

Article

Effects of the Application of Different Types of Vermicompost Produced from Wine Industry Waste on the Vegetative and Productive Development of Grapevine in Two Irrigation Conditions

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Abstract

This study evaluates the agronomic potential of two types of vermicompost—one produced solely from wine industry residues (WIR) and one incorporating sewage sludge (WIR + SS)—under rainfed and deficit irrigation conditions in Mediterranean vineyards. The vermicompost was obtained through a two-phase process involving initial thermophilic pre-composting, followed by vermicomposting using *Eisenia fetida* for 90 days. The conditions were optimized to ensure aerobic decomposition and maintain proper moisture levels (70–85%) and temperature control. This resulted in end products that met the legal standards required for agricultural use. However, population dynamics revealed significantly higher worm reproduction and biomass in the WIR treatment, suggesting superior substrate quality. When applied to grapevines, WIR vermicompost increased soil organic matter, nitrogen availability, and overall fertility. Under rainfed conditions, it improved vegetative growth, yield, and must quality, with increases in yeast assimilable nitrogen (YAN), sugar content, and amino acid levels comparable to those achieved using chemical fertilizers, as opposed to the no-fertilizer trial. Foliar analyses at veraison revealed stronger nutrient uptake, particularly of nitrogen and potassium, which was correlated with improved oenological parameters compared to the no-fertilizer trial. In contrast, WIR + SS compost was less favorable due to lower worm activity and elevated trace elements, despite remaining within legal limits. These results support the use of vermicompost derived solely from wine residues as a sustainable alternative to chemical fertilizers, in line with the goals of the circular economy in viticulture.

Keywords: vermicompost; grapevine waste; fertilization; circular economy; sewage sludge



Academic Editor: Gederts Ievinsh

Received: 19 June 2025

Revised: 18 July 2025

Accepted: 23 July 2025

Published: 25 July 2025

Citation: Sánchez-Suárez, F.; Palenzuela, M.d.V.; Campos-Vazquez, C.; Santos-Dueñas, I.M.; Ramos-Muñoz, V.M.; Rosal, A.; Peinado, R.A. Effects of the Application of Different Types of Vermicompost Produced from Wine Industry Waste on the Vegetative and Productive Development of Grapevine in Two Irrigation Conditions. *Agriculture* **2025**, *15*, 1604. <https://doi.org/10.3390/agriculture15151604>

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1. Introduction

The cultivation of vines for wine production is of great importance in the Mediterranean region. Italy, France, and Spain together account for 49.2% of global production,

equivalent to around 111.2 million hectoliters of wine [1]. Therefore, it is reasonable to assume that climate change, as well as soil loss and contamination, will significantly impact global wine production in this region. An increase in temperature results in an earlier phenological advance, meaning the grapes ripen during a warmer period [2,3]. This leads to an increase in alcohol content and a reduction in aromatic potential and titratable acidity [4–9]. Conversely, changes in rainfall patterns are resulting in less precipitation, albeit of a more torrential nature [10]. This decreases water infiltration into the soil, favoring runoff and soil loss. The result is usable surface areas with lower levels of organic matter, nutrients, and water retention capacity [11,12].

To mitigate the above-mentioned environmental problems, the use of organic fertilizers or amendments derived from the treatment of organic waste emerges as an alternative solution [13–16] that aligning with European guidelines [17] on the circular economy and the reduction in synthetic chemical fertilizer use [18]. Compared to other approaches such as animal feed, biogas production, and biorefinery, vermicomposting is a promising and sustainable option for the valorization of by-products generated by viticulture and the wine industry [19–21].

The vermicomposting process stabilizes this type of organic waste through the combined action of the existing microbiota and the inoculated earthworms, most commonly the species *Eisenia fetida* and *Eisenia andrei* [22]. The resulting vermicompost can be used as a soil improver and plant growth promoter thanks to its organic matter and nutrient content, porosity, and water retention capacity [23]. However, very few studies have been conducted on the vermicomposting of wine residues or the effects of vermicompost on soil and crops [22]. Most studies focus on pomace residue, with positive results showing that the application of this technology reduces polyphenol content and improves nutrient [24,25]. Few studies have investigated other types of by-products, such as lees and vine shoots [26].

This study adopts a novel approach to examining the effects of applying two types of vermicompost to rainfed and irrigated vineyards in a Mediterranean climate. It examines the use of vermicompost obtained from the treatment of wine by-products (vine shoots, lees and grape marc), as well as vermicompost obtained from the treatment of these same materials with sewage sludge.

2. Materials and Methods

2.1. Organic Waste Used and Earthworms

Three types of wine residue (vine shoots, lees, and grape pomace) were used. These were provided by Bodegas Alvear in Montilla, Córdoba, and Bodegas Viñas de Alange in Almendralejo, Badajoz, both of which are in the southwestern Spain. Sludge from the San Jerónimo Urban Wastewater Treatment Plant (WWTP) in Seville was also used. The physicochemical characteristics of waste are shown in Table 1. Clitellated earthworms of the species *Eisenia fetida* were used for the vermicomposting process. These came from a breeding bed of horse manure and sawdust in the basement of the Chemical Engineering laboratory of the Pablo de Olavide University (Seville, Spain). Wine residues and sludge were collected in September 2023.

Table 1. Physico-chemical characterization of the starting materials.

	Vine Shoots	Lees	Grape Marc	Sewage Sludge
Humidity (%)	3.3	66.9	76.3	77.1
pH	5.2 ± 0.0	3.7 ± 0.0	4.0 ± 0.0	7.5 ± 0.0
EC (dS·m ^{−1})	1.1 ± 0.0	3.1 ± 0.1	1.5 ± 0.0	4.2 ± 0.2
OM (%)	91 ± 4	69.2 ± 0.1	96.6 ± 0.4	59 ± 1
N (%)	0.6 ± 0.1	1.6 ± 0.1	1.9 ± 0.3	3.6 ± 0.1
C/N	88.18	25.15	29.6	9.48

EC: Electrical Conductivity; OM: Organic Matter; C: Total Carbon (Waskman, 1.72). Data expressed in dry weight basis.

2.2. Precomposting and Vermicomposting

Two pilot-scale experiments were designed for pre-composting using an open trapezoidal windrow system (4.5 m³). In one trial (WIR), the pile consisted of shredded vine shoots, lees, and grape pomace at a mass ratio of 1:1:2 (dry weight), respectively. In the other trial (WIR + SS), the pile also contains sewage sludge being the mass ratio of 1:1:2:2 (dry weight). In both trials, the material was turned and irrigated weekly, allowing it to reach a temperature above 50 °C for a total of ten days during the first 30 days (TWIR_{max.} = 66.7 °C; TWIR + SS_{max.} = 68.3 °C). The imposed operating conditions allowed moisture percentages in the material to be maintained between 40% and 70%.

Forty days after the beginning of pre-composting, after the most pronounced thermal phase, approximately 120 kg (fresh mass) of representative material was collected from each pile to set up two vermicomposting trials in triplicate. The experimental beds were made up of pre-composted material, which was distributed among 54-L rectangular PVC containers. These were kept in darkness and initially contained 300 clitellated *Eisenia fetida* earthworms. Holes located at the bottom and sides of each container were used to prevent leachate accumulation and to promote gas exchange. The frequency of aeration and watering (three times per week) allowed the internal temperature of each bed to remain below 28 °C and the humidity percentage to be maintained between 70% and 85%. According to Domínguez and Gómez-Brandon [27], these conditions are considered optimal for vermicomposting produced by this type of earthworm.

The vermicomposting trials lasted 90 days to ensure the third generation of worms [28]. At 30-, 60-, and 90-day intervals, the total volume of each bed was counted (including adult and juvenile worms and cocoons), and the biomass was determined by live weighing of all the adult and juvenile worms, which had been previously classified by hand and cleaned.

Precomposting and vermicomposting were carried out from October 2023 to January 2024.

2.3. Location of the Vineyard and Assay Conditions

Both types of vermicompost were applied in a vineyard of cv. Cayetana Blanca in Ribera del Fresno (Badajoz, Spain), under two conditions: deficit irrigation and rainfed. Both vineyards have an integrated cultivation with double Royat cordon pruning and 5 or 6 two-bud pruning, with planting densities of 1850 and 2469 plants/ha for dry farming and irrigated farming, respectively. The vineyard is trained on east–west oriented trellises.

