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ORIGINAL ARTICLE

Evaluation of a Biodegradable and Sprayable Mulch Material for Weed Control in Vineyards and Orchards

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Abstract
Alternative weed management strategies are needed to reconcile the production, health, and environmental goals in agriculture. In this study, a recently developed sprayable self-hardening mulch material based on renewable raw materials (mainly rapeseed oil, starch and sodium alginate) was tested for its potential for weed control in vineyards and orchards. Field trials were conducted in Austria, Germany, and Italy. Weed coverage and biomass were assessed after the application of the mulch material and common in-row weed management practices, namely, herbicide use and mechanical weeding. The present trials showed that the mulch material is largely able to reduce weed growth at a rate comparable to herbicide use and mechanical weeding. The strongest effect on weed coverage was observed shortly after its application (three to four weeks) with a reduction of 83–97% compared with the untreated control. The greatest reduction in biomass was observed in May and June (83–99%). Weed growth then increased to varying degrees depending on the site. The mulch material reached its limits when persistent weeds with extensive root systems (e.g. *Cirsium arvense*) were prevalent or when high weed pressure was present before the application. For a broader application, optimizations in the use of the mulch material are needed, for example, regarding the application timing and optimal layer thickness. Above all, further development of the application technology and an improvement in cost efficiency are required.

Keywords Weed management · Sustainable agriculture · Permanent crops · Biodegradable polymers

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Introduction

Weeds reduce the productivity of vineyards and orchards by competing with grapevines and fruit trees for water and nutrients (Pardini et al. 2002). The area between rows can be easily cultivated, whereas intra-row weed control requires special techniques. In recent decades, herbicides and mechanical weeding have dominated intra-row weed control in most vineyards and orchards. However, herbicides have been criticised for their negative effects on human health and the environment, such as contamination of surface and ground water (e.g. Louchart et al. 2001), residues in food (Ying and Williams 1999), and the development of resistant weed populations (Doğan et al. 2022). Mechanical weeding increases soil erosion, especially on slopes (Ruiz-Colmenero et al. 2011) and can cause root and trunk injuries (Pergher et al. 2019). Therefore, there is a need for sustainable weed control strategies that maintain productivity, fruit quality, and other ecosystem services such as soil erosion mitigation.

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Mulching has been identified as an alternative to herbicides and mechanical weeding for vineyards and orchards (Mia et al. 2020). A wide variety of materials can be used as mulches, such as living plants, organic materials (straw and wood chips), and plastics (Mia et al. 2020). Both living (e.g. white clover) and organic (wood chips) mulches can effectively control weeds and prevent soil erosion, but have system trade-offs, such as increased damage from rodents and high material input (e.g. wood chips) (Granatstein and Mullinix 2008). Plastic mulch based on polyethylene has already been used, but is highly controversial due to its negative environmental impact, as considerable amounts of plastic waste are produced (Steinmetz et al. 2016).

An alternative is the use of biodegradable plastic mulch made from natural or synthetic polymers, which can be mixed into the soil after harvest and leaves with almost no residues in the field (Abbate et al. 2023). Biodegradable polymers can also be applied to soil in liquid form, allowing for broader use and flexibility in the timing of application (Gloeb et al. 2023). Sprayable mulches, e.g. those based on sodium alginate (Immirzi et al. 2009), chitosan, and/or cellulose (Giaccone et al. 2018; Borrowman et al. 2020) have shown significant weed suppression. Its application in a narrow strip within the row combined with other inter-row weed management options (e.g. tillage and mowing) offers the potential for sustainable weed control in permanent crops. Nevertheless, sprayable mulch material should ensure long-term weed control, and the method of application must be suitable for use in the field.

A recently developed, self-hardening liquid mulch material based exclusively on renewable raw materials (Kirchinger et al. 2024) offers a new approach for weed control in permanent crops. The purpose of this study was to investigate the potential of this sprayable mulch material for weed control in vineyards and orchards in field trials, and to evaluate its suitability for practical use.

Table 1 Composition of component A (oil-based phase) and component B (water-based phase) in mass percent

Ingredients of component A		Ingredients of component B	
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

Material & Methods

Composition of the Sprayable Mulch Material

The development and composition of the sprayable mulch material are described in detail in Kirchinger et al. (2024). In overview, the material consists of two components: an oil-based sodium alginate compound (A) and a water-based starch compound (B). In addition to the main ingredients (rapeseed oil, starch), both components contain ingredients such as fillers, plasticizers and gelling agents. The composition of both components is shown in Table 1. Both components are mixed directly on site and the material solidifies immediately (Fig. 1b). This is important to obtain a homogenous mulch layer even on rough surfaces.

