DOI: https://doi.org/10.20870/oeno-one.2024.58.4.8265

OPEN ACCESS

ORIGINAL RESEARCH ARTICLE

Impact of organic mulches on grapevine health, growth and grape composition in nutrient-poor vineyard soils

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Associate editor:
Vivian Zufferey

Received:
8 August 2024

Accepted:
4 November 2024

Published:
3 December 2024

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ABSTRACT

Effective vineyard management is essential for maintaining grapevine cultivation in semi-arid regions impacted by climate change. Utilising organic mulches is a viable soil management practice that improves soil properties, such as moisture retention, erosion control and soil structure. However, the effect of organic mulches on plant development and grape composition remains unclear. The present study analysed the effects of three organic mulches and two conventional soil management practices on vine physiology, agronomy and grape composition over three years under semi-arid conditions in northern Spain. Three organic mulches (spent mushroom compost-SMC, straw-STR and grapevine pruning debris-GPD) were compared with two conventional soil management practices (herbicide-HERB and tillage-TILL) in nutrient-poor soil. Physical and chemical soil properties, grapevine physiological response, leaf nutrition, growth development, yield and grape composition were evaluated in the Tempranillo cultivar. The SMC mulch improved soil water content, leaf nitrogen concentrations and vegetative growth, resulting in higher yields without compromising grape composition. Conversely, STR mulch increased soil water content, reduced soil temperature, and improved plant water status and leaf gas exchange variables without affecting vine growth and yield. However, no significant differences in grape carbon isotopic discrimination ($\delta^{13}C$) were observed between soil management treatments. SMC's nutrient-rich composition, fine granularity and low C/N ratio could thus promote short-term plant development in poor-nutrient soils, and STR and GPD organic mulches may offer long-term benefits for vine development. A strong correlation was obtained between reflectance values and vegetative growth, yield and leaf nutritional content, offering a non-destructive and rapid assessment method. Overall, organic mulches represent a viable soil management alternative that enhances plant development and yield without reducing grape composition. This research provides valuable insights for winegrowers interested in suitable viticultural practices and highlights the importance of analysing soil and mulch properties to select the most appropriate organic mulch.

KEYWORDS: viticulture, nutrition, plant physiology, fertilisation, water deficit, soil management

INTRODUCTION

Viticulture is an important economic sector that has a profound cultural impact in wine-growing regions. The water demands of vine ranges from 300 to 700 mm, often surpassing local precipitation levels (Medrano *et al*., 2015). Moreover, climate change is currently reducing effective rainfall and altering its seasonal distribution, increasing the frequency of heat waves, limiting water availability for irrigation (Drobinski *et al*., 2020), and thus negatively affecting grape composition (van Leeuwen *et al*., 2024). In addition, vine cultivation is commonly carried out on sloping soils low in organic matter (Salomé *et al*., 2016) and highly prone to erosion (García-Ruiz, 2010). Common soil management practices, such as herbicide use and tillage, can lead to alterations in soil structure, a loss of soil nutrients and organic matter, damage to vine roots and trunks, soil erosion, the evolution of herbicide-resistant species and environmental pollution (García-Ruiz, 2010; Guerra *et al*., 2012). For this reason, adapting vine crops to new environmental conditions and promoting sustainability through novel viticultural strategies is crucial if it is to be maintained in semi-arid regions.

Adapting viticulture to more sustainable practices involve making essential decisions, such as relocating vineyards to colder areas (Ollat *et al*., 2016) or selecting varieties and genotypes with higher tolerance to water stress (Mairata *et al*., 2022; Medrano *et al*., 2015). These adaptations imply significant socio-political changes and affect the lifestyle and culture of many communities. However, agricultural strategies can help to mitigate climate change effects and adapt the vineyard through ecological soil management practices. Cover crops bring numerous advantages, including increasing organic matter, reducing soil erosion, improving biodiversity and controlling weeds (Garcia *et al*., 2018). Despite these advantages, permanent cover crops may negatively affect vineyards due to direct competition for soil resources and embed pests, potentially reducing production and grape composition (Celette *et al*., 2013). One viable alternative is the application of organic mulch on the soil surface. This soil management technique provides other useful features in the shallow soil layer, such as controlling excessive weed growth and improving soil properties by reducing soil erosion, bulk density and compaction, while increasing porosity, aggregate stability and nutritional content (Guerra *et al*., 2012; Mairata *et al*., 2023; Pinamonti, 1998). In addition, organic mulches mitigate extreme soil temperatures (Pou *et al*., 2021), which are increased by the higher frequency of heat waves (Drobinski *et al*., 2020).

Previous research on the effect of organic mulch on vine physiology, development and grape composition has produced contradictory results. Some studies associate organic mulches with improvements in leaf physiology parameters, such as photosynthesis and stomatal conductance, as well as increased vegetative growth, yield and grape composition (Burg *et al*., 2022; Cabrera-Pérez *et al*., 2023; Nguyen *et al*., 2013; Pinamonti, 1998; Zengin *et al*., 2022). However, other studies have not revealed any such enhancement in plant development and grape composition (DeVetter *et al*., 2015; Ferrara *et al*., 2012; Tarricone *et al*., 2018). Therefore, it is essential to determine which organic mulches are most effective and under what conditions they should be applied to achieve the desired outcomes in vineyards.

Sensors for estimating plant characteristics based on plant reflectance are a non-destructive, quick and easy way to assess leaf nutrient content, vegetative growth and harvest yield (Taskos *et al*., 2015). Moreover, grapevine water status can be analysed through grape carbon isotopic discrimination [$\delta^{13}C$] (Bchir *et al*., 2016; Farquhar *et al*., 1984; van Leeuwen *et al.*, 2009). This parameter measures the $^{12}C/^{13}C$ ratio of sugar content in grapes, mainly synthesised between veraison and ripening, the most hydric-stressful stage for grapevines. The $\delta^{13}C$ is a time-integrated measure that reflects longer-term environmental conditions and is, therefore, independent of the specific environmental conditions at the time of sampling (Mairata *et al*., 2022). Some authors have stated that organic mulches enhance the optimum conditions for vine growth and can enhance grape composition (Burg *et al*., 2022). However, the impact of organic mulches on plant development varies depending on the physical and

TABLE 1. Physical and chemical properties of the organic mulches based on spent mushroom compost (SMC), straw (STR) and grapewine pruning debris (GPD) were analysed by the regional laboratory of the Government of La Rioja (Logroño, Spain).

	SMC	STR	GPD
Humidity (%)	52.0	13.7	25.4
Ashes (%)	48.1	5.7	3.7
Organic matter (%)	51.9	94.3	96.3
N (%)	2.38	0.77	0.88
C/N	12.6	71.3	63.6
Al (ppm)	3921	46	182
Cd (ppm)	0.25	0.04	0.07
Ca (‰)	10.98	5.16	11.94
Cu (ppm)	62	2	40
Cr (ppm)	9	7	3
P (ppm)	7516	1110	881
Fe (ppm)	3577	154	182
Mg (ppm)	9724	373	2899
Mn (ppm)	450	20	31
Hg (ppm)	0.029	0.010	0.017
Ni (ppm)	11	3	7
Pb (ppm)	4	1	1
K (ppm)	24668	11943	7864
Na (ppm)	3519	202	1059
SO_4 (ppm)	106932	2856	1762
Zn (ppm)	301	9	44

ppm: parts per million

chemical properties of the mulch, soil conditions and field management practices (Guerra *et al*., 2012).