A total of 780 m³/ha of deficit irrigation was applied to the deficit irrigation vineyard, distributed between the pea berry phenological stage and grape harvest (i.e., from June to early September). The vineyard uses a drip irrigation system, with each dripper providing 2.3 L per hour per plant and an irrigation frequency of three to five days. The amount of water applied equated to 30% of the total requirements for a vineyard with a 2.70 m interrow distance and a vertical shoot positioning training system.

The trial involved applying four types of fertilizer in triplicate in three blocks of ten plants each, under each watering condition: (1) vermicompost of wine industry residues (WIR Verm.) (vine shoots, grape marc and lees); (2) vermicompost of wine industry residues and sewage sludge (WIR + SS Verm.); (3) positive control with a conventional chemical fertilizer providing a nutritional balance of 17-9-12 (%N-%P₂O₅-%K₂O); (4) A negative control with no fertilizer application.

The fertilizer doses were adjusted according to the potential yields of 7 t/ha in rainfed areas and 18 t/ha in irrigated vineyards, at doses of 40 and 80 kg of N/ha, respectively [29]. Therefore, the equivalent of 235 kg/ha of conventional fertilizer and 1870 kg/ha of WIR vermicompost or 1536 kg/ha of WIR + SS vermicompost were applied to rainfed vineyards and double these quantities to irrigated vineyards. Fertilization was carried out at the end of February 2024.

2.4. Climate and Soil Characterization

The climate analysis was carried out by processing data from the publicly owned climate station (Red de Asesoramiento al Regante de Extremadura, REDAREX) [30] located in Villafranca de los Barros, at a straight line distance of less than 20 km from the test plots. For this analysis, the averages for the period 2011–2023 were extracted and considered, as well as the data relating to the 2024 campaign being extracted separately.

Each soil sample was initially dried at 60 °C in an oven (Indelab, Labolan S.L., Esparza de Galar, Spain) until it reached a constant weight, after which the moisture content was determined by measuring the weight difference. The dry sample was then crushed in a blade mill (Mf 10, Ika-Werke, Staufen, Germany). After conditioning, each sample was stored at −20 °C until further analysis. pH and electrical conductivity were determined in an aqueous extract obtained from the suspension at a mass to volume ratio of 1:5 after centrifugation at 3000 rpm for 20 min using a Rotofix 32A centrifuge (Hettich Zentaurifugen, Tuttlingen, Germany) and subsequent membrane filtration (0.45 µm). A pH meter (Hanna-5521, Hanna Instruments, Woonsocket, RI, USA) and a conductivity meter (XS-51+, Scharlab S.L., Barcelona, Spain) were used for this purpose. Organic matter content was determined by calcination at 550 °C for four hours in a muffle furnace (Hobersal 230, Fornis Hobersal, Barcelona, Spain), and nitrogen content was determined using a variant of the Kjeldahl method described by Rosal (2007) [31], with a UDK 129 distillation unit (Velp Scientifica Srl, Usmate, Italy).

Finally, the soil science unit of the University of Córdoba determined the main cations and micronutrients. The exchangeable cations were determined by extraction with 1 M ammonium acetate buffered at pH 7 and were measured using atomic absorption spectrophotometry for calcium (Ca²⁺) and magnesium (Mg²⁺), and flame emission spectrophotometry for sodium (Na⁺) and potassium (K⁺). The amount of available phosphorus in the soil was estimated according to Olsen's method [32]. The labile iron, copper, manganese, and zinc content was determined using the diethylenetriaminepentaacetic acid (DTPA) extraction method according to Lindsay and Norvell [33].

2.5. Physicochemical and Phytotoxic Characterization of Vermicompost

The vermicompost samples were obtained by sieving the material through a 25 mm mesh and then dried at 60 °C in an oven (Indelab, Labolan S.L., Esparza de Galar, Spain) to constant weight. They were then crushed using a blade mill (Cecotec, Cecotec Innovaciones, Altafar, Spain). Samples were conditioned and parameters such as pH, electrical conductivity, organic matter content, and total nitrogen were determined using the same methods and equipment as for the solid soil samples in Section 2.4. Assimilable phosphorus was quantified using UV–visible spectrophotometry (GENESYS 10S UV-Vis, Thermo Fisher Scientific, USA) and the Olsen method [32]. The degree of maturity was assessed based on the C/N ratio obtained using the Waskman coefficient (1.72), while phytotoxicity was assessed using the germination index (GI) [34], as described by Palenzuela et al. [35].

$$GI = \frac{\text{Germination rate of treated seeds (\%)} \times \text{Root length of treated seeds (\%)}}{\text{Germination rate of control seeds (\%)} \times \text{Root length of control seeds (\%)}}$$

In addition, macronutrients (K, Ca, and Mg) and micronutrients (B, Na, Mn, Fe, Cu, Zn, and Mo) were analyzed by ICP-MS (Agilent 7800, Agilent Technologies, Santa Clara, CA, USA) after acid digestion (HNO₃ and HCl) using a microwave digester (CEM Mars One, CEM Corporation, Matthews, NC, USA). Finally, the particle size was determined using the method specified in the official regulations [36].

2.6. Determination of Agronomic Parameters

2.6.1. Foliar Analysis

Foliar analysis was carried out in triplicate to determine the nutritional status of the vines at two points in their vegetative cycle: flowering and veraison. The foliar sample was dried in an oven at 60 °C, crushed using a blade mill (Cecotec, Cecotec Innovaciones, Altafar, Spain), and stored at −20 °C until analysis. The following elements were determined for each dry sample: macronutrients (N, P, K, Ca, Mg); micronutrients (B, Na, Mn, Fe, Cu, Zn, Mo); and heavy metals (Cr, Cd, Hg, Pb). The nitrogen content was determined using the method described by Rosal (2007) [31], while the other elements were analyzed using ICP-MS (Agilent 7800, Agilent Technologies, Santa Clara, CA, USA) after acid digestion (HNO₃, H₂O₂) using a CEM Mars One microwave (CEM Corporation, Matthews, NC, USA).

2.6.2. General Agronomic Parameters

The general agronomic parameters were determined at harvest and winter pruning. These parameters include the following: (1) vegetative parameters, such as exposed leaf area at harvest, calculated using the vineyard leaf mass as a parallelepiped [37], and the number of spurs, shoots, and pruning wood weight at winter Detpruning; (2) production parameters, such as the number and weight of bunches, yield per plant, and the fertility index, calculated as the ratio of bunches to shoots per plant; and (3) the Ravaz index and the SA/Yield ratio, which provide important information on the plant's vegetative-productive balance [29].

2.7. Determination of Must Parameters and Amino Acid Profile

Once the grapes were harvested, they were destemmed and pressed to extract and characterize the must. The usual parameters, such as sugar content (expressed as probable ethanol content), pH and titratable acidity, were determined using official methods [38]. Additionally, the Yeast Assimilable Nitrogen (YAN) content was determined using the method described by Shively [39].

Amino acids were analyzed by using HPCL 1260 Infinity II (Agilent) equipped with an ACE[®] C18-HL (5 µm × 25 cm) column that was connected to and UV detector. The analysis was carried out by derivatization with ethoxymethylenmalonate (DEEMM) using an adapted version of the method described by Gómez-Alonso [40]. In this method, 0.250 mL of sample, 0.75 mL of a borate buffer solution At pH 9, 0.500 mL of methanol, 0.050 mL of internal standard (1 g/L L-2-acidoamino adipic acid), and 0.003 mL of DEEMM were added to 0.250 mL of sample. The derivatization reaction was carried out for 30 min in an ultrasonic bath and 2 h in a 70 °C bath to ensure complete degradation of all unconsumed DEEMM. The gradient was as follows: 25 mM acetic/acetate buffer at pH 5.8 and 0.02% sodium azide and 80/20 acetonitrile/methanol. The identification was carried out using standard subjected to the same conditions as the samples. Quantification was performed using calibration curves.

2.8. Statistical Analysis

Earthworm biomass density data (adults and juveniles) and individual density data (adults, juveniles and cocoons) were analyzed in triplicate using ANOVA, and significant differences were analyzed using the Tukey HSD test. Before carrying out any statistical analysis, the normality of all the data was studied using the Kolmogorov–Smirnov test. The statistical study of significant differences in the means of these parameters between the two treatments, and of the means determined for the analyzed parameters of the two vermicompost, was carried out using Student's *t*-test with the software package SigmaPlot v11.0.