Application of the Sprayable Mulch Material

An application device (Fig. 1a) was developed for the field trials (Kirchinger et al. 2023). It consisted of two separate tanks for the components A and B, two peristaltic pumps, pressure and flow sensors and a control unit. The two components were pumped through tubes and were then applied

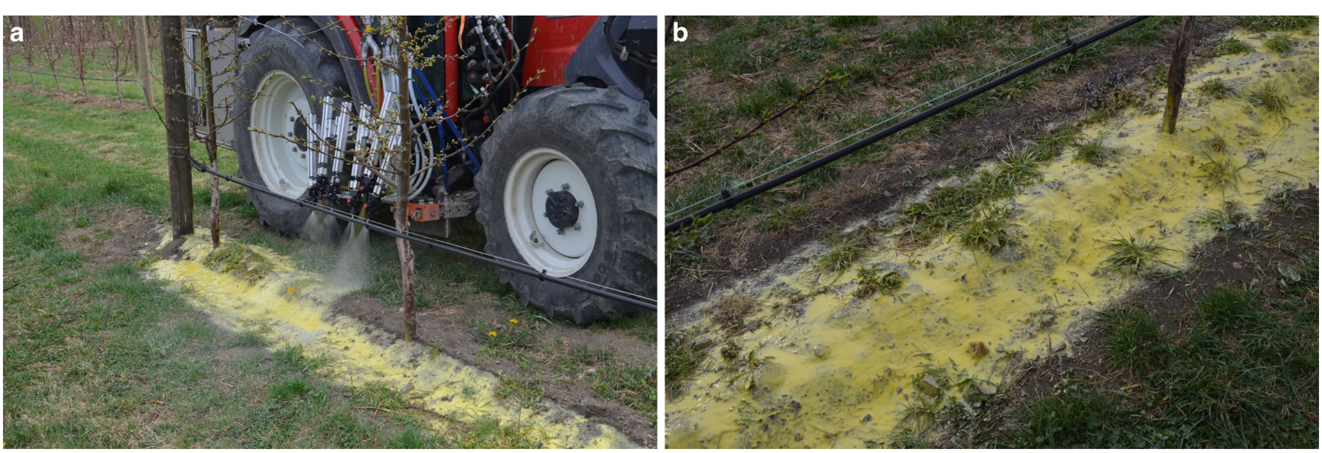

Fig. 1 **a** Application of the sprayable mulch material in an orchard with the self-designed application unit, **b** the material solidifies immediately after application. (© Swen Follak)

Table 2 Overview of the field trial sites, the crops involved, geographic coordinates, and the site characteristics (sea level; precipitation and average temperature in 2022)

Sites	Crop	Coordinates		Site characteristics		
		N	E	m a.s.l.	mm	°C
Kierling	Plum	48°17′42.0″	16°17′08.2″	396	456	11.3
Langenzersdorf	Grapes	48°18′37.5″	16°22′06.2″	250	473	11.9
Laimburg	Apple	46°23′09.3″	11°17′28.4″	222	607	12.8
Ölleiten	Grapes	46°23′23.9″	11°15′04.5″	320	709	13.5
Veitshöchheim	Grapes	49°51′17.3″	09°51′49.8″	295	646	11.6

via a set of flat spray jet nozzles. Due to the mixing ratio one nozzle was used for the oil component while two nozzles were used for the water phase. Two sets of that nozzle system were used, aligned at a precisely tuned angle to each other to prevent gaps in the mulch layer due to unevenness in the ground. The pump flow and thus, the mixing ratio of the two components was set using a control software (LabVIEW, Bitter et al. 2006).

Field Trial Locations

This study was conducted in Austria in Kierling & Langenzersdorf (Lower Austria), in Italy in Laimburg & Ölleiten (South Tyrol), and in Germany in Veitshöchheim (Bavaria) in 2022 (Table 2).

Experimental Design

At the Kierling site, the orchard was planted with the plum variety 'Haroma' on the rootstock St. Julien A in 2020. The inter-row space was 3.6 m, and the in-row space was 2.0 m. The experiment was arranged as a randomized block design with four replicates. Each replicate consisted of five plum trees. The treatments were an untreated control (UC), mechanical weeding (MW) and the sprayable mulch material (MM), which was applied once on 30th March 2022, at a width of 80 cm (thickness: 5 mm). Mechanical weeding (MW) was carried out using a Clemens SL Radius Plus round-the-vine weeder (Clemens GmbH & Co. KG, Wittlich, Germany) four times (03rd May, 16th May, 07th June and 06th July 2022).