To address this mismatch observed in previous research, a field experiment was conducted over three consecutive years (2020, 2021 and 2022) in a nitrogen- and organic matter-deficient vineyard in northeastern Spain under semi-arid conditions. Five soil management treatments were assessed within the vine rows. Three treatments involved organic mulches: (i) spent mushroom compost (SMC), (ii) straw (STR), and (iii) shredded vine pruning remains from previous years (GPD). These were compared with two traditional management practices: (iv) herbicide (HERB) and (v) tillage in the vine row (TILL). This study aimed to evaluate each soil management practice's effects on vine physiological and nutritional status, growth development, yield production and grape composition of the Tempranillo cultivar. Moreover, we corroborate the practical use of plant reflectance indices for estimating leaf nutritional status, vegetative growth and yield.

MATERIALS AND METHODS

1. Field and experimental design

The experiment was conducted in a commercial vineyard in northeastern Spain (Aldeanueva de Ebro, La Rioja) over three consecutive years (2020, 2021 and 2022). The vineyard design was 2.6 m x 1.2 m and 3205 vines per hectare of Tempranillo cultivar spur-pruned in a bilateral Royat Cordon system and grafted on R-110 rootstock. The vineyard had previously been managed under Spanish regulation for integrated pest management (IPM), with the application of herbicide to avoid weed presence and of drip water irrigation.

As Mairata *et al*. (2024) have explained, all soil management treatments were established in February 2019 and reapplied annually between March and April. These treatments were applied to a strip that was up to 25 cm wide on each side of the vine row (*i.e*., 50 cm in total), and comprised three organic mulch substrates: grapevine pruning debris (GPD) from previous years, straw mulch (STR) composed of wheat (*Triticum* sp) and sourced from the Government of La Rioja (Logroño, Spain), and spent mushroom compost (SMC) derived from mushroom (*Agaricus bisporus*) and containing a rich composition of animal manure and urea provided by "Sustratos de La Rioja SL." Two conventional soil management practices were examined: under-row tillage (TILL) and herbicide application (HERB). The herbicide, only applied in the HERB treatment, comprised Terafit (25 %, Flazasulfuron) and Atila (36 %, Glyphosate) at a rate of 100 litres per hectare. The experimental design followed a randomised complete block divided into experimental plots, with each soil management treatment consisting of three plots containing 40–50 vines each.

TABLE 2. Texture and general properties of the soil composition of the field (Aldeanueva de Ebro, Spain) at the beginning (2018) and at the end of the field experiment in each soil management treatment (2022).

	2018	2022				
	$\bar{x}$	SMC	STR	GPD	HERB	TILL
Texture						
Sand (%)	50.1 ± 1.8	49.6	50.0	48.9	48.6	47.1
Silt (%)	32.7 ± 1.5	33.1	32.5	33.3	33.2	34.4
Clay (%)	17.3 ± 0.6	17.2	17.5	17.8	18.2	18.6
General properties						
pH	8.20 ± 0.05	8.11 a	8.46 b	8.45 b	8.46 b	8.46 b
$EC_{1:5}$ (dS/m)	0.16 ± 0.01	0.52 a	0.17 b	0.15 b	0.16 b	0.15 b
Nutrients						
C/N	9.4 ± 0.6	10.4	10.8	11.4	10.9	11.0
Organic matter (%)	1.1 ± 0.1	1.4 a	0.9 b	1.0 b	1.0 b	1.0 b
N (‰)	0.8 ± 0.1	1.0 a	0.7 b	0.7 b	0.7 b	0.7 b
P (ppm)	51.0 ± 14.3	78.6	37.9	37.2	42.9	49.4
K (ppm)	254.3 ± 51.1	914.0 a	214.6 b	209.2 b	202.5 b	245.9 b
Mg (ppm)	275.1 ± 5.1	376.6	282.2	304.6	294.7	327.6
Ca (‰)	21.4 ± 5.1	12.0	16.6	16.1	17.3	13.1
Fe (ppm)	44.7 ± 5.1	58.0	55.3	49.2	44.1	57.1
Mn (ppm)	53.1 ± 23.8	97.9	72.2	63.2	66.2	98.7
Zn (ppm)	3.7 ± 0.7	5.3 a	2.0 b	2.8 b	3.3 b	3.6 b
Cu (ppm)	7.6 ± 1.4	5.9	5.4	5.9	6.3	6.9
Na (ppm)	10.8 ± 4.2	95.3	77.4	81.6	73.4	73.2

ppm: parts per million

The regional laboratory of the Government of La Rioja analysed the composition of the three organic mulches (Table 1) and the soil samples (Table 2). SMC mulch had an ash content of 48.1 %, higher than that of the STR (5.7 %) and GPD (3.7 %) mulches. The organic matter content of the STR and GPD mulches was approximately 95 %, whereas that of SMC was 51.9 %. However, SMC exhibited higher nitrogen concentration (2.38 %) than STR (0.77 %) and GPD (0.88 %). Moreover, the C/N ratio of SMC mulch was lower (12.6) than that of STR (71.3) and GPD (63.6). The concentrations of other essential elements, such as phosphorus (P), magnesium (Mg) and calcium (Ca), were up to three times higher in SMC than those measured in GPD and STR.

2. Climate and soil analysis

The study region is characterised by a Mediterranean climate with warm and dry summers (Table S1). In addition, soil temperature (°C) and volumetric soil water content (%) were recorded in each plot (n = 3) every 30 min at three soil depths (5, 15 and 25 cm) with Sentek equipment (Sentek Pty Ltd., Stepney, Australia) and "Drill & Drop" probes (Pou *et al*., 2021). The equipment was installed in October 2020, and soil data were recorded in 2021 and 2022. Before the establishment of the soil treatments in December 2018, soil texture and nutritional composition were analysed (Table 2) in ten shallow soil samples (0-30 cm) distributed throughout the vineyard. Each soil sample was a mixture of ten independent drill samples. Furthermore, soil composition was examined at the end of the experimental study (2022) in all plots following the same methodology applied throughout the experiment. The soil samples were dried at 40 °C for one week and sent to the regional laboratory of the Government of La Rioja for analysis of soil texture (sand, silt and clay), pH, electrical conductivity (1:5; soil/water using a conductivity metre), organic matter, macro-nutrients (NPK), oligo-nutrients (Mg and Ca), micro-nutrients (Fe, Mn, Zn and Cu), oligo-nutrients (Mg, Ca, SO4) and Na as described in Mairata *et al*. (2023).

3. Grapevine water status, leaf gas exchange and whole-plant hydraulic conductance

Grapevine and soil water status, leaf gas exchange and whole-plant hydraulic conductance were analysed in the same six plants (n = 6) per soil treatment at four key stages: flowering, fruit set, veraison and ripening. Fruit set analyses in 2020 were not conducted. Midday and predawn leaf water potentials (Ψ_{leaf} and Ψ_{soil}, respectively) were measured in one leaf per plant (n = 6) using a Scholander pressure chamber (Soil Moisture Equipment Corp., Santa Barbara, CA, USA). On the same day, net photosynthesis rate (A_N), stomatal conductance (g_s) and transpiration rate (E) were measured in one sun-exposed leaf per plant (n = 6) using a portable open gas exchange system (Li- 6400; Li-Cor Inc., Lincoln, NE, USA) at a CO_2 concentration of 400 mmol CO_2/mol air. Leaf gas exchange measurements were conducted on sunny days from 10:00 to 12:00. Intrinsic water use efficiency (WUE_i) was calculated as the ratio of A_N to g_s (Mairata *et al*., 2022; Pou *et al*., 2022). Whole-plant hydraulic conductance (K_{plant}) was calculated using the method described by Nardini *et al.* (2000), which is based on Ohm's law analogy for continuous the soil-plant-atmosphere flow: $K_{plant} = E_{max}/(\Psi_{soil} - \Psi_{leaf})$, where E_{max} is the maximum daily transpiration rate.