For the statistical analysis of agronomic parameters and must composition, ANOVA and post hoc Tukey's HSD tests were performed using IBM SPSS Statistics 25 (Armonk, NY, USA). Cluster analysis and heatmaps were performed using the open-source Python 3.9.7. programming language in the Anaconda Jupyter Project environment (Anaconda Inc., Austin, TX, USA).

All the analyses were carried out by triplicate during the year 2024. The data of the tables shows means $\pm$ standard deviation.

3. Results and Discussion

3.1. Earthworm Population Dynamics During Vermicomposting

An initial population of 300 clitellated earthworms was inoculated into each bed. This corresponded to an initial density of 1802 worms per m^2 and a biomass of 1236 ± 62 g per m^2 for WIR and 1298 ± 122 g per m^2 for WIR + SS. These biomass density values are like those reported by other researchers for the vermicomposting of various organic waste materials, such as grape marc, pineapple, and sludge, and have produced favorable outcomes in terms of both worm development (*Eisenia fetida* and *Eisenia andrei*) and material biodegradation [28,41,42].

Figure 1 illustrates the evolution of worm biomass density (adult and juvenile) during the vermicomposting process (WIR, WIR + SS). In the case of WIR process, although biomass density decreased to 1049 ± 183 in the first 30 days of the trial, no statistically significant changes were observed. A continuous and statistically significant increase in biomass density was observed until the end of the trial, reaching 2523 ± 58 g m^{-2} , an increase of about 104% compared to the beginning ($F_{3,11} = 101.93$; $p < 0.001$). Regarding the WIR + SS trial of the vermicomposting process, earthworm biomass density decreased slightly in the first 30 days of the process, remaining stable until the end of the trial (1149 ± 72 g m^{-2}). However, no statistically significant changes were observed ($F_{3,11} = 2.16$; $p = 0.17$).

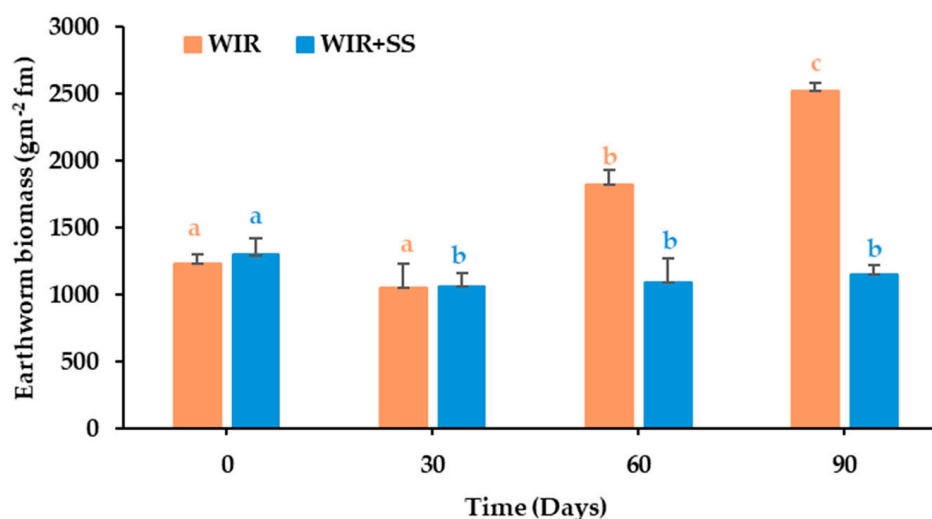


Figure 1. Earthworm biomass (g m^{-2} fresh mass, fm) during vermicomposting of wine residues industry. Orange letters (WIR) and blue letters (WIR + SS) indicate significant differences among the sampling times according to Tukey's HSD test.

Figure 2 shows the evolution of individual density (adult and juvenile worms, cocoons). In the case WIR process, the density of adult worms decreased slightly ($F_{3,11} = 20.38$; $p < 0.001$) during the first 30 days of treatment, after which it remained unchanged until the end of the trial (1392 ± 113 adults m^{-2}). This decrease is due to the worms being

inoculated directly into the pre-composted substrate without pre-conditioning [43]. The density of juvenile worms and cocoons increased significantly throughout the process (juveniles: $F_{3,11} = 381.2$; $p < 0.001$; cocoons: $F_{3,11} = 131.86$; $p < 0.001$), reaching values of 4445 ± 113 juveniles m^{-2} and 7373 ± 875 cocoons m^{-2} . Regarding the WIR + SS trial of the vermicomposting process, Figure 2 shows that the density of adult worms decreased markedly during the first 60 days ($F_{3,11} = 238.72$, $p < 0.001$), after which there were no statistically significant changes until the end of the trial (572 ± 39 adults m^{-2}). Conversely, the density of juvenile worms increased significantly during the first 30 days ($F_{3,11} = 150.1$; $p < 0.001$), reaching a value of 1280 ± 173 juveniles m^{-2} ; this increase continued until the end of the trial (1618 ± 78 juveniles m^{-2}), though there were no statistically significant changes. As for cocoons density, the final value was 1278 ± 82 cocoons m^{-2} , which represented a statistically significant increase ($F_{3,11} = 273.3$; $p < 0.001$).

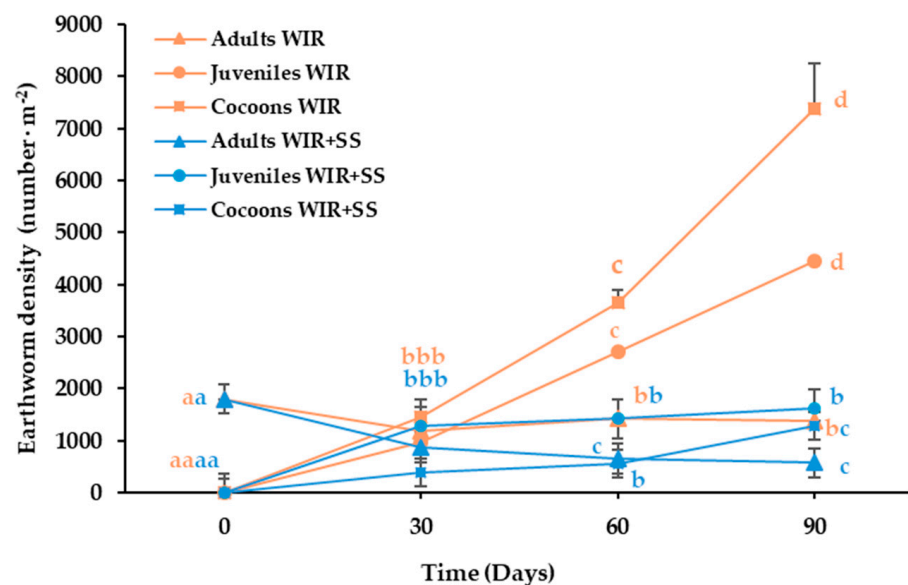


Figure 2. Earthworm density (number of adults, juveniles, and cocoons per m^2) during vermicomposting (WIR, WIR + SS). Values are means $\pm$ standard deviation. Different letters indicate significant differences for adults, juveniles, and cocoons for WIR (orange) and WIR + SS (blue) treatments among the sampling times according to Tukey's HSD test.

The high rates of earthworm reproduction and biomass evolution observed in this study are comparable to those found in other studies on vermicomposting of grape pomace [44–46]. In the case WIR + SS, the results of this study suggest that earthworm development decreases in vermicomposting of wine waste when sewage sludge is added. This is probably due to the presence of toxic pollutants, such as ammonium [47].

As shown in Table 2, both earthworm biomass density and density of individuals were significantly higher in WIR than in WIR + SS.

Table 2. Earthworm biomass density ($g \cdot m^{-2}$ fresh mass, fm) and earthworm density (number of adults, juveniles, and cocoons per m^2) after 90 days of vermicomposting (WIR Verm., WIR + SS Verm.).

	Earthworm Biomass ($g \cdot m^{-2}$ fm)	Adults $\cdot m^{-2}$	Juveniles $\cdot m^{-2}$	Cocoons $\cdot m^{-2}$
WIR Verm.	2523 ± 58	1392 ± 113	4445 ± 252	7373 ± 875
WIR + SS Verm.	1149 ± 72	572 ± 39	1618 ± 78	1278 ± 82
t-test	***	***	***	***

WIR Verm.: Vermicompost of wine industry residues; WIR + SS Verm.: Vermicompost of wine industry residues and sewage sludge. *** indicates significant differences ($p < 0.001$) between treatments.