At the Langenzersdorf site, the vineyard was planted with 21 different vine varieties. The inter-row space was 3.0 m, the in-row space was 1.0 m, and the heads of the vines were at a height of approximately 1.0 m. Each treatment consisted of 20 vines in four replicates. Treatments were an untreated control (UC), mechanical weeding (MW), herbicide application (H) and the sprayable mulch material (MM), which was applied once on 30th March 2022, at a width of 60 cm (thickness: 5 mm). Herbicides were applied three times on 04th April 2022 (flazasulfuron 0.2 kg/ha, cycloxydim 2 l/ha), 02nd June 2022 and 26th July 2022 (each carfentrazone-ethyl 0.5 l/ha, pyraflufen-ethyl, 0.1 l/ha) with a sprayer (Bauer, Voitsberg, Austria). MW was conducted on the same dates using a Tournesol round-the-vine weeder (Pellenc SAS, Notre Dame, France). Treatments UC, MW and H have already been applied in the same plots in the previous year.

At the Laimburg site, the orchard was planted with the apple variety 'Granny Smith' on the rootstock M9 in 2013. The distance between the rows was 3.2 m, and the intra-row space was 0.8 m. At the Ölleiten site (IT), the vineyard was planted with the vine variety 'Lagrein' in 2000. The inter-row space was 1.8 m, the intra-row space was 0.9 m, and the heads of the vines were at a height of approximately 0.9 m. Both experiments were arranged as a randomized block design with four replicates. Each replicate consisted of 7 trees and 15 vines, respectively. The treatments were an untreated control (UC), weed brushing (WB), herbicide application (H), mechanical weeding (MW), the sprayable mulch material (MM) and a brushed mulch material application (BM). On 22nd March 2022, WB and BM were brushed in the vineyard with a Vine Cleaner (W1, Braun Maschinenbau GmbH, Landau/Pfalz, Germany) and in the orchard with an inter-row weed mower (BioSystem.Series BS, Aedes, Andriano, Italy) in the inter-row space to remove existing weeds. In the variant MW, a Ladurner 7H (Ladurner, Laas, Italy) was used and in H, glyphosate (vineyard: 1 kg/ha, orchard: 1.3 kg/ha) was applied on the same date in the intra-row space using a portable powder sprayer Lochmann BP 200 (Lochmann, Nals, Italy). In the variants MM and BM (in BM additionally to the brush treatment) the mulch material was applied on 23rd March 2022 (thickness: 5 mm). No further intra-row treatments were performed. All treatments were carried out at an intra-row width of 40 cm in the vineyard site and of 80 cm in the orchard site.

At the Veitshöchheim site, the vineyard was planted with the variety 'Silvaner' in 2016. The trial was arranged as a randomized complete line design with four replicates. Each treatment consisted of four replicates with 26 vines grown about 1.2 m apart within a row. The treatments were an untreated control (UC), a mechanical weeding (MW), a herbicide application (H), the sprayable mulch material with an early (MM-E) and a late application (MM-L) (thickness each: 5 mm, width of 40 cm). MM-E was applied on 17th March 2022 and MM-L on 20th May 2022. MW and H were carried out on 03rd May and 28th June 2022. MW was performed using a Dished Ploughshare Cultivator

Table 3 Effects of orchard treatments (*UC* untreated control, *MM* mulch material, *MW* mechanical weeding) on intra-row weed coverage in Kierling (Austria) in 2022. Each data point indicates a weed coverage estimation at the given date. First data point shows initial weed coverage before MM treatment. Letters indicate significant differences within the variants at the given date (Dunn-Bonferroni-Test, $\alpha = 0.05$)

Treatment	Intra-row weed coverage [%]						
	28/03/22	06/04/22	20/04/22	18/05/22	07/06/22	06/07/22	30/08/22
UC	10.7 a	13.4 a	29.6 b	75.6 c	79.4 b	69.1 c	57.3 c
MM	8.9 a	12.2 a	3.7 a	14.5 b	17.8 a	22.8 b	20.5 b
MW	12.2 a	18.7 a	33.0 b	2.1 a	16.1 a	6.0 a	11.1 a

round-the-vine weeder (LUV Perfekt, Braun Maschinenbau GmbH, Landau/Pfalz, Germany). In H, glyphosate (5 l/ha) was applied with a backpack sprayer (SOLO Kleinmotoren GmbH, Sindelfingen, Germany).