4. Carbon isotopic discrimination in grapes

The carbon isotope ratio ($\delta^{13}C$) was determined from 50 mixed berries per plot collected at harvest. Three grape samples, one per plot, and three instrumental replicates of each one were analysed. The berry samples were oven-dried without seeds (Mairata *et al*., 2022) and powdered in an ultra-centrifugal mill (ZM1, Retsch, Haan, Germany). Aliquots of 2 ± 0.1 mg of grape powder were combusted in an elemental analyser (Thermo Flash EA 1112 Series, Bremen, Germany), separated by chromatography and directly injected into a continuous-flow isotope ratio mass spectrometer [Thermo Finnigan Delta Plus, Bremen, Germany] (Bchir *et al*., 2016). Carbon isotope discrimination was expressed as $\delta^{13}C = [(Rs-Rb)/Rb] \times 1000$ (Farquhar *et al*., 1984), where Rs and Rb are the $^{13}C/^{12}C$ ratio of grape sample and PDB (PeeDee Belemnite), respectively.

5. Grape yield components

At harvest, the yield mass, number of clusters and cluster weights of 36 plants per plot uniformly distributed along the row were recorded. At pruning, the annual shoot mass per vine, the number of shoots per vine and the average shoot weight were determined in six representative plants per experimental plot of each soil management treatment. Moreover, the Ravaz index was calculated as the ratio between the yield and the pruning mass (Pou *et al*., 2022). These variables were recorded annually from 2020 to 2022 except for pruning data in 2021, which was unavailable due to prior pruning carried out by the vineyard owner.

6. Plant reflectance index and leaf nitrogen content

Vine vigour was assessed by canopy reflectance using Crop-Circle ACS-430 [Holland Scientific, Inc., Lincoln, NE, USA] (Pou *et al*., 2022; Taskos *et al*., 2015). Measurements were carried out one metre from the canopy and in one go: ten measurements per second, amounting to 35 seconds for the entire plot. The ACS-430 sensor recorded the reflectance of an active light sensor at 630 nm (red), 730 nm (red-edge) and 780 nm (NIR). From the reflectance values, NDVI (normalised difference vegetation index) and NDRE (normalised difference red edge) were calculated according to Taskos *et al.* (2015):

$$NDVI = (NIR - red)/(NIR + red)$$

$$NDRE = (NIR - red\ edge)/(NIR + red\ edge)$$

At flowering and veraison, 30 healthy leaves (one per plant) from fruit-bearing shoots were sampled from each plot to determine total leaf blade nitrogen content (organic and inorganic). At flowering, leaves from one side of the first bunch were collected, and at veraison, leaves from the opposite side were collected following the methodology outlined by Romero *et al.* (2013). The sampling was carried out on alternate sides of the trellis. The collected leaf blades

were washed three times, rinsed with distilled water and oven-dried at 70 °C for 48 hours. Subsequently, they were ground using an ultra-centrifugal mill (ZM1, Retsch, Haan, Germany) and sieved through a mesh (< 0.5 mm). Two hundred milligrams of ground sample was analysed following the Dumas method (Etheridge *et al*., 1998) and using a Leco CNS analyser (St. Joseph, MI, USA). The concentrations reported are equivalent to grams of nitrogen per 100 grams of dry matter (g N/100 g dry matter).

7. Grape and must analysis

From 2020 to 2022, grape and must quality variables were assessed via random berry sampling. In the three replicates of the five soil management treatments, 500 random berries were sampled within the entire row to analyse physical, chemical and oenological variables. Total soluble solids (TSS) were analysed using a refractometer, and pH, total acidity (TA), malic acid and potassium were determined using EEC methods. Tartaric acid in the berry juice was measured using the Rebelein method. All the methodologies for these measurements, including yeast assimilable nitrogen (YAN), have been described by Portu *et al*. (2017). Following the methods described by Pou *et al*. (2022), two hundred berries were weighed and extracted twice using 50 mL of 1 % HCl in a mixer. The mixture was heated to 40 °C while being stirred. An additional 1 % HCl was introduced, followed by further heating and stirring to 60 °C. The mixture was subsequently cooled to 10 °C using an ice bath and filtered through a cloth, and the extract volume was recorded. Following dilution, total phenolics were measured as the total polyphenol index (TPI) using spectrophotometric absorbance at 280 nm and determined by a Helios Omega spectrometer (Thermo Fisher Scientific). Total anthocyanin was measured by decolorising with sulphur dioxide.

8. Statistical analysis

The phenological stages were analysed independently to preserve information through the vine vegetative cycle. Exploratory data analysis was conducted to assess data normality through Q-Q plots. For all variables, an initial analysis of variance (ANOVA) was carried out using a generalised linear model (GLM) to detect differences among independent variables (soil management treatment, year, and phenological stage), as well as their interactions. Subsequently, a linear mixed model (LMM) was employed for variables without interaction between treatment and year, treating the experimental year as a random variable. A linear model (LM) was conducted when interactions were observed within each subgroup. When differences among the various soil management practices were identified, a post-hoc Tukey analysis was conducted to enable multiple comparisons between soil management treatments. Detailed statistical results are provided in Tables S2 to S5. Data analysis was performed using RStudio software (version 4.3.1), and graphs were generated by GraphPad Prism (version 8.0.1). Any statistical significance was accepted with a $p < 0.05$.

RESULTS

1. Climate and soil characteristics

Climatic data for the critical grapevine growth period (May to September) is summarised in Table S1. The year 2022 is characterised by warmer and drier conditions, with accumulated precipitation of 89.6 mm and growing degree-days (GDD) of 1924.4 °C. By contrast, in 2020 and 2021, higher precipitation levels of 117.4 mm and 142 mm were recorded, respectively, with corresponding GDD values of 1684 °C and 1587 °C.

Table 2 provides an overview of the physical and chemical soil properties before the application of the soil treatments and at the end of the experimental assay (2022). The texture analysis revealed a soil composition of 50.1 % sand, 32.7 % silt and 17.3 % clay, indicating that it is loamy to sandy-loam soil with a significant amount of sand particles. The soil management treatment did not alter the soil structure. The initial soil pH was alkaline (8.2), with an electrical conductivity (CE) of 0.16 dS/m. The C/N ratio of 9.4 indicates a balanced relationship conducive to microbial activity and organic matter decomposition despite the low percentage (1.1 %). The nutrient analysis revealed a relatively low nitrogen (N) content (0.84 ppm; parts per million), moderate phosphorus (P) levels (up to 51 ppm) and a relatively high concentration of potassium (K) concentration (254.3 ppm). Sodium (Na) content was relatively low (10.8 ppm), and Magnesium (Mg) and calcium (Ca) were abundant (reaching 275.1 ppm and 21400.8 ppm, respectively). Iron (Fe) concentration was moderate (44.7 ppm), and manganese (Mn) was 53.1 ppm. Finally, Zinc (Zn) and copper (Cu) concentrations were moderate (3.7 and 7.6, respectively). After four years of the experiment, soil properties of the SMC treatment exhibited disparities relative to the other soil treatments. Specifically, the SMC treatment decreased the soil pH to 8.11, whereas the other treatments increased the pH to 8.46. Moreover, SMC increased the soil's electrical conductivity to 0.52 dS/m and enhanced levels of organic matter and nutrients such as N, K and Zn.