3.2. Physico-Chemical and Phytotoxic Parameters of Vermicompost

Table 3 shows the results obtained when determining the various parameters that characterize the agronomic potential of each vermicompost used as an organic fertilizer in the experimental plots. In the trial involving exclusively wine-making waste, the process resulted in a vermicompost with a pH approximately one point higher than that of the vermicompost in the trial incorporating sludge (pH 7.4). Crop response to organic amendments is more favorable when the pH is around 7 [48]. Electrical conductivity was below 4 dS m^{-1} in both vermicompost, though significantly higher in the case of WIR + SS vermicompost. This is due to the higher inorganic content of sewage sludge (Table 1), which has led to a significant increase in species such as Na, Mg, and Ca in the vermicompost. In any case, the conductivity values of both amendments are similar to those reported by other authors [23]. Regarding nutrients, the concentrations of N, K, P, B, and Mn in these vermicompost were of a similar order to those reported by other authors for vermicompost obtained from fresh pomace, but notably higher for Mg, Ca, and Fe [44].

Table 3. Physicochemical characteristics of the vermicompost used.

Parameter	WIR Verm.	WIR + SS Verm.
pH	$8.13 \pm 0.09 \text{ a}$	$7.39 \pm 0.07 \text{ b}$
EC ($\text{dS} \cdot \text{m}^{-1}$)	$1.10 \pm 0.06 \text{ a}$	$2.66 \pm 0.06 \text{ b}$
OM (%)	$65.63 \pm 2.39 \text{ a}$	$53.00 \pm 2.30 \text{ b}$
N (%)	$2.26 \pm 0.16 \text{ a}$	$2.75 \pm 0.32 \text{ a}$
C/N	16.88	11.21
GI (%)	111,0	82.6
P ($\text{mg} \cdot \text{kg}^{-1}$)	4095 ± 173	7097 ± 275
Available P (%)	$0.32 \pm 0.04 \text{ a}$	$0.27 \pm 0.01 \text{ a}$
B ($\text{mg} \cdot \text{kg}^{-1}$)	$163 \pm 14 \text{ a}$	$98 \pm 9 \text{ b}$
Na ($\text{mg} \cdot \text{kg}^{-1}$)	$604 \pm 50 \text{ a}$	$935 \pm 63 \text{ b}$
Mg ($\text{mg} \cdot \text{kg}^{-1}$)	$3995 \pm 212 \text{ a}$	$5243 \pm 49 \text{ b}$
K ($\text{mg} \cdot \text{kg}^{-1}$)	$30,998 \pm 697 \text{ a}$	$15,378 \pm 852 \text{ b}$
Ca ($\text{mg} \cdot \text{kg}^{-1}$)	$55,669 \pm 568 \text{ a}$	$63,921 \pm 985 \text{ b}$
Cr ($\text{mg} \cdot \text{kg}^{-1}$)	$89 \pm 5 \text{ a}$	$66 \pm 19 \text{ a}$
Mn ($\text{mg} \cdot \text{kg}^{-1}$)	$192 \pm 8 \text{ a}$	$304 \pm 10 \text{ b}$
Fe ($\text{mg} \cdot \text{kg}^{-1}$)	$7787 \pm 535 \text{ a}$	$10,873 \pm 489 \text{ b}$
Cu ($\text{mg} \cdot \text{kg}^{-1}$)	$53 \pm 3 \text{ a}$	$202 \pm 12 \text{ b}$
Ni ($\text{mg} \cdot \text{kg}^{-1}$)	$10 \pm 3 \text{ a}$	$18 \pm 7 \text{ a}$
Zn ($\text{mg} \cdot \text{kg}^{-1}$)	$96 \pm 6 \text{ a}$	$455 \pm 44 \text{ b}$
Mo ($\text{mg} \cdot \text{kg}^{-1}$)	$1.0 \pm 0.2 \text{ a}$	$2.7 \pm 0.9 \text{ b}$
Cd ($\text{mg} \cdot \text{kg}^{-1}$)	$0.1 \pm 0.0 \text{ a}$	$1.1 \pm 0.3 \text{ b}$
Hg ($\text{mg} \cdot \text{kg}^{-1}$)	<LOD	0.2 ± 0.0
Pb ($\text{mg} \cdot \text{kg}^{-1}$)	$5.9 \pm 0.3 \text{ a}$	$45 \pm 4 \text{ b}$
Granulometry (mm)	25.0 *	25.0 *

WIR Verm.: Vermicompost of wine industry residues; WIR + SS Verm.: Vermicompost of wine industry residues and sewage sludge; EC: Electrical Conductivity; OM: Organic Matter; C: Total Carbon (Waskman, 1.72); GI, germination index; Data expressed in dry weight basis. LOD, Limit of detection. * > 90% particles passed through a 25 mm sieve. Different letters indicate significant differences at $p < 0.05$.

The values obtained for organic matter content (>35%), C/N ratio (<20), and particle size (<25 mm) in both vermicompost were within the legal limits for vermicompost use in agriculture. With respect to heavy metals (Cr, Cu, Ni, Zn, Cd, and Hg), the total concentrations were lower than the Class B limits according to RD 506/2013 [35]. Different authors report that a C/N ratio of <20 is indicative of maturity, while a ratio of ≤ 15 is preferable for the agronomic use of vermicompost [49]. Regarding the germination rate,

the WIR vermicompost was significantly higher, with values exceeding 80% in both cases. This is the limit considered by Zucconi et al. [50] to indicate the absence of phytotoxicity.

Both types of vermicompost were applied according to its fertilizing capacity rather than as a soil amendment, which resulted in much lower amounts being used. The aim is to determine the effectiveness of vermicompost as an alternative fertilizer when the quantity of nutrients is like that of conventional fertilization. In other studies, much larger quantities are applied when vermicompost is used as an organic amendment. This means that the effect on the plant may be due not only to the type of fertilizer, but also to the quantity applied [13].

3.3. Climate

The climate in which the trial was conducted is a temperate Mediterranean climate, with dry and very hot summers [50]. This climate is characterized by high rainfall concentrations during the winter rest period of the vines, and low rainfall during the growing cycle. Figure 3 shows the average ombrothermal diagram from 2011 to 2024. The average rainfall in the study area is 106 mm. Temperatures are warm, with frequent heatwaves in summer and maximum temperatures averaging over 35 °C in July and August.

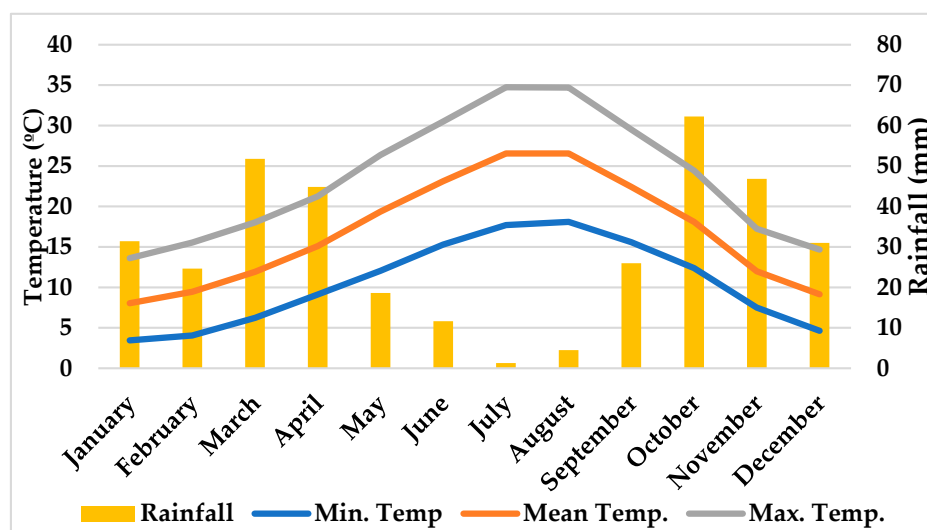


Figure 3. Average ombrothermal diagram 2011–2024.

The year in which the trial was conducted was characterized by a significant drought (Table 4). During the growing season, rainfall was 45 mm, which is 42% of the usual amount [30]. Additionally, July and August were warmer than usual, with average and maximum temperatures approximately 1 °C higher than the ten-year average [30].