Data Collection and Analysis

Weed coverage was recorded at all sites before the first treatment, after which multiple efficacy assessments were carried out depending on the site. At the Kierling and the Langenzersdorf sites, intra-row weed coverage (0 to 100%) was estimated visually using a 0.1 m^2 frame (Goettinger estimation frame) at four points per plot with 16 (sub-)samples per treatment. At the Laimburg, Ölleiten and Veitshöchheim sites, intra-row percent weed coverage was estimated using an open-source image analysis tool (ImageJ Fiji; Schindelin et al. 2012). This method involves capturing a two-dimensional image of the green canopy with a digital camera followed by an automatic calculation of the percentage of green pixels used as a parameter for weed coverage. Images (Olympus OM-D E-M10 Mark III, Olympus Tokio, Japan) were taken using a 0.15 m^2 frame at four points per plot on 6 dates with 16 (sub-)samples (Veitshöchheim) and at two points per plot on 7 dates with 8 (sub-) samples (Laimburg, Ölleiten) per treatment. The intra-row above-ground biomass was collected at all sites (except at the Langenzersdorf site) by using the respective frame and cutting the vegetation at ground level. Samples were dried in an oven at 80 °C for 24 h and weighed to determine dry matter. At the Kierling site, biomass was collected using a 0.1 m^2 frame with 8 samples per treatment on three dates. At the Laimburg, Ölleiten and Veitshöchheim sites, biomass was collected using a 0.15 m^2 frame with 8 samples and 16 samples, respectively, per treatment on two dates.

The effects of the variants on weed coverage and biomass were assessed using one-way analysis of variance (ANOVA). Mean comparisons between treatments were performed using Tukey tests, and differences with a significance level of $\alpha = 0.05$ were considered significant. Alternatively, a Kruskal-Wallis test and post-hoc tests (Dunn-Bonferroni tests, $\alpha = 0.05$) were performed to determine significant differences between the variants. Statistical analyses were performed using IBM SPSS Statistics (version 26.0, IBM Corp, Armonk, New York) or in R version 4.3.0. (R Core Team 2023).

Results

Orchards

At the Kierling site, the main weeds before the treatments (28th March 2022) were as follows: *Taraxacum sect. Ruderalia, Lolium perenne, Stellaria media*, and *Veronica persica*. Other species (at lower cover levels) included *Lamium purpureum, Senecio vulgaris, Lactuca serriola, Capsella bursa-pastoris, Geranium* spp., and *Trifolium repens*. Weed coverage ranged from 9 to 12% in the variants (Table 3).

In the UC variant, weed coverage increased over time, reaching nearly 80% in June, and declining toward the end of August (<60%). In the MM variant, the lowest cover value was reached three weeks after the application (20th April 2022) at approximately 4% (Table 3). The initial weeds were controlled sufficiently. Thereafter, the weed coverage increased to a maximum of 23%. Perennial species, such as *Convolvulus arvensis, Elymus repens*, and annual grasses (*Setaria pumila, Digitaria sanguinalis*) increased during the growing season. *Convolvulus arvensis* sprouted through the mulch layer, whereas annual grasses emerged in the cracks of the MM that had developed (Fig. 2). However, overall, weed coverage was significantly reduced compared to the UC treatment from April onwards. The first treatment in the MW variant was performed on 03rd May 2022. Weed coverage was 33%, which was reduced to approximately 2 to max. 16% depending on the assessment date. A total of four passes were performed.

Intra-row above-ground biomass was significantly reduced by the MW and the MM treatments compared to the UC, by 98% (MW) and 91% (MM) on the first sampling date, by 97% (MW) and 78% (MM) on the second sampling date and 93% (MW) and 80% (MM) on the third sampling date (Table 4). Statistically significant differences were observed between the MM and MW variants.

At the Laimburg site, a weed survey was conducted before the treatments on 14th March 2022. With coverage of less than 6%, only *Taraxacum sect. Ruderalia, Elymus repens* and *Poa trivialis* were found. On 04th May 2022,

Fig. 2 Images of the effect of the sprayable mulch material (*MM*) on weed growth: orchard—Kierling, **a** MM, **b** untreated control (each recorded 06th July 2022, approx. 14 weeks after application). Note the emergence of annual panicoid grasses in the cracks in **a**; vineyard—Langenzersdorf, timeline of weed control: **c** before treatment of MM 29th March 2022, **d** 26th April 2022, **e** 31st May 2022; **f** MM shows effective grass control, but insufficient control of *Cirsium arvense* (26th April 2022). (© Swen Follak, Markus Redl)

a total of eight different plant species were recorded, with the dominant species *Taraxacum sect. Ruderalia, Elymus repens*, and *Carex hirta*. Other species with lower coverage were *Potentilla reptans, Veronica* spp., *Oxalis* spp., *Poa pratensis* and *Poa trivialis*. On 05th September 2022, 19 species were identified with the most frequent being *Elymus repens, Carex hirta*, and *Potentilla reptans*.