Throughout 2021 and 2022, soil water content (Figure 1) and soil temperature (Figure S1) were consistently monitored at three depths (5, 15 and 25 cm) from mid-May to late September (indicated by day of the year, DOY), aligning with the main grapevine phenological stages: flowering (F), fruit set (S), veraison (V) and berry ripening (R). Daily precipitation (Figure 1) and air temperature (Figure S1) are also represented in the figures. Soil water content (Figure 1) remained relatively stable across both years. Specifically, water content at 25 cm depth (Figure 1C) exhibited fewer fluctuations and minimised differences between treatments compared to shallower layers. In particular, the 5 cm depth (Figure S1) displayed significant oscillations throughout the growing cycle.

Differences in soil water content were observed over both years (Table S6). STR and SMC mulching treatments resulted in higher moisture levels. Moreover, the SMC treatment also enhanced water retention capacity during

precipitation events. At a depth of 25 cm, notable changes in water content were observed whenever precipitation exceeded 10 mm. Nonetheless, on two occasions (DOY 212 in 2021 and DOY 175 in 2022), a substantial increase in soil water content was observed due to drip irrigation inputs, which mitigated differences between the water content levels of the analysed soil treatments. Temperature data (Figure S1) followed a similar trend to water content. Soil temperatures across the soil profile were generally consistent, though more variation was noted among sensors at 5 cm depth. Organic mulches, especially STR, effectively reduced soil temperatures by up to 5 °C compared to conventional HERB and TILL treatments during the year›s hottest days.

2. Grapevine water status, leaf gas exchange and grape $\delta^{13}C$ analysis

Significant interactions were observed in soil water potential (Ψ_{soil}), leaf water potential (Ψ_{leaf}), plant conductivity (K_{plant}), photosynthesis rate (A_N), stomatal conductance (g_s) and intrinsic water use efficiency (WUE_i) between phenological stages, years and soil management treatments. For this reason, differences in soil management treatments were analysed independently for each phenological stage (flowering, fruit set, veraison, and ripening) in 2020 (Table 3), 2021 (Table 4) and 2022 (Table 5).

In general, Ψ_{leaf} and Ψ_{soil} showed higher values in the STR mulch treatment. By contrast, the SMC treatment exhibited more variability, with lower soil water potentials at flowering and fruit set in 2021 and at veraison and ripening in 2022. However, both STR and SMC achieved higher soil water potentials at veraison and ripening in 2021. The GPD, HERB and TILL treatments showed similar soil and leaf water potentials. Soil water potential values remained relatively stable between -0.3 MPa and -0.5 MPa across most phenological stages, except at veraison and ripening in 2022, when they decreased to -0.7 MPa. This trend was also observed in leaf water potentials with higher variability, generally oscillating between -1 MPa and -1.6 MPa.

Plant hydraulic conductivity (K_{plant}), calculated from transpiration and soil/leaf water potentials, showed scattered differences between soil management treatments without a clear behavioural trend. Leaf gas exchange values (A_N, g_s and WUE_i) differed depending on the phenological stage

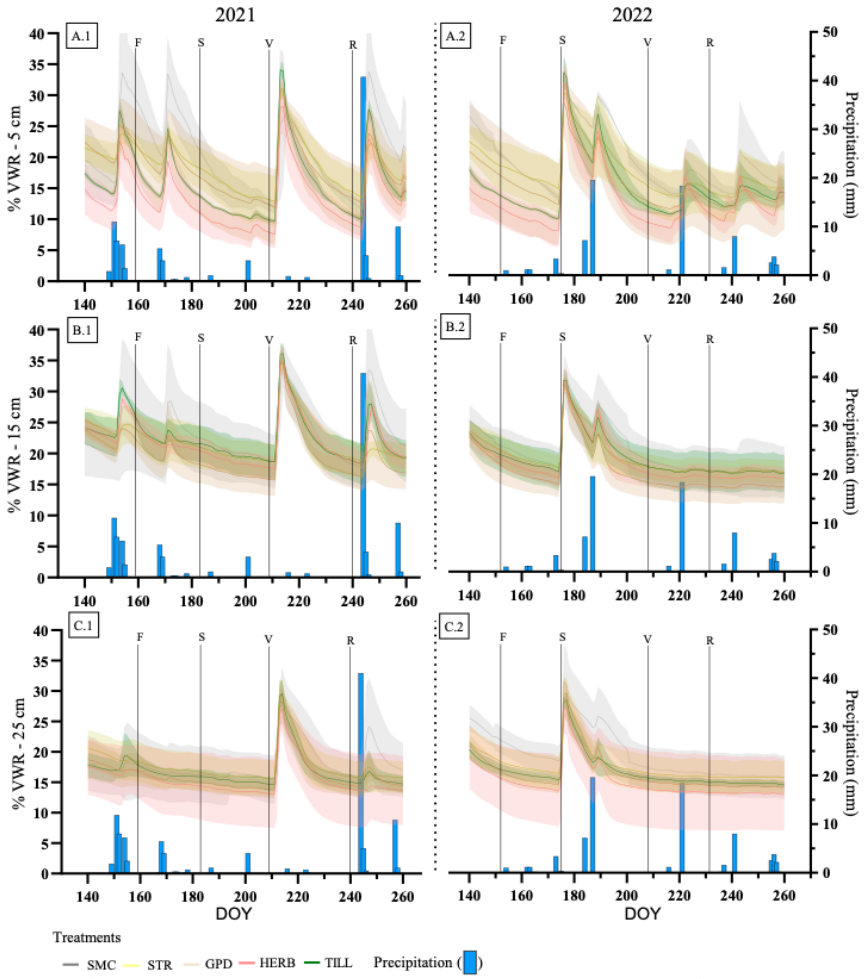


FIGURE 1. Volumetric soil water content (VWR) at 5 cm (A), 15 cm (B) and 25 cm (C) of the soil profile and accumulated daily precipitation (mm) of the soil management treatments from the end of May (DOY 140) to the end of September (DOY 260) in 2021 and 2022 (Aldeanueva de Ebro, Spain). The mean of the soil probes (n = 3) and the standard deviation are shown. The vertical black lines represent the phenological stages at flowering (F), fruit set (S), veraison (V) and ripening (R).

TABLE 3. Mean values of midday (Ψ_{leaf}) and pre-dawn (Ψ_{soil}) water potentials, whole plant hydraulic conductance and leaf gas exchange measures at flowering, fruit set, veraison and ripening (cv. Tempranillo) 2020. For each dependent variable, different letters indicate statistically significant differences. Statistical differences were accepted when $p < 0.05$.