Table 4. Rainfall and temperature during the 2024 growing season. Also included is the amount of irrigation applied each month in the deficit irrigation vineyard.

	Min. Temp. (°C)	Mean Temp. (°C)	Max. Temp. (°C)	Rainfall (mm)	Irrigation (mm)
April	9.7	16.3	23.2	12.9	0
May	11.0	18.8	26.2	1.6	0
June	15.6	22.7	29.7	29.7	15
July	18.6	27.6	35.7	0.0	28
August	19.6	28.3	36.5	0.0	28
September	14.6	21.7	28.9	1.0	7

3.4. Agronomic Parameters

3.4.1. Soil Parameters

Soil analyses carried out one year after application of different fertilizers revealed that only those where vermicompost was applied have a higher quantity of organic matter and nitrogen regardless of the water regime (Table 5). This may be due to greater nitrogen stability of organic matter and to its gradual mineralization [50], whereas the ammonium content does not differ. Another macronutrient that increased was phosphorus (P), with the trials where fertilizer was applied in the rainfed conditions show a higher content of this macronutrient. Other macronutrients (K, Ca, and Mg) show no differences one year after application, which can be due to fertilizer applications equivalent to the plants' consumption. Slightly higher values of sodium were observed in the deficit irrigation conditions, possibly due to the irrigation water, but no significant differences were found between the fertilizers.

Table 5. Parameters determined in the soils of the different trials.

	Rainfed Vineyard				Deficit Irrigation Vineyard			
	Control	Chemical Fertilizer	WIR Verm.	WIR + SS Verm.	Control	Chemical Fertilizer	WIR Verm.	WIR + SS Verm.
pH	7.36 ± 0.06 B	7.43 ± 0.06 B	8.41 ± 0.05 A	7.46 ± 0.03 B	8.40 ± 0.05 a	7.92 ± 0.04 b	8.01 ± 0.01 b	8.46 ± 0.05 a
C.E. (dS·m ⁻¹)	1.09 ± 0.05 B	0.9 ± 0.02 C	1.0 ± 0.1 BC	1.5 ± 0.2 A	1.08 ± 0.01 c	1.25 ± 0.02 b	1.24 ± 0.03 b	1.45 ± 0.01 a
OM (%)	2.8 ± 0.2 C	3.5 ± 0.2 B	4.8 ± 0.1 A	4.5 ± 0.1 A	2.7 ± 0.1 c	3.2 ± 0.1 b	4.1 ± 0.1 a	3.9 ± 0.2 a
NH ₄ ⁺ (mg·kg ⁻¹)	0.03 ± 0.01 A	0.05 ± 0.01 A	0.04 ± 0.01 A	0.05 ± 0.01 A	0.03 ± 0.01 a	0.05 ± 0.02 a	0.03 ± 0.01 a	0.04 ± 0.02 a
N (%)	0.12 ± 0.02 B	0.12 ± 0.02 B	0.17 ± 0.02 A	0.22 ± 0.01 A	0.13 ± 0.02 b	0.12 ± 0.03 b	0.18 ± 0.02 a	0.19 ± 0.02 a
P (mg·kg ⁻¹)	19.6 ± 0.8 B	24.1 ± 1.8 A	23.7 ± 0.9 A	22.2 ± 1 A	9.7 ± 0.3 b	9.1 ± 0.3 b	6.6 ± 0.1 c	11.4 ± 0.4 a
K (mg·kg ⁻¹)	365 ± 18 A	364 ± 6 A	356 ± 6 A	383 ± 12 A	435 ± 19 a	427 ± 21 a	435 ± 13 a	428 ± 4 a
Ca (mg·kg ⁻¹)	5477 ± 258 A	4730 ± 126 A	5605 ± 338 A	5171 ± 180 A	6729 ± 127 a	7178 ± 299 a	6690 ± 104 a	6614 ± 221 a
Mg (mg·kg ⁻¹)	332 ± 16 A	307 ± 10 AB	289 ± 11 B	289 ± 7 B	444 ± 18 a	423 ± 18 a	438 ± 7 a	418 ± 32 a
Na (mg·kg ⁻¹)	113 ± 5 B	134 ± 6 A	110 ± 3 B	109 ± 4 B	175 ± 13 b	165 ± 7 b	214 ± 13 a	186 ± 19 ab
Fe (mg·kg ⁻¹)	17 ± 1.4 A	13.2 ± 1.1 B	13.3 ± 0.9 B	16.2 ± 0.2 A	6.2 ± 0.2 b	6.6 ± 0.3 b	5.8 ± 0.6 b	8.3 ± 0.2 a
Cu (mg·kg ⁻¹)	0.81 ± 0.08 A	0.76 ± 0.06 A	0.77 ± 0.08 A	0.74 ± 0.07 A	0.62 ± 0.04 a	0.54 ± 0.08 a	0.64 ± 0.02 a	0.63 ± 0.02 a
Mn (mg·kg ⁻¹)	13.3 ± 0.5 A	14.1 ± 0.3 A	13.2 ± 0.5 A	15. ± 1 A	12.07 ± 0.07 b	12.5 ± 0.4 b	14.5 ± 0.3 a	13.1 ± 0.8 a
Zn (mg·kg ⁻¹)	0.5 ± 0.02 B	0.6 ± 0.04 B	0.81 ± 0.03 A	0.77 ± 0.05 A	0.51 ± 0.02 b	0.53 ± 0.01 b	0.5 ± 0.04 b	0.92 ± 0.05 a

OM: Organic matter; WIR Verm.: Vermicompost of wine industry residues; WIR + SS Verm.: Vermicompost of wine industry residues and sewage sludge. Different letters indicate significant differences at $p < 0.05$. Different capital letters indicate significant differences ($p < 0.05$) in rainfed vineyard. Different lower-case letters indicate significant differences ($p < 0.05$) in deficit irrigation vineyard.

3.4.2. Foliar Parameters

In the foliar analyses, it is worth noting that the differences in nitrogen are greater at veraison than at flowering (Tables 6 and 7). This is because in the first stage of plant growth, between budding and flowering, the nitrogen used comes mainly from the permanent parts (the trunk and roots), while the absorption of this nutrient from the soil begins to increase a few weeks before flowering [51,52]. This makes the effect of the fertilizer more evident at veraison.

Additionally, the nitrogen content at flowering is higher with chemical fertilizer than with vermicompost. This may be due to the nutrients being released more gradually by vermicompost. It may even be the case that organic fertilizers release nutrients so slowly that there is a time lag between the plant's needs and the nutrients being available in the soil [50]. Conversely, in irrigated trials at veraison, the nitrogen content is higher in vermicompost-fertilized trials. Similar results are shown for other macronutrients, such as potassium and magnesium. The first one is involved in the accumulation of sugars in the berry and the pH of the must [53], and the second is related to the photosynthetic capacity of the plant [54]. Generally, the values are higher in the fertilized trials than in the control, although there are no significant differences between the different fertilizers.

Regarding micronutrients and heavy metals, there were reductions or no difference among trials fertilized with vermicompost and the control and chemical fertilizer. This may be due to the complex relationship between these metals and the organic matter in the soil. In this sense, some metals, such as zinc, can form complexes with mature

organic matter, which initially reduces the availability of this element. However, when the organic matter decomposes, the availability of these elements increases, making them more accessible to plants [55]. Additionally, considering that only 45 mm of rainfall was collected during the growing season, there may have been less dissolution of micronutrients from the vermicompost into the soil solution, resulting in limited absorption by plants [56]. Furthermore, organic fertilizers release nutrients more gradually, so there is a lag between nutrient availability and the plants' needs. This process is highly dependent on soil moisture, temperature and soil microbial activity [50].

Table 6. Parameters determined in the foliar analysis at flowering.