The estimation of weed coverage one week after the treatments (29th March 2022), showed that all treatments had a significantly lower coverage than the UC. One month after the treatments, the weed coverage of the BC and MW treatments did not differ statistically from that of the UC. From 26th May 2022 to 23rd June 2022, only the MM and BM treatments showed significantly lower weed coverage than the UC. On 20th July 2022 only the treatment BM had significantly lower weed coverage than the UC. In the evaluation conducted on 24th August 2022, no significant differences were found between any of the treatments (Table 5).

On the first sampling date (05th May 2022), weed biomass was lowest in the treatment H (11.7 g/m^2) followed by MM (14.0 g/m^2) and BM (19.7 g/m^2), which was significantly less biomass than BC (98.0 g/m^2) and UC (139.5 g/m^2). On the second sampling date (06th October 2022) no significant differences were observed between the treatments (Table 6).

Vineyards

At the Langenzersdorf site, weed coverage before the treatments (29th March 2022) ranged from 10 to 31% (Table 7). In all plots, the main weeds were *Lepidium draba* and *Cirsium arvense*. Because the treatments UC, MW and H were applied in the same plots in the previous year, the H treatment had a significant lower weed coverage than the UC. The MM treatment showed the significant best effect with only 7% weed coverage compared to 22 and 37% of the treatments H and MW after the application on the first sampling date (26th April 2022). However, MM had a significantly higher weed coverage compared to H and MW in July and August. On 24th August 2022, weed coverage in MM, MW and H was approximately at the initial level but still significantly lower than the UC, which was more than twice as high in the treatments MW and H (18 and

Table 4 Effects of orchard treatments (*UC* untreated control, *MM* mulch material, *MW* mechanical weeding) on intra-row above-ground biomass in Kierling (Austria) in 2022. Each data point indicates the determination of biomass at the given date. Letters indicate significant differences within the variants at the given date (Dunn-Bonferroni-Test, α = 0.05)

	Intra-row above-ground biomass [dry matter in g/m^2]		
Treatment	18/05/22	06/07/22	30/08/22
UC	231.6 c	322.7 c	369.5 c
MM	20.9 b	71.4 b	73.7 b
MW	5.4 a	9.3 a	26.8 a

Table 5 Effects of orchard treatments (*UC* untreated control, *MM* mulch material, *MW* mechanical weeding, *H* herbicide, *BC* brushed control, *BM* brushed mulch material) on intra-row weed coverage in Laimburg (Italy) in 2022. Each data point indicates a weed coverage estimation at the given date. First data point shows initial weed coverage before MM treatment. Letters indicate significant differences within the variants at the given date (Tukey-HSD, α = 0.05)

	Intra-row weed coverage [%]						
Treatment	14/03/22	29/03/22	21/04/22	26/05/22	23/06/22	20/07/22	24/08/22
UC	6.0 a	26.2 b	64.2 b	94.1 b	86.7 b	86.0 b	74.6 a
MM	5.6 a	5.2 a	7.2 a	40.5 a	54.0 a	68.5 ab	87.3 a
MW	3.9 a	3.2 a	33.5 ab	91.5 b	87.3 b	78.8 b	91.3 a
H	4.0 a	11.7 a	22.5 a	77.3 b	85.1 b	83.5 b	88.8 a
BC	3.2 a	10.5 a	38.8 ab	95.2 b	88.3 b	85.9 b	91.3 a
BM	3.5 a	0.9 a	7.8 a	26.2 a	49.9 a	46.1 a	81.0 a

6% vs. 54%). Corresponding to the Kierling site results, the cover of perennial species, such as *Convolvulus arvensis, Cirsium arvense* and *Lepidium draba* increased in the MM treatment. For example, the percentage of *Convolvulus arvensis* on weed coverage was significantly ($p < 0.001$) higher in treatments MM and MW compared to UC on 24th August 2022.

At the Ölleiten site, a weed survey was conducted before the treatments on 14th March 2022. Weed coverage ranged from 17 to 25% (Table 8) and 17 plant species were recorded. The dominant species were *Elymus repens, Poa trivialis*, and *Potentilla reptans*. On 04th May 2022, a total number of 24 plant species was recorded. *Carex hirta, Potentilla reptans*, and *Poa trivialis* had the highest proportion. On 05th September 2022, 24 species were identified. The most dominant species was *Potentilla reptans* (mean cover of 19%), followed by *Elymus repens* and *Arrhenatherum elatius*.