Phenology	Treatment	Ψ_{leaf} (MPa)	Ψ_{soil} (MPa)	K_{plant} (mmol H_2O/ MPa·s·m^2)	A_N (µmol CO_2/ m^2·s)	g_s (mol H_2O/m^2·s)	WUE_i (µmol CO_2/mol H_2O)
Flowering	SMC	-1.14	-0.43	4.6 a	16.8	0.25 ab	66.7
	STR	-1.28	-0.44	2.7 b	16.9	0.24 b	73.4
	GPD	-1.17	-0.44	4.2 ab	18.3	0.30 ab	61.7
	HERB	-1.28	-0.43	4.0 ab	18.7	0.28 ab	67.1
	TILL	-1.18	-0.43	4.9 a	19.2	0.33 a	59.2
Veraison	SMC	-1.36 b	-0.16 b	3.7	20.8	0.43	48.8
	STR	-1.19 a	-0.05 a	3.7	20.1	0.42	47.6
	GPD	-1.43 c	-0.11 ab	3.6	20.8	0.50	42.6
	HERB	-1.41 bc	-0.17 b	3.4	20.2	0.41	50.2
	TILL	-1.43 c	-0.14 b	3.2	20.2	0.44	46.3
Ripening	SMC	-1.37 bc	-0.41 b	4.3 ab	15.5 a	0.17 abc	92.7 a
	STR	-1.27 a	-0.33 a	4.0 abc	15.4 a	0.20 ab	77.2 ab
	GPD	-1.38 c	-0.43 b	4.7 a	14.7 a	0.21 a	69.9 b
	HERB	-1.32 ab	-0.43 b	3.2 c	9.9 b	0.12 c	84.8 ab
	TILL	-1.38 c	-0.42 b	3.6 bc	11.7 b	0.15 bc	77.8 ab

Ψ_{leaf} = leaf water potential; Ψ_{soil} = leaf water potential; K_{plant} = plant hydraulic conductivity; A_N = net photosynthesis rate; g_s = stomatal conductance; WUE_i = intrinsic water use efficiency.

TABLE 4. Mean values of midday (Ψ_{leaf}) and pre-dawn (Ψ_{soil}) water potentials, whole plant hydraulic conductance and leaf gas exchange measures at flowering, fruit set, veraison and ripening (cv. Tempranillo) in 2021. For each dependent variable, different letters indicate statistically significant differences. Statistical differences were accepted when $p < 0.05$.

Phenology	Treatment	Ψ_{leaf} (MPa)	Ψ_{soil} (MPa)	K_{plant} (mmol H_2O/ MPa·s·m^2)	A_N (µmol CO_2/ m^2·s)	g_s (mol H_2O/m^2·s)	WUE_i (µmol CO_2/mol H_2O)
Flowering	SMC	-1.53	-0.43 b	2.9 b	12.5 c	0.17 b	77.3 a
	STR	-1.08	-0.32 a	4.8 ab	17.7 a	0.28 a	63.3 b
	GPD	-1.35	-0.37 ab	3.9 ab	14.7 b	0.24 a	61.6 b
	HERB	-1.17	-0.35 ab	5.1 a	15.7 ab	0.28 a	58.0 b
	TILL	-1.57	-0.34 ab	3.2 ab	14.7 b	0.25 a	60.7 b
Fruit set	SMC	-1.45 ab	-0.46 c	4.3 b	12.7 c	0.13 c	101.9 a
	STR	-1.32 a	-0.30 a	5.6 a	20.1 a	0.40 a	49.7 c
	GPD	-1.40 ab	-0.39 b	5.7 a	15.9 b	0.21 b	75.2 b
	HERB	-1.52 b	-0.38 b	5.2 ab	18.7 ab	0.29 b	65.0 b
	TILL	-1.35 a	-0.36 b	6.3 a	16.8 b	0.27 b	63.6 b
Veraison	SMC	-1.4 ab	-0.38 a	4.9 a	18.2 a	0.26 a	74.2 b
	STR	-1.29 a	-0.32 a	4.3 a	18.4 a	0.28 a	66.0 b
	GPD	-1.61 c	-0.49 b	2.7 b	12.1 b	0.12 b	101.2 a
	HERB	-1.50 bc	-0.48 b	2.6 b	11.0 b	0.11 b	99.2 a
	TILL	-1.50 bc	-0.49 b	2.6 b	10.2 b	0.10 b	99.2 a
Ripening	SMC	-1.69 c	-0.34 a	5.0 a	21.6 a	0.29 a	76.1 bc
	STR	-1.40 a	-0.29 a	4.1 ab	18.1 b	0.30 a	61.4 c
	GPD	-1.65 bc	-0.48 b	3.3 bc	14.1 c	0.15 b	94.1 a
	HERB	-1.53 ab	-0.46 b	3.0 c	11.3 d	0.14 b	83.0 ab
	TILL	-1.63 bc	-0.48 b	2.7 c	11.6 cd	0.12 b	94.5 a

Ψ_{leaf} = leaf water potential; Ψ_{soil} = leaf water potential; K_{plant} = plant hydraulic conductivity; A_N = net photosynthesis rate; g_s = stomatal conductance; WUE_i = intrinsic water use efficiency.

TABLE 5. Mean values of midday (Ψ_{leaf}) and pre-dawn (Ψ_{soil}) water potentials, whole plant hydraulic conductance and leaf gas exchange measures at flowering, fruit set, veraison and ripening (cv. Tempranillo) in 2022. For each dependent variable, different letters indicate statistically significant differences. Statistical differences were accepted when $p < 0.05$.

Phenology	Treatment	Ψ_{leaf} (MPa))	Ψ_{soil} (MPa))	K_{plant} (mmol H_2O/ MPa·s·m^2)	A_N (µmol CO_2/ m^2·s)	g_s (mol H_2O/m^2·s)	WUE_i (µmol CO_2/mol H_2O)
Flowering	SMC	-1.48 bc	-0.30 ab	4.4 bc	18.6	0.21 d	89.4 a
	STR	-1.63 c	-0.27 a	3.8 c	19.2	0.33 a	58.6 c
	GPD	-1.42 ab	-0.32 ab	5 ab	18.2	0.24 cd	77.4 b
	HERB	-1.28 a	-0.33 b	5.7 a	18.7	0.26 bc	72.3 b
	TILL	-1.38 ab	-0.32 ab	5.4 a	19.8	0.28 b	72.3 b
Fruit set	SMC	-1.32 b	-0.30 ab	6.2	19.3 a	0.24 a	80.2 a
	STR	-1.09 a	-0.24 a	6.0	16.0 ab	0.21 ab	76.4 ab
	GPD	-1.13 a	-0.30 b	5.9	15.7 b	0.19 ab	83.2 a
	HERB	-1.17 ab	-0.33 b	5.2	16.0 ab	0.25 a	65.1 b
	TILL	-1.05 a	-0.30 ab	5.6	15 b	0.18 b	82.7 a
Veraison	SMC	-1.71	-0.69 c	3.0	10.3 b	0.10 b	103.5
	STR	-1.59	-0.44 a	2.7	14.6 a	0.16 a	92.6
	GPD	-1.63	-0.55 b	2.8	10.8 b	0.11 b	100.1
	HERB	-1.59	-0.56 b	2.5	10.7 b	0.10 b	108.9
	TILL	-1.62	-0.56 b	2.7	11.8 b	0.11 b	108.4
Ripening	SMC	-1.59	-0.91 b	3.2 a	10.4	0.08	136.1
	STR	-1.56	-0.62 a	2.0 b	8.7	0.07	119.1
	GPD	-1.53	-0.66 a	1.8 b	7.7	0.06	130.7
	HERB	-1.65	-0.72 a	1.5 b	7.7	0.06	138.9
	TILL	-1.60	-0.62 a	1.6 b	8.7	0.07	130.0