	Rainfed Vineyard				Deficit Irrigation Vineyard			
	Control	Chemical Fertilizer	WIR Verm.	WIR + SS Verm.	Control	Chemical Fertilizer	WIR Verm.	WIR + SS Verm.
N (%)	1.45 ± 0.05 B	1.59 ± 0.06 A	1.36 ± 0.06 B	1.45 ± 0.04 B	0.58 ± 0.03 b	0.88 ± 0.06 a	0.6 ± 0.01 b	0.83 ± 0.02 a
P (%)	0.5 ± 0.01 B	0.49 ± 0.02 B	0.54 ± 0.02 AB	0.58 ± 0.04 A	0.37 ± 0.01 b	0.34 ± 0.01 bc	0.33 ± 0.02 c	0.45 ± 0 a
K (%)	1.4 ± 0.09 A	1.31 ± 0.04 A	1.3 ± 0.1 A	1.5 ± 0.1 A	1.38 ± 0.02 b	1.78 ± 0.02 a	1.48 ± 0.08 b	1.85 ± 0.06 a
Ca (%)	1.8 ± 0.08 B	1.81 ± 0.08 B	2.01 ± 0.09 B	2.4 ± 0.2 A	2.31 ± 0.03 a	2.34 ± 0.08 a	2.35 ± 0.08 a	2.28 ± 0.05 a
Mg (%)	0.47 ± 0.02 A	0.4 ± 0.03 B	0.41 ± 0.03 AB	0.47 ± 0.02 A	0.66 ± 0.03 a	0.61 ± 0.03 a	0.68 ± 0.03 a	0.69 ± 0.04 a
Na (mg·kg ⁻¹)	606 ± 28 B	633 ± 40 AB	691 ± 15 A	358 ± 39 C	746 ± 61 b	645 ± 30 bc	912 ± 69 a	586 ± 35 c
Fe (mg·kg ⁻¹)	63 ± 3 B	59 ± 4 B	73 ± 3 A	56 ± 4 B	67 ± 8 a	59 ± 1 b	40 ± 3 d	41 ± 2 c
B (mg·kg ⁻¹)	45 ± 3 B	41 ± 5 B	50 ± 7 B	58 ± 3 A	40 ± 1 b	50 ± 2 a	53 ± 2 a	44 ± 5 ab
Mn (mg·kg ⁻¹)	37 ± 1 A	15.8 ± 0.5 B	11.8 ± 0.5 C	12.5 ± 0.9 C	34.1 ± 0.8 ab	35.2 ± 0.8 a	30 ± 2 b	35 ± 3 a
Cu (mg·kg ⁻¹)	9.1 ± 0.2 A	9.3 ± 0.5 A	9.7 ± 0.2 A	8.9 ± 0.5 A	7.2 ± 0.1 b	16.2 ± 0.6 a	6.63 ± 0.07 bc	6 ± 0.3 c
Zn (mg·kg ⁻¹)	15.3 ± 0.9 A	17.1 ± 0.7 A	15.1 ± 0.9 A	16 ± 1 A	20 ± 2 b	24 ± 1 a	14 ± 1 c	17.7 ± 0.1 b
Mo (mg·kg ⁻¹)	7.3 ± 0.4 A	7.2 ± 0.2 A	7.2 ± 0.3 A	0.19 ± 0 B	0.27 ± 0.01 a	0.18 ± 0.01 b	0.1 ± 0 c	0.08 ± 0 d
Cr (mg·kg ⁻¹)	7.3 ± 0.4 A	2.61 ± 0.01 B	1.96 ± 0.06 C	1.63 ± 0.08 C	5 ± 0.2 a	2.29 ± 0.05 b	0.82 ± 0.04 c	0.89 ± 0.01 c
Ni (mg·kg ⁻¹)	4.8 ± 0.2 A	2 ± 0.1 B	1.83 ± 0.07 C	1.42 ± 0.04 C	4 ± 0.2 a	2.37 ± 0.09 b	0.93 ± 0.04 c	0.94 ± 0.02 c
As (mg·kg ⁻¹)	0.71 ± 0.03 A	0.07 ± 0 B	0.06 ± 0 B	0 ± 0 C	0.07 ± 0.01 a	0.04 ± 0 b	0.02 ± 0 d	0.03 ± 0 c
Cd (mg·kg ⁻¹)	0.05 ± 0 A	0.05 ± 0 A	0.04 ± 0 AB	0.03 ± 0 B	0.03 ± 0 ab	0.04 ± 0 b	0.02 ± 0 a	0.03 ± 0 ab
Hg (mg·kg ⁻¹)	0.19 ± 0.01 A	0.13 ± 0.01 B	0.14 ± 0 B	0.05 ± 0 A	n.d.	n.d.	n.d.	n.d.
Pb (mg·kg ⁻¹)	1.12 ± 0.03 A	0.48 ± 0.02 B	0.51 ± 0 B	0.38 ± 0.02 C	0.28 ± 0.01 c	0.71 ± 0.03 a	0.33 ± 0 c	0.17 ± 0 d

WIR Verm.: Vermicompost of wine industry residues; WIR + SS Verm.: Vermicompost of wine industry residues and sewage sludge. Different letters indicate significant differences at $p < 0.05$. Different capital letters indicate significant differences ($p < 0.05$) in the rainfed vineyard. Different lower-case letters indicate significant differences ($p < 0.05$) in deficit irrigation vineyard. n.d.: not detected.

Table 7. Parameters determined in the foliar analysis at veraison.

	Rainfed Vineyard				Deficit Irrigation Vineyard			
	Control	Chemical Fertilizer	WIR Verm.	WIR + SS Verm.	Control	Chemical Fertilizer	WIR Verm.	WIR + SS Verm.
N (%)	0.46 ± 0.02 C	0.74 ± 0.02 A	0.74 ± 0.01 A	0.67 ± 0.03 B	0.37 ± 0.01 c	0.49 ± 0.02 b	0.54 ± 0.01 ab	0.57 ± 0.05 a
P (%)	0.52 ± 0 A	0.55 ± 0.02 A	0.48 ± 0.01 B	0.38 ± 0.01 C	0.37 ± 0.01 a	0.38 ± 0.01 a	0.08 ± 0 c	0.13 ± 0.01 b
K (%)	1.43 ± 0.01 C	2.6 ± 0.01 B	3.15 ± 0.06 A	2.7 ± 0.1 B	1.4 ± 0.1 b	2 ± 0.04 a	1.28 ± 0.02 b	1.43 ± 0.01 b
Ca (%)	2.09 ± 0.03 C	3.2 ± 0.3 A	2.7 ± 0.2 AB	2.4 ± 0.2 C	2.64 ± 0.07 ab	2.9 ± 0.2 a	2.5 ± 0.2 b	2.7 ± 0.1 ab
Mg (%)	0.46 ± 0.03 C	0.84 ± 0.03 A	0.73 ± 0.03 B	0.85 ± 0.03 A	0.63 ± 0.04 b	0.62 ± 0.03 b	1.1 ± 0.05 a	1.02 ± 0.04 a
Na (mg·kg ⁻¹)	285 ± 10 C	445 ± 10 A	372 ± 11 B	422 ± 15 A	798 ± 76 bc	715 ± 6 c	1033 ± 41 a	866 ± 50 b
Fe (mg·kg ⁻¹)	83 ± 4 A	45 ± 9 B	47 ± 2 B	78 ± 2 A	57 ± 9 a	66 ± 1 a	45 ± 1 b	36 ± 2 c
B (mg·kg ⁻¹)	43 ± 3 B	50 ± 2 A	30 ± 2 C	36 ± 1 C	43 ± 3 bc	49 ± 3 ab	53 ± 4 a	35.4 ± 0.7 c
Mn (mg·kg ⁻¹)	38.4 ± 0.2 A	25.9 ± 0.5 B	18.6 ± 0.7 C	18 ± 1 C	38 ± 1 c	41.9 ± 0.9 bc	46 ± 1 ab	50 ± 3 a
Cu (mg·kg ⁻¹)	8.9 ± 0.3 A	4.9 ± 0.3 B	3 ± 0.1 C	3.5 ± 0.2 C	7.8 ± 0.3 b	17.4 ± 0.3 a	2.9 ± 0.1 c	2.5 ± 0.2 c
Zn (mg·kg ⁻¹)	15 ± 0.5 C	18.2 ± 0.6 B	28 ± 2 A	13.3 ± 0.6 C	23.5 ± 0.5 ab	24.7 ± 0.8 a	21.7 ± 0.6 b	22 ± 2 ab
Mo (mg·kg ⁻¹)	0.32 ± 0 A	0.32 ± 0.02 A	0.09 ± 0 C	0.28 ± 0.01 B	0.28 ± 0.01 a	0.14 ± 0.01 c	0.05 ± 0 d	0.17 ± 0.01 b
Cr (mg·kg ⁻¹)	5.6 ± 0.4 A	6.2 ± 0.3 A	0.23 ± 0 C	1.3 ± 0.07 B	4.97 ± 0.09 a	1.85 ± 0.04 b	0.22 ± 0.01 c	n.d.
Ni (mg·kg ⁻¹)	3.9 ± 0.2 A	3.19 ± 0.09 B	0.9 ± 0.06 D	1.83 ± 0.05 C	3.9 ± 0.1 a	2.4 ± 0.2 b	0.81 ± 0.06 c	0.68 ± 0.02 c
As (mg·kg ⁻¹)	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Cd (mg·kg ⁻¹)	0.03 ± 0 B	0.05 ± 0 A	0.01 ± 0 C	0.02 ± 0 C	0.04 ± 0 b	0.05 ± 0 a	0.04 ± 0 b	0.02 ± 0 c
Hg (mg·kg ⁻¹)	0.03 ± 0 B	0.03 ± 0 B	0.03 ± 0 B	0.16 ± 0.01 A	0.04 ± 0 a	0.04 ± 0 a	0.04 ± 0 a	0.03 ± 0 a
Pb (mg·kg ⁻¹)	1.64 ± 0.01 A	0.68 ± 0.02 C	0.22 ± 0 D	1.18 ± 0.04 B	0.32 ± 0.02 c	0.58 ± 0.01 a	0.26 ± 0.02 d	0.49 ± 0.03 c