Table 6 Effects of orchard treatments (*UC* untreated control, *BC* brushed control, *H* herbicide, *MW* mechanical weeding, *MM* mulch material, *BM* brushed mulch material) on intra-row above-ground biomass in Laimburg (Italy) in 2022. Each data point indicates the determination of biomass at the given date. Letters indicate significant differences within the variants at the given date (Tukey-HSD, α = 0.05)

	Intra-row above-ground biomass [dry matter in g/m^2]	
Treatment	04/05/22	06/10/22
UC	139.6 b	312.8 a
MM	14.0 a	195.1 a
MW	82.9 ab	254.8 a
H	11.7 a	108.0 a
BC	98.0 b	277.4 a
BM	19.7 a	61.3 a

The estimation of weed coverage one week after the treatments (29th March 2022) showed that all treatments except H had a significantly lower weed coverage than UC. One month after treatments (04th April 2022), the BC and H treatments were not statistically different from UC. In contrast, treatments MM and BM differed significantly from UC (weed coverage of 48%), with intermediate coverage of 4.3 and 3.8%, respectively. From 26th May 2022, until the evaluation on 20th July 2022, only the MM and BM treatments showed statistically significant lower weed coverage than the UC treatment. On 24th August 2022, no statistically significant differences between the treatments were detected (Table 8).

On 04th May 2022, biomass was significantly higher in UC with 225.59 g/m^2 compared to the other treatments (Table 9). BM with 12.4 g/m^2 and MM with 37.4 g/m^2 were the two treatments with the lowest biomass. BM had the lowest biomass (75.8 g/m^2) on the second sampling date (21st September 2022). Biomass of the treatments BM and MM were significantly lower compared to UC (Table 9).

At the Veitshöchheim site, the main weeds were *Elymus repens, Lepidium draba* and *Torilis japonica*. Weed coverage in all variants was significantly lower than in the UC at the beginning of the trial (17th March 2022). The results show that weed coverage of both MM variants was significantly lower than the UC over the entire trial period (except in July for MM-E) and MM-L performed better than MM-E (Table 10). In MM-E, weed coverage reached a peak value of 25% on 25th May 2022, whereas weed cov-

Table 7 Effects of vineyard treatments (*UC* untreated control, *MM* mulch material, *MW* mechanical weeding, *H* herbicide) on intra-row weed coverage in Langenzersdorf (Austria) in 2022. Each data point indicates a weed coverage estimation at the given date. First data point shows initial weed coverage before MM treatment. Letters indicate significant differences within the variants at the given date (Tukey-HSD, α = 0.05)

Treatment	Intra-row weed coverage [%]				
	29/03/22	26/04/22	31/05/22	25/07/22	24/08/22
UC	26.8 bc	41.7 c	73.6 c	42.9 c	53.6 c
MM	31.2 c	6.9 a	35.6 b	42.3 c	35.3 b
MW	20.1 b	36.7 c	16.1 a	0.81 a	18.1 a
H	10.0 a	21.9 b	29.3 ab	20.5 b	6.3 a

Table 8 Effects of vineyard treatments (*UC* untreated control, *MM* mulch material, *MW* mechanical weeding, *H* herbicide, *BC* brushed control, *BM* brushed mulch material) on intra-row weed coverage in Ölleiten (Italy) in 2022. Each data point indicates a weed coverage estimation at the given date. First data point shows initial weed coverage before MM treatment. Letters indicate significant differences within the variants at the given date (Tukey-HSD, α = 0.05)

Treatment	Intra-row weed coverage [%]						
	14/03/22	29/03/22	21/04/22	26/05/22	23/06/22	20/07/22	24/08/22
UC	23.1 a	20.1 c	48.5 b	64.0 ab	74.1 bc	61.9 ab	68.6 a
MM	18.0 a	7.1 ab	4.3 a	37.9 a	60.2 ab	53.1 ab	58.9 a
MW	17.1 a	2.5 a	26.6 ab	66.6 ab	87.6 c	77.4 b	66.8 a
H	25.1 a	14.0 bc	23.2 ab	46.7 ab	81.8 bc	74.2 b	70.2 a
BC	17.9 a	1.7 a	18.8 a	62.9 ab	83.8 bc	73.7 b	69.5 a
BM	21.2 a	0.1 a	3.8 a	46.3 ab	53.5 a	41.3 a	52.8 a

Table 9 Effects of vineyard treatments (*UC* untreated control, *MM* mulch material, *MW* mechanical weeding, *H* herbicide, *BC* brushed control, *BM* brushed mulch material) on intra-row above-ground biomass in Ölleiten (Italy) in 2022. Each data point indicates the determination of biomass at the given date. Letters indicate significant differences within the variants at the given date (Tukey-HSD, α = 0.05)

Treatment	Intra-row above-ground biomass [dry matter in g/m^2]	
	04/05/22	06/10/22
UC	225.6 b	308.0 b
MM	37.4 a	166.1 a
MW	53.2 a	304.8 b
H	66.9 a	211.2 ab
BC	71.7 a	161.3 a
BM	12.4 a	75.8 a

erage in MM-L remained < 5% until the end of the trial. The highest weed coverage for H and MW treatments was 22%. Biomass was significantly reduced in all variants compared to the UC on 16th June 2022 (Table 11). The lowest value was recorded in MM-E (2.2 g/m^2), and the value in MM-L was significantly higher (42.3 g/m^2). At the end of the trial (28th September 2022) biomass of the variants MM-L, H and MW was still significantly lower compared to UC, but not for MM-E.