Ψ_{leaf}: leaf water potential; Ψ_{soil}: leaf water potential; K_{plant}: plant hydraulic conductivity; A_N: net photosynthesis rate; g_s: stomatal conductance; WUE_i: intrinsic water use efficiency.

and year. In 2020, differences were only observed during ripening. Organic mulch treatments (SMC, STR and GPD) exhibited higher photosynthesis rates than conventional management practices (HERB and TILL). GPD showed the highest stomatal conductance values (0.21 mol H_2O/ m^2·s), while HERB showed the lowest (0.12 mol H_2O/ m^2·s). Additionally, SMC showed higher WUE_i values than GPD. In 2021, differences between all the phenological stages were recorded. During flowering and fruit set, SMC exhibited lower photosynthesis and stomatal conductance values but higher WUEi than the other treatments. However, at veraison and ripening, SMC and STR (only at veraison) showed higher photosynthesis and stomatal conductance values, thus reducing the WUE_i ratio. In 2022, STR showed higher stomatal conductance ratios at flowering, while SMC showed lower ratios, inversely affecting the WUE_i ratio. During the fruit set, SMC and HERB showed higher stomatal conductance ratios. SMC achieved a higher WUE_i ratio due to a higher photosynthesis ratio. At version, STR had higher photosynthesis and stomatal conductance values than other treatments, without differences in WUE_i. Carbon isotopic discrimination ($\delta^{13}C$) data from Table S7 revealed no differences between soil management treatments in any of the analysed years.

TABLE 6. Mean values (2020-2022) of harvest and pruning data (cv. Tempranillo) of the five soil managements analysed. Significant differences between soil management treatments were represented when $p < 0.05$.

Treatment	YW	CW	CV	PW	ASW	NMS	RI
SMC	5.94 a	0.37 a	16.05	1.2 a	89.0 a	12.7	4.6
STR	4.24 b	0.28 b	14.69	0.9 b	61.4 b	12.8	4.2
GPD	4.81 b	0.32 b	14.77	1.0 ab	77.8 ab	12.7	4.0
HERB	4.19 b	0.29 b	14.08	0.8 b	59.5 b	12.7	4.5
TILL	4.09 b	0.28 b	14.27	0.7 b	52.9 b	12.7	5.0

YW = yield weight (kg/vine); CW = cluster weight (kg); CV = clusters/vine; PW = pruning weight (kg/vine); ASW = average shoot weight (g); NMS = number of main shoots/vine; RI = Ravaz Index (yield/pruning mas).

TABLE 7. Mean values (2020-2022) of normalised difference vegetation index (NDVI), normalised difference red edge (NDRE), and leaf blade nitrogen content (N, g N/100 g dry matter) of the five soil management treatments at flowering and veraison (cv. Tempranillo). Significant differences between soil management treatments were represented when $p < 0.05$.

Phenology	Treatment	NDVI	NDRE	N
Flowering	SMC	0.757	0.252 a	3.63 a
	STR	0.731	0.218 b	3.02 b
	GPD	0.741	0.232 ab	3.11 b
	HERB	0.733	0.225 ab	3.20 ab
	TILL	0.738	0.235 ab	3.30 ab
Veraison	SMC	0.820 a	0.350 a	2.42 a
	STR	0.783 b	0.278 b	1.89 b
	GPD	0.789 b	0.292 b	2.00 b
	HERB	0.790 b	0.294 b	2.08 b
	TILL	0.799 ab	0.314 ab	2.15 ab

3. Grapevine yield

Table 6 summarises three years of data for the production and vegetative growth per plant, including yield weight (YW), average cluster weight (CW), number of clusters per vine (CV), pruning weight (PW), average shoot weight (ASW) and number of main shoots (NMS). Additionally, it includes the Ravaz Index (RI), which represents the ratio of harvest weight to pruning weight. Two-way ANOVA analysis highlights differences between soil management treatments (p-value < 0.05). The SMC treatment exhibited higher YW and PW values than the other soil treatments, except for GPD in PW. This difference was reflected in increased CW and ASW. However, no differences were detected between the soil management treatments for CV, NMS and RI.

4. Plant reflectance and leaf nitrogen analysis

Table 7 shows the NDVI (normalised difference vegetation index), NDRE (normalised difference red edge), and leaf nitrogen content (N) at flowering and veraison over the three analysed years. No interactions between soil management treatment and years were observed in the two phenological stages analysed. At flowering, no differences in NDVI were detected. However, NDVI and NDRE rates increased at veraison compared to flowering, while nitrogen concentration decreased. For the flowering stage, the SMC treatment obtained higher NDRE values than STR and higher nitrogen amounts than STR and GPD. More pronounced differences between the soil treatments were observed during veraison, with variations in all the variables: specifically, the SMC treatment exhibited higher NDVI, NDRE and leaf nitrogen values than STR, GPD, and HERB.

5. Grape and must quality

Grape yield and must quality parameters were evaluated over the three years, as shown in Table 8. The SMC soil treatment recorded the highest pH values (3.65), followed by the GPD treatment (3.59). The STR, HERB and TILL treatments showed the lowest pH values, ranging from 3.51 to 3.49. Soil management treatments affected malic acid content, with SMC having the highest concentration (1.8 g/L), and HERB (1.16 g/L) and TILL (1.22 g/L) the lowest amounts. Potassium levels in the must differed depending on the soil treatment, with SMC again showing the highest amounts (1442.9 mg/L), and HERB (1168.5 mg/L) and TILL the lowest (1166 mg/L). Must yeast assimilable nitrogen (YAN) levels also differed among treatments, with SMC showing the highest concentration (210.3 mg/L), followed by the TILL treatment (174.4 mg/L), and the STR treatment with the lowest value (113.1 mg/L). The STR and GPD treatments showed the highest berry mass (226.4 g/100 berries and 221.2 g/100 berries, respectively), and HERB and TILL the lowest (202.8 g/100 berries and 202.7 g/100 berries, respectively). Anthocyanin content was lower with the SMC treatment (1.23 mg/L) than with the TILL treatment (1.46 mg/L). No significant differences were found between soil management treatments in total acidity (TA), tartaric acid (TAR) and total polyphenol index (TPI).

DISCUSSION

This three-year study aimed to evaluate the impact of alternative soil management strategies based on organic mulches on vine development, plant physiology and grape composition. The discussion is intricate due to the multiple variables studied, including soil water content and temperature, yield and pruning mass, leaf nutritional content, leaf physiological variables, soil and plant water potentials,

TABLE 8. Mean values (2020-2022) of must and grape physical-chemical variables (cv. Tempranillo) of the five soil management treatments. Significant differences between soil management treatments were represented when $p < 0.05$.