WIR Verm.: Vermicompost of wine industry residues; WIR + SS Verm.: Vermicompost of wine industry residues and sewage sludge. Different letters indicate significant differences at $p < 0.05$. Different capital letters indicate significant differences ($p < 0.05$) in rainfed vineyard. Different lower-case letters indicate significant differences ($p < 0.05$) in deficit irrigation vineyard. n.d.: not detected.

3.4.3. Vegetative and Productive Vineyard Parameters

Differences in agronomic parameters were observed in the rainfed conditions, but not in the irrigated trials (Table 8). This may be because, when soil moisture conditions improve or water storage capacity increases, nutrient uptake becomes easier and differences in plant development become smaller [57].

Table 8. Vegetative and productive parameters determined in different conditions.

		Rainfed Vineyard				Deficit Irrigation Vineyard			
		Control	Chemical Fertilizer	WIR Verm.	WIR + SS Verm.	Control	Chemical Fertilizer	WIR Verm.	WIR + SS Verm.
Shoots	(n°)	12.1 ± 2.5 A	10.9 ± 1.3 A	11.1 ± 1.5 A	10.8 ± 1.6 A	11.5 ± 1 b	13.8 ± 3.6 ab	14.6 ± 0.5 ab	16.2 ± 1.3 a
Clusters	(n°)	12.8 ± 4.1	12.5 ± 2.1	13.9 ± 3.2	11.9 ± 4.7	20 ± 4.9	16.8 ± 3.3	17.8 ± 4.1	20.6 ± 5.7
Yield	(kg vine ⁻¹)	2.8 ± 1.1	3.7 ± 1	3.7 ± 0.7	3.2 ± 1.2	8.8 ± 2	7.1 ± 1.7	6.5 ± 1.7	9.6 ± 2.3
Cluster weight	(g)	217 ± 55 B	309 ± 108 A	271 ± 60 AB	274 ± 48 AB	439 ± 37 a	429 ± 106 a	373 ± 78 a	522 ± 265 a
Fertility	(clusters shoot ⁻¹)	1.1 ± 0.4	1.2 ± 0.2	1.3 ± 0.3	1.1 ± 0.5	1.7 ± 0.3	1.3 ± 0.3	1.2 ± 0.3	1.3 ± 0.3
SA	(m ² vine ⁻¹)	3.9 ± 0.4 B	4.6 ± 0.4 A	4.5 ± 0.2 A	4.6 ± 0.4 A	3.7 ± 0.3 a	3.8 ± 0.3 a	3.8 ± 0.4 a	4 ± 0.3 a
Pruning weight	(kg vine ⁻¹)	0.7 ± 0.2	0.7 ± 0.2	0.7 ± 0.1	0.6 ± 0.1	0.63 ± 0.05	0.6 ± 0.2	0.6 ± 0.1	0.7 ± 0.2
SA/Yield	(m ² kg ⁻¹)	1.7 ± 0.9	1.3 ± 0.5	1.3 ± 0.2	1.7 ± 0.7	0.4 ± 0.1	0.6 ± 0.1	0.6 ± 0.1	0.4 ± 0.1
Ravaz index	(kg kg ⁻¹)	4 ± 2	5 ± 1	6 ± 2	5 ± 2	15 ± 5	11 ± 3	12 ± 2	14 ± 4

SA: Surface Area; WIR Verm.: Vermicompost of wine industry residues; WIR + SS Verm.: Vermicompost of wine industry residues and sewage sludge. Different letters indicate significant differences at $p < 0.05$. Different capital letters indicate significant differences ($p < 0.05$) in rainfed vineyard. Different lower-case letters indicate significant differences ($p < 0.05$) in deficit irrigation vineyard.

In the rainfed trials, an increase in yield was observed in the fertilized trials compared to the control, although no significant differences were found between plants within the same trial. This high variability between plants may be due to multiple factors, such as the yield and photoassimilate distribution of the previous year, which affect fertility, and the budding conditions in the current year, which affect the number of flowers per bunch [58]. Conversely, an increase in bunch weight was observed in the fertilized trials compared to the control, particularly with conventional fertilizer. These results are consistent with those of other studies, such as Badalíková et al. [59], who found an increase in yield when fertilizing two vineyards of cv. Sauvignon Blanc and cv. Pinot Gris with compost or compost + Biostimulant Lignohumax 20, compared to a control without fertilizer. The increase in yield in this experiment was between 12% and 33%.

In terms of vegetative growth, the leaf area generated in the fertilized rainfed trials increased compared to the control, although this difference was less evident in terms of pruning weight. The same occurred in the irrigated trials, albeit without significant differences. This increased leaf mass is directly related to improved nutritional content, particularly regarding nitrogen, as shown in Tables 7 and 8. This leads to greater plant growth, increased leaf area and higher pruning wood weight [52,57].

However, the differences in the number of shoots, number of bunches and their quotient (fertility) are not attributable to the trials because shoot fertility is determined before bud break, specifically from the previous year's flowering. It is also influenced by water stress and nitrogen availability [60]. This is why this trial could affect fertility the following year, demonstrating the long-term impact of viticultural practices [29].

Correct values were found for the parameters reflecting the plant's vegetative-productive balance in the rainfed trials. Values were higher than 1 m²/kg in all cases for the SA/Yield ratio, and between 4 and 6 for the Ravaz index [29]. There were no significant differences between the trials due to the fertilized trials having greater leaf area and pruning weight, as well as higher yields.

Conversely, the balance between yield and vegetative development is questionable in the case of irrigated vineyards, with SA/Yield balances of 0.6 m²/kg and Ravaz index values above 10. However, it seems that trials fertilized with chemical fertilizer and vermicompost from vineyard waste have better results in the latter. Such low SA/Yield balance values can lead to deficient sugar accumulation in the berry [61,62] and even vine depletion.

In general, fertilized trials show an increase in yield and leaf area generated by the plant. This increase is significantly more noticeable in rainfed trials than in irrigated trials due to the homogenizing effect of the water supply in the vineyard.

3.5. Must Parameters and Amino Acid Profile

Similar trends were observed in the oenological parameters analyzed in the must obtained from the rainfed and irrigated trials. There was an increase in the levels of yeast assimilable nitrogen (YAN), ammonium, pH, titratable acidity, and probable ethanol in the fertilized trials compared to the control (Table 9). However, values differ between rainfed and irrigated plots due to idiosyncrasies of each vineyard and cultivation method.

Table 9. Must parameters determined in the different trials.