Discussion

Efficacy of Weed Control

The present trials show that the sprayable mulch material (MM) has the potential to control weed growth in the rows. It was demonstrated that applying it early in the season (pre-emergence, e.g. MM-E Veitshöchheim site) and over the top of established and emerging weeds (post-emergence, e.g. Kierling site) was effective in reducing weed coverage and biomass. The weeds under the mulch layer turned brown, and partially died, and it provided a (temporal) physical suppression of weed emergence (Fig. 2c–e). These observations showed that the mode of action of the MM is most likely based on gluing the stomata so that cell respiration is restricted, and the weed suffocates (Kirchinger et al. 2023). The strongest effect on weed coverage was observed approximately three to four weeks after the application of MM (i.e. end of April), with a reduction of 83 to 97% compared to the UC, depending on the site. The greatest reduction in biomass was observed in May and June (83–99%). Weed growth increased to varying degrees during the trials. It should be noted that the weed biomass of the MM (and BM) treatments was significantly reduced at the time of the most vigorous weed growth (May) and the beginning of the increasing nutrient demand of the grapes and fruit trees (Walg 2022; Fischer 2002; Fig. 2e).

The efficacy of the conventional methods (H, MW) compared to the MM did not show consistent results across the field trials. The general trend was that the MM was largely

Table 10 Effects of vineyard treatments (*UC* untreated control, *MM-E* early application, *MM-L* late application, *MW* mechanical weeding, *H* herbicide) on intra-row weed coverage in Veitshöchheim (Germany) in 2022. Each data point indicates a weed coverage estimation at the given date. First data point shows initial weed coverage before MM treatment. Letters indicate significant differences within the variants at the given date (Tukey-HSD, $\alpha = 0.05$)

	Intra-row weed cover [%]					
Treatment	17/03/22	24/03/22	19/04/22	25/05/22	11/07/22	28/09/22
UC	20.0 a	25.8 a	48.4 a	67.4 a	28.7 a	24.2 a
MM-E	3.1 b	0.7 b	1.5 b	25.0 b	12.4 a	10.5 b
MM-L	0.5 b	0.6 b	4.4 b	3.2 c	1.0 b	3.0 b
MW	8.3 b	9.9 a	21.9 a	20.0 b	0.1 b	15.4 a
H	5.0 b	5.0 b	13.1 b	8.1 bc	2.7 b	22.1 a

able to reduce weed coverage and biomass at a comparable rate to H and MW. Under practical conditions, several passes are usually needed (e.g. Hammermeister 2016; in the present study Kierling: 4 × MW, Veitshöchheim: 2 × MW, 2 × H). Thus, MM has a distinct advantage here, as only one application is generally required. The effect of the MM on yield has not been investigated in detail so far. Preliminary data from the Laimburg and Ölleiten sites did not reveal a yield benefit (data not shown), which is in line with several other studies that tested biodegradable sprayable mulch material (Braunack et al. 2021).

Factors Affecting Efficacy of Weed Control

Previous studies have demonstrated the potential of biodegradable sprayable mulch materials to reduce weed growth, but this varied depending on several factors (Giaccone et al. 2018; Gloeb et al. 2023). Accordingly, the results of this study indicate that the efficacy of the MM was influenced by several factors, such as weed coverage before application and the present weed species. On sites with comparably lower weed coverage before the application of the MM (< 10%; e.g. sites Kierling, Laimburg), weed coverage in these treatments was significantly reduced compared to the UC until the end of June and August. In contrast, weed coverage at the Ölleiten and Langenzersdorf sites was considerably higher, ranging between 20 and 30%, which resulted in a significant suppression of weed coverage only until the end of May (Ölleiten site) and the end of April (Langenzersdorf site) indicating that sites with lower weed coverage are especially suitable.