Treatment	TSS (Brix)	pH	TA (g/L)	Tartaric acid (g/L)	Malic acid (g/L)	Potassium (mg/L)	YAN (mg/L)	Berry mass (g/100 berries)	Anthocyanins (mg/L)	TPI
SMC	22.3	3.65 a	4.03	6.43	1.80 a	1442.9 a	210.3 a	211.5 ab	1.23 b	69.4
STR	22.6	3.51 c	4.00	6.14	1.36 bc	1279.5 bc	113.1 c	226.4 a	1.33 ab	78.0
GPD	22.9	3.59 b	4.00	6.20	1.52 b	1350.4 ab	133.2 bc	221.2 a	1.34 ab	75.9
HERB	22.3	3.49 c	3.96	6.32	1.16 c	1168.5 c	142.6 bc	202.8 b	1.35 ab	75.2
TILL	22.3	3.51 c	3.91	6.32	1.22 c	1166.0 c	174.4 b	202.7 b	1.46 a	77.1

TSS = total soluble solids; TA = total acidity; YAN = yeast assimilable nitrogen; TPI = total polyphenol index (280 nm).

isotopic carbon discrimination in grapes, plant reflectance parameters and the assessment of grape and must quality.

1. Effects of mulches on soil physico-chemical properties and soil water content

The soil organic matter content in the experimental vineyard was generally low (≈ 1 %), which can be attributed to high summer temperatures causing rapid organic matter degradation, intensive vineyard management and limited organic matter incorporation (Constantin *et al*., 2023). A nitrogen deficiency (≈ 1 ‰) was also observed, which restricted plant vegetative growth, as shown in Constantin *et al*. (2023). Li *et al*. (2024) suggested 1.5 to 2 % organic matter between 1.5 % and 2 % and nitrogen 1 to 1.5 ‰ nitrogen for optimal vine development. Based on these ranges, the soil in the experimental vineyard can be classified as nutrient-poor. Furthermore, the slightly alkaline soil pH (8.2)–typical of arid regions–diminished the capacity for macro- and micronutrient assimilation (Gökçen, 2023).

Organic mulches constitute an important nutrient input for the soil (Ferrara *et al*., 2012; Guerra *et al*., 2012). In this study, GPD and STR mulches shared similar compositions, with high organic matter concentrations and a high C/N ratio associated with long-term decomposition. By contrast, SMC mulch exhibited elevated organic matter and nitrogen levels with a low C/N ratio, leading to rapid incorporation into the soil after four years (Table 1 and Table 2).

Gómez de Barreda *et al*. (2023) and Mairata *et al*. (2023) observed a 24 % increase in soil organic matter after three years of organic mulch application to the soil relative to an initial organic matter content of just over 2.4 %. In the present study, using the same organic mulches as those in Mairata *et al*. (2023), the organic matter and nitrogen soil content increased to 32.4 % after four years, probably due to the poor initial organic matter content. Nitrogen inputs in the soil may have enhanced microbial activity, accelerating the decomposition of organic matter and increasing the nutrient availability to the plants (Ralte *et al*., 2005). However, despite the mobilisation of soil organic matter, our results show that soil nutrients increased over the years.

Morlat (2008) conducted a long-term study with organic mulch similar to SMC and observed that total soil carbon content was saturated after 20 years. Even so, high soil nitrogen content may be toxic for plants and reduce yield when high organic amendment rates are used. In our study, the soil nitrogen in the SMC soil treatment remained within non-toxic levels after four years (Li *et al*., 2024). Additionally, although the SMC treatment increased the soil's electrical conductivity, it remained below < 1.2 dS/m, indicating the absence of salinity problems in the vineyard (Martínez-Moreno *et al*., 2023). Therefore, monitoring soil properties and adapting the intensity and type of organic amendment to the requirements of each vineyard is essential.

The effects of mulching on soil moisture depend on precipitation, climatic conditions and the mulching material. Our results agree with those obtained by Moreno *et al*. (2023), who reported a 22.9 % increase in volumetric soil water content after applying hydro mulches. STR and SMC organic mulches increased water content by 15-30 % at 25 cm depth and 40-60 % at 5 cm depth compared to bare soil (HERB) over the two years of analysis (Table S6). However, these differences were minimised due to substantial drip irrigation affecting the entire soil profile.

The differences in soil water content can be attributed to reduced water loss through soil evaporation. This aligns with studies conducted by López-Urrea *et al*. (2020), who, employing a weighing lysimeter, estimated that direct soil evaporation contributes to up to 30-40 % of the seasonal vineyard evapotranspiration under drip-irrigated conditions in a semi-arid region of south-eastern Spain. Consequently, adopting mulching techniques to envelop the vineyard soil surface may result in considerable water conservation.

2. How organic mulches affect plant physiology

Few studies have focused on the physiological responses of grapevines to applying organic mulches. To address this gap, various plant physiological variables were measured to assess the impact of different organic mulches on plant performance. The dynamics of plant water status, reflected by predawn water potential (assumed to represent the mean soil water potential near the roots), varied depending on the organic mulch treatment. Soil water potential is a more stable parameter for estimating vine water availability (van Leeuwen *et al*., 2009). The STR mulch notably enhanced the vine's water status in this study, improving leaf and soil water potential values (Čížková *et al*., 2021; Myburgh, 2013; Nguyen *et al*., 2013; Pou *et al*., 2021; Zengin *et al*., 2022). This enhancement can be attributed to reduced soil water evaporation and lower temperatures. Indeed, López-Urrea *et al*. (2020) reported reductions in vineyard evapotranspiration of 16-18 % when applying pruning waste mulch.

Throughout the three study years, the vines experienced mild to moderate water stress (> -0.5 MPa Ψ_{soil}), except at veraison and ripening in 2022, when moderate to severe water stress (-0.5 to -0.8 MPa Ψ_{soil}) was detected due to the arid and warmer conditions that year (van Leeuwen *et al*., 2009). These results were consistent with the stomatal conductance analysis, which generally indicated no water stress (g_s > 0.15 mol $H_2O/m^2 \cdot s$), except at veraison and ripening in 2022, when moderate (0.05 < g_s < 0.15 mol $H_2O/m^2 \cdot s$) and severe (g_s > 0.05 mol $H_2O/m^2 \cdot s$) water stress was detected (Medrano *et al*., 2002).

The results associated with STR mulch are in line with those of previous studies that showed increases in A_N (Nguyen *et al*., 2013), g_s (Zengin *et al*., 2022) and Ψ_{leaf} (Ferrara *et al*., 2012). However, no solid conclusions can be drawn between the other soil treatments (SMC, GPD, HERB, and TILL) regarding K_{plant}, A_N, g_s, and WUE_i. Moreno *et al*. (2023) studied the effects of organic mulches derived from vine pruning debris, straw and mushroom substrate on the physiology of olive trees grown in pots, reporting an increase in soil water content without any

discernible differences in leaf gas exchange measurements (g_s and A_N), as a consequence of the lack of water stress. Similarly, with an application of solid organic waste mulch, Tarricone *et al*. (2018) found increases in the soil water content of the Chardonnay grapevine cultivar without any differences in leaf gas exchange. The lack of conclusive evidence in plant physiology variables is attributed to high variability between years and phenological stages. Therefore, the vine's physiological response to organic mulches differs between trials due to the specific water stress conditions, characteristics of the organic substrate applied, soil properties and environmental conditions.

Carbon isotopic discrimination ($\delta^{13}C$) is a reliable indicator of water stress, providing an integrative measurement of plant water status during the crucial water stress period from veraison to harvest (Bchir *et al*., 2016; Mairata *et al*., 2022). To our knowledge, no previous work has studied the effect of organic mulches on $\delta^{13}C$ in grape berries. In line with the leaf gas exchange findings, no discernible differences in $\delta^{13}C$ were recorded in any of the three years analysed. Furthermore, according to van Leeuwen *et al*. (2009), the $\delta^{13}C$ values indicate a low level of plant water stress (< -25, p. 1000). The absence of significant water stress could be attributed to the substantial water irrigation supplied before veraison in 2021 and 2022 (no data in 2020), potentially masking any differences between the analysed soil management techniques.

