced.

Pruning weight was recorded at both sites over two years to assess the possible effects of mulch treatments on vegetative vine growth. In field trial A, 2021 showed significantly higher pruning weight for all mulch treatments compared with the untreated control (UC), whereas no differences were observed relative to MW. In 2022, MW recorded the highest value and was significantly higher than SM-2.5E, but not significantly different from UC or the other mulch treatments. In field trial B, in which the vines were older and had higher baseline pruning weights, no significant differences among treatments were found in 2023. However, in 2024, SM-2.5E exhibited the highest mean value, differing significantly from SM-5.0L. The results indicate that pruning weight was affected by mulch treatments in most years. However, the extent of this influence may have depended on site conditions, vine age, and weather patterns during the growing season, which could explain the inconsistent results. Similar observations were reported by Mairata *et al.* (2024), who found that organic mulches sometimes led to higher pruning weights, especially compared with conventional tillage, which may limit vegetative growth by destroying near-surface roots. This effect is plausible here, but was not demonstrated consistently.

Across all years and sites, no consistent effects of mulch treatments on key must parameters (TSS, pH, titratable acidity) were observed. Only in 2021 did SM-5.0E exhibit a significantly reduced titratable acidity compared with the untreated control, an effect not reproduced in later years. No significant differences were found for total soluble solids or pH values; the observed fluctuations were likely due to vintage effects and site-specific conditions, such as climate and ripening progression. Recent literature corroborates these results: Mairata *et al.* (2024) reported that while organic mulches can influence acid profiles, the effects depend on the material used and do not necessarily compromise must quality. Overall, the results indicate that the biodegradable-sprayable mulch material has no direct impact on must quality.

CONCLUSION

Across the two independent two-year field trials, the application of biodegradable-sprayable mulch derived from renewable materials provided weed control performance at least equivalent to, and in some cases more efficient than, mechanical weeding, which typically requires multiple passes per season (*e.g.*, two to four cultivations between spring and early summer). In particular, the SM-5.0L treatment (5 L m^{-2}) was found to consistently yield the lowest late-season weed biomass. Thicker mulch films persist longer than thinner ones, and post-emergence applications may offer growers greater operational flexibility in timing – as treatments can be delayed until the field access and workload conditions become favourable – without substantially reducing efficacy.

Importantly, no significant alterations were detected in grape yield, pruning weight, or must quality parameters (TSS, pH, titratable acidity) among mulched, mechanically weeded, and untreated vines, indicating that biodegradable-sprayable mulch can maintain vine performance comparable to conventional tillage. However, yield data from the driest season suggest that thicker mulch layers may help stabilise or slightly improve yields under dry conditions, likely due to improved soil moisture retention. Furthermore, it was noted that vigorous rhizomatous weeds such as *Cirsium arvense* and *Lepidium draba* penetrate intact mulch layers over time. Overall, biodegradable-sprayable mulch emerged as a promising and eco-friendly alternative for integrated vineyard weed management, which does not compromise vine productivity or fruit quality. However, further research is needed to improve the practical feasibility of the biodegradable-sprayable mulch system and to evaluate its performance across different soil types and climate and water-limited conditions before it can be considered ready for practical use.

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