The efficacy of the MM also depends on the weeds present. Perennial weeds with extensive root systems and rhizomes, such as *Cirsium arvense, Elymus repens*, and *Convolvulus arvensis*, readily penetrate the mulch layer. At the Langenzersdorf site, for example, *Cirsium arvense* sprouted through the material after approximately four weeks (data not shown, Fig. 2f). This indicates that the MM has a comparably low resistance to perforation. Therefore, application at sites where high populations of these perennial weeds with rhizomes existed led to a comparably lower efficacy of the MM (Table 7). However, other perennial weeds, such as *Lolium perenne* and *Taraxacum sect. Ruderalia*, were suppressed quite efficiently (Kierling site, data not shown). It is presumed that they were sufficiently covered with the material so that the suffocation effect occurred. Furthermore, as hemicryptophytes, they do not have the regeneration capacity of the above-mentioned perennial species (Holzner and Glauninger 2005). It is well-known from other studies that perennial weeds are generally not easily controlled by mulch (Mia et al. 2020).

The efficacy of a mulch material also depends on the formation of a thick and solid barrier on the soil surface to prevent weed emergence from seeds by avoiding light stimulus (Immirzi et al. 2009; Gloeb et al. 2023). In this study, the thickness of the MM was not always uniform under field conditions owing to the accuracy of the application, surface roughness, and weed coverage. In the field trials, it was observed that the MM flowed into the cracks and cavities in the soil. Moreover, the mulch layer shrunk within a couple of weeks after application, causing gaps of several millimeters. Such openings ensure that sunlight reaches the seeds in the soil and triggers their germination (e.g. annual grasses, *Amaranthus retroflexus* at the Kierling site; Fig. 2a). This led to an increase in the weed coverage over time. Moreover, the application of the MM on existing (dense) weed vegetation led to poor coverage of the soil (e.g. Langenzersdorf site, visual observation). Preparing the

Table 11 Effects of vineyard treatments (*UC* untreated control, *MM-E* early application, *MM-L* late application, *MW* mechanical weeding, *H* herbicide) on intra-row above-ground biomass in Veitshöchheim (Germany) in 2022. Each data point indicates biomass at given date. Letters indicate significant differences within the variants at the given date (Tukey-HSD, $\alpha = 0.05$)

	Intra-row above-ground biomass [dry matter in g/m^2]	
Treatment	16/06/22	28/09/22
UC	332.9 a	112.3 a
MM-E	2.2 c	65.2 ab
MM-L	42.3 b	1.6 b
MW	99.4 a	9.4 b
H	14.1 b	12.9 b

soil before applying the MM can thus increase its effectiveness. However, these results are not entirely consistent. The BM variant at the Laimburg site led to significantly lower weed coverage than the UC over a longer period than the MM variant. This effect was not observed at the Ölleiten site.

Caveats, Considerations for Improvements and Further Studies

The application technology is based on a self-developed device, i.e. it cannot be carried out with standard equipment available on farms. Thus, for broader applications in agriculture, application technology needs to be further developed. Even with appropriate application equipment and under the prerequisite of a single application, the use of the MM is still associated with a certain effort (e.g. supply and storage of material), handling is more complex, and many farmers already have equipment for weed control. This renders the MM difficult to use in practice. In addition, many of the included materials are expensive; thus, the application of the MM is significantly more costly compared to standard methods, such as mechanical weeding (Kirchinger et al. 2023). Thus, future efforts should aim to increase the cost efficiency by purchasing larger units and reducing the amount of materials for an application. The MM has the potential to reduce weed growth, but reaches its limits when persistent weeds with extensive root systems are prevalent or when high weed pressure is present before treatment is carried out. Such orchards and vineyards should be controlled by alternative means (Hammermeister 2016).

Further studies should focus on the definition of an optimal layer thickness that maintains a solid barrier throughout the growing season (Gloeb et al. 2023) while limiting material expenditure and costs to a minimum. In general, the growth stage of weeds should not be too advanced at the time of application (Gloeb et al. 2023). Results from the Veitshöchheim site indicated that late application (May) of the MM was quite effective. Thus, studies should be conducted to define the most suitable application timing of the MM according to weed growth stages. Soil preparation to remove weeds from the previous year and clods prior to MM application is considered beneficial and needs to be further explored (e.g. timing and preparation of optimal soil conditions). Likewise, the practicability of a combination of the MM and (subsequent) application of other management options (e.g. pelargonic acid) to control weeds emerging through the mulch layer can be tested.

The effects of the MM on the soil properties need to be explored. Preliminary results have shown that MM has a positive effect on soil water content and furthermore, based on the teabag index, no negative effects on soil life are suspected (Kirchinger et al. 2023).

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Availability of data Derived data supporting the findings of this study are available from the corresponding author on request.

Conflict of interest S. Follak, M. Kirchinger, A. Menger, M. Redl, A. Schmid, D. Heßdörfer, E. Lardschneider, E. Remmele, M. Riedle-Bauer, F. Rosner, S. Steinkellner, S. Winter and J. Rathbauer declare that they have no competing interests.

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