3. Effects of mulching on vegetative growth, yield production and grape composition

Recent studies have consistently demonstrated the positive impact of organic mulches on vegetative growth and yield across various agricultural contexts (Burg *et al*., 2022; Chan *et al*., 2010; Čížková *et al*., 2021; Nguyen *et al*., 2013; Varga *et al*., 2012; Zengin *et al*., 2022). Specifically, our investigation found that SMC mulch notably increased vegetative growth and yield (Table 6) in a vineyard with low soil nitrogen and organic matter content (Li *et al*., 2024). The increase in pruning weight and yield production resulted from the increase in cane and bunch weight, as previously described in other studies (Nguyen *et al*., 2013; Tarricone *et al*., 2018; Zengin *et al*., 2022). Despite these improvements, no changes to the Ravaz index were observed, indicating that the plant balance remained unaffected (Taskos *et al*., 2015). These results agreed with those obtained by Burg *et al*. (2022), who attributed the rapid improvement of soil fertility to the low C/N ratio of nutrient-rich organic mulch.

However, some other studies did not find organic mulch to affect vine development (Buesa *et al*., 2021; DeVetter *et al*., 2015; Ferrara *et al*., 2012). Meanwhile, the present study showed no differences between conventional soil management practices (HERB and TILL) and GPD and STR regarding their effect on vine vegetative development. These mulches, characterised by a higher proportion of carbon and slower decomposition, could improve soil structure and fertility in the long term (Buesa *et al*., 2021; Morlat, 2008).

Reflectance indices, such as NDVI and NDRE, are practical parameters for estimating vegetative growth development (Taskos *et al*., 2015). The SMC mulch soil treatment achieved the highest NDVI, especially at veraison, accentuating the effects of soil treatments in the vineyard during the most demanding periods. By contrast, NDVI did not increase during flowering due to its saturation at high vegetation density (Silva Costa *et al*., 2023). The NDRE index accurately predicted differences in vegetative growth in vineyards with SMC at flowering and veraison. Although the NDVI index is a traditional reflectance vegetation indicator (Rouse *et al*., 1973), some studies have found better correlations for pruning weight using the NDRE index (Taylor *et al*., 2021). However, in our study, as in other research, a higher correlation was observed between the NDVI growth index and both yield (Pinter *et al*., 2003) and pruning weight (Stamatiadis *et al*., 2010) for both of the analysed phenological stages (p-value < 0.001).

A strong relationship was established between leaf nitrogen content and NDVI and NDRE values (p-value < 0.01), similar to results obtained by Walker *et al*. (2021). Leaf blade nitrogen content was within the range observed in previous work on the Tempranillo cultivar (Romero *et al*., 2013). The decrease in nitrogen content from flowering to veraison can be attributed to nutrient translocation to the growing tissues (Keller, 2005; Peuke, 2009). The SMC mulch treatment enhanced nitrogen concentrations in the leaf blades due to increased nutrient availability and assimilation capacity (Keller, 2005; Özdemir *et al*., 2008). Nitrogen concentration in leaves is closely related to the plant's photosynthetic capacity and vegetative growth due to the proteins and thylakoids of the Calvin cycle, which account for most of the total leaf nitrogen (Evans, 1989). Furthermore, organic mulch (*i.e*., the SMC) and the higher soil water content facilitated the assimilation of soil nutrients, leading to higher nitrogen concentration in the leaves (Burg *et al*., 2022; Keller, 2005; Özdemir *et al*., 2008; Pinamonti, 1998; Tarricone *et al*., 2018).

The grape composition parameters were within the range obtained in previous studies conducted on the Tempranillo cultivar (Garde-Cerdán *et al*., 2014; Portu *et al*., 2017), with grapes treated with SMC showing the highest pH, malic acid, potassium and YAN values. The higher malic acid content was associated with low light intensity (Kliewer, 1971) due to increased canopy growth. Similar to Chan *et al*. (2011), we observed an increase in grape potassium with organic mulches. The higher berry K was related to higher soil exchangeable K, increasing the pH values as a result of the substitution of K^+ for H^+ in the grapes. Although high pH values could be a problem in the wine-making process, the pH obtained in grape must was tolerable for vinification and lower than that obtained by Serrano *et al*. (2024) in the Tempranillo cultivar. The YAN levels in STR and GPD musts were below the minimum required quantities of 140 mg N/L, necessitating nitrogen addition for fermentation (Bely *et al*., 1990). HERB and TILL grapes had lower berry mass and higher anthocyanin concentration. However, the lower anthocyanin

content of SMC grapes can be due to multiple factors, such as lower cluster light interception, prioritisation of primary over secondary metabolism, and reduced biotic and abiotic stress (Mairata *et al*., 2024). Overall, the STR and GPD organic mulches slightly differed regarding grape variables compared to HERB and TILL soil management treatments. The SMC soil management treatment has the most effect on grapes. However, all the parameters were within the optimal range for winemaking. Additionally, a sensory panel of tasters did not detect any differences in the wines produced from the grapes in this trial (Mairata *et al*., 2024).

CONCLUSION

This research demonstrates that organic mulch and the physical and chemical properties of soil influence grapevine development and grape parameters. Applying SMC mulch in vineyards with deficient nitrogen and organic matter increased soil water content during the grapevine growth period, increased leaf nitrogen content and promoted vegetative growth, leading to enhanced yield production without compromising grape composition. By contrast, STR mulching increased soil water content, reduced soil temperature and lowered evaporation. These effects improved the plant water status and gas exchange values (A_N and g_s) but did not affect vigour or production variables. Berry $\delta^{13}C$ measurements showed no differences among soil management treatments, likely because irrigation practices mitigated water stress and masked the effects of organic mulches on grapevine physiology between veraison and ripening. Furthermore, no differences were observed in grape composition variables between STR and GPD organic mulches and conventional soil management practices.

The varying effects of different organic mulches can be attributed to their physical-chemical composition. The SMC mulch had an early impact due to its rich nutrient content, fine granularity and low C/N ratio. By contrast, STR and GPD mulches, characterised by a higher C/N ratio, exhibited slower decomposition rates, suggesting potential long-term benefits. These distinctions were evident in the higher nitrogen levels in the leaves of SMC mulch plants. Moreover, the high potassium content of SMC organic mulch increased grape potassium content and pH. Despite these changes, all the parameters of grapes resulting from SMC mulch remained within the optimal range for winemaking. Reflectance indices, such as NDVI and NDRE, emerged as reliable parameters for estimating vegetative growth and production (p-value < 0.001) in grapevines, offering non-destructive and rapid data acquisition. Regular assessments of soil properties are imperative for determining specific growing requirements and selecting the most appropriate organic mulch to improve vine development and achieve optimal grape composition.

ACKNOWLEDGEMENTS

The authors thank D. Mateos for sharing their vineyards, and the staff of the regional laboratory of La Grajera. This research was supported by the European regional development fund (ERDR) and Ministerio de Ciencia e Innovación (MCIN) [RTI2018-095748-R-I00]. A.M. thanks ERDR/MCIN for his pre-doctoral fellowship (PRE2019-089110). MP and DL thank Gobierno de La Rioja for their FPI research grants.

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