		Rainfed Vineyard				Deficit Irrigation Vineyard			
		Control	Chemical Fertilizer	WIR Verm.	WIR + SS Verm.	Control	Chemical Fertilizer	WIR Verm.	WIR + SS Verm.
Ethanol probable	(% v/v)	12.3 ± 0.1 C	12.8 ± 0.06 AB	13.0 ± 0.1 A	12.77 ± 0.06 B	11.17 ± 0.06 b	11.3 ± 0.1 b	11.8 ± 0.2 a	11 ± 0.1 b
pH		4.13 ± 0.02 C	4.2 ± 0.01 A	4.18 ± 0.01 AB	4.15 ± 0.02 BC	3.82 ± 0.02 c	3.87 ± 0.02 b	3.93 ± 0.01 a	3.8 ± 0.02 c
Titratable acidity	(g L ⁻¹ TH ₂)	3.81 ± 0.02 B	3.95 ± 0.09 A	3.88 ± 0.03 AB	3.9 ± 0.05 AB	3.5 ± 0.03 a	3.3 ± 0.1 b	3.27 ± 0.03 b	3.59 ± 0.02 a
YAN	mg L ⁻¹	234 ± 5 B	277 ± 8 A	278 ± 7 A	261 ± 5 A	149 ± 8 ab	147 ± 6 ab	159 ± 8 a	135 ± 8 b
NH ₄ ⁺	mg L ⁻¹	83 ± 4 C	138 ± 8 B	132 ± 9 B	171 ± 9 A	58 ± 3 a	65 ± 5 a	52 ± 3 bc	47 ± 2 c

TH₂: Tartaric acid; YAN: Yeast assimilable nitrogen; WIR Verm.: Vermicompost of wine industry residues; WIR + SS Verm.: Vermicompost of wine industry residues and sewage sludge. Different letters indicate significant differences at $p < 0.05$. Different capital letters indicate significant differences ($p < 0.05$) in rainfed vineyard. Different lower-case letters indicate significant differences ($p < 0.05$) in deficit irrigation vineyard.

Fertilization results in an increase in sugars, expressed as probable ethanol content. This is because the better nutritional status of the plant, particularly regarding nitrogen and magnesium, promotes greater photosynthetic activity and consequently higher sugar production in the leaves [54,63]. Additionally, a higher potassium content promotes the transportation of sugars from the leaves to the berries via the phloem, facilitating their accumulation [64].

In the case of pH and titratable acidity, trials in which fertilizer has been applied, and the foliar potassium content is higher, show an increase in pH and a decrease in acidity. This can be due to the salification of tartaric acid in the form of potassium bitartrate [65]. High pH levels can result in lower microbiological stability of the final wine because, for the same total dose of SO₂, there is less active SO₂ [64]. Additionally, higher pH levels favor the oxidation of phenolic compounds [66].

Regarding YAN, a higher content was observed in the trials in which fertilizer was applied. This finding is consistent with that of Miliordos et al. [67], who fertilized vines with ammonium sulfate in combination with a nitrification inhibitor. They found increases of 51% and 57% in YAN in the trials fertilized with ammonium sulfate and ammonium sulfate + DMPP, respectively, compared to the control. The YAN content of the must is crucial for fermentation, so adequate values (>150 mg/L) are important [65]. Low levels can lead to slower fermentation and even stuck fermentation [67], as well as lower levels of aroma compounds [68].

Table 10 shows the amino acid content of the must obtained after the different treatments, as well as the total sum. Amino acids play several key roles in alcoholic fermentation: they constitute a significant portion of YAN, which is vital for yeast growth and fermentation vigor [69]. They influence central carbon metabolism through signaling pathways related to cell growth and cell cycle progression [70]; many higher alcohols and esters are produced from amino acid catabolism via the Ehrlich pathway [71]. As can be seen, total amino acid content is higher in the rainfed trials than in the irrigated trials, with slight differences between the latter. However, these differences are greater in the case of the rainfed trials, with the lowest values in the control trial and the highest values in the trial with conventional fertilizer.

Table 10. Amino acid content (mM) determined in the must obtained from the different trials.

	Rainfed Vineyard				Deficit Irrigation Vineyard			
	Control	Chemical Fertilizer	WIR Verm.	WIR + SS Verm.	Control	Chemical Fertilizer	WIR Verm.	WIR + SS Verm.
L-aspartic acid	0.16 ± 0.01 C	0.27 ± 0.01 A	0.23 ± 0.01 B	0.27 ± 0.01 A	0.14 ± 0.01 a	0.14 ± 0.01 a	0.13 ± 0.01 a	0.1 ± 0.01 b
L-glutamic acid	0.38 ± 0.02 C	0.6 ± 0.02 A	0.39 ± 0.01 BC	0.42 ± 0.01 B	0.32 ± 0.01 b	0.35 ± 0.01 a	0.29 ± 0.01 bc	0.28 ± 0.01 c
L-glutamine	0.07 ± 0.01 C	0.16 ± 0.01 A	0.11 ± 0.01 B	0.13 ± 0.01 B	0.03 ± 0 b	0.03 ± 0 a	0.03 ± 0 b	0.03 ± 0 b
L-histidine	0.24 ± 0.01 C	0.5 ± 0.03 A	0.36 ± 0.02 B	0.36 ± 0.02 B	0.12 ± 0.01 b	0.14 ± 0.01 a	0.12 ± 0.01 b	0.11 ± 0 b
Glycine	0.22 ± 0.01 C	0.38 ± 0.02 A	0.3 ± 0.01 B	0.31 ± 0.03 B	0.17 ± 0.01 b	0.2 ± 0.01 a	0.16 ± 0.01 b	0.15 ± 0.01 b
L-threonine	0.01 ± 0 C	0.05 ± 0 B	0.06 ± 0 A	0.07 ± 0 A	0.01 ± 0 b	0.01 ± 0 b	0.01 ± 0 b	0.06 ± 0 a
L-arginine	1.3 ± 0.06 C	2.6 ± 0.1 A	1.82 ± 0.06 B	1.9 ± 0.1 B	0.88 ± 0.03 a	0.9 ± 0.04 a	0.85 ± 0.04 a	0.74 ± 0.02 b
L-alanine	0.4 ± 0.02 C	0.67 ± 0.03 A	0.54 ± 0.02 B	0.63 ± 0.03 A	0.3 ± 0.01 ab	0.33 ± 0.04 a	0.27 ± 0.02 ab	0.25 ± 0.01 b
γ-amino-n-butyric acid	0.17 ± 0.01 C	0.36 ± 0.02 A	0.24 ± 0.01 B	0.37 ± 0.02 A	0.11 ± 0.01 b	0.15 ± 0.01 a	0.12 ± 0.01 b	0.08 ± 0 c
L-α-amino-n-butyric acid	0.24 ± 0.01 D	0.44 ± 0.01 C	0.59 ± 0.02 B	0.71 ± 0.03 A	0.01 ± 0 c	0.21 ± 0.01 a	0.17 ± 0.01 b	0.01 ± 0 c
L-proline	0.33 ± 0.01 D	0.53 ± 0.02 B	0.42 ± 0.02 C	0.65 ± 0.03 A	0.46 ± 0.02 a	0.27 ± 0.01 b	0.24 ± 0.01 b	0.43 ± 0.02 a
L-valine	0.17 ± 0.01 C	0.31 ± 0.01 A	0.26 ± 0.01 B	0.28 ± 0.01 B	0.15 ± 0.01 a	0.17 ± 0.01 a	0.13 ± 0.01 b	0.09 ± 0 c
L-methionine	0.02 ± 0 B	0.02 ± 0 B	0.01 ± 0 C	0.04 ± 0 A	0.01 ± 0 a	0.01 ± 0 b	0.01 ± 0 ab	0.01 ± 0 ab
L-isoleucine	0.04 ± 0 C	0.06 ± 0 B	0.05 ± 0 B	0.07 ± 0 A	0.04 ± 0 ab	0.04 ± 0 a	0.04 ± 0 bc	0.03 ± 0 c
L-tryptophan	0.04 ± 0 C	0.06 ± 0 A	0.05 ± 0 B	0.07 ± 0.01 A	0.03 ± 0 a	0.03 ± 0 a	0.02 ± 0 b	0.02 ± 0 b
L-leucine	0.05 ± 0 D	0.09 ± 0 B	0.07 ± 0 C	0.11 ± 0 A	0.05 ± 0 ab	0.05 ± 0 a	0.05 ± 0 b	0.05 ± 0 ab
L-phenylalanine	0.05 ± 0 C	0.07 ± 0 B	0.06 ± 0 B	0.09 ± 0.01 A	0.03 ± 0 a	0.03 ± 0 a	0.03 ± 0 b	0.03 ± 0 c
L-ornithine	0.14 ± 0.01 D	0.29 ± 0.01 A	0.2 ± 0.01 C	0.26 ± 0.01 B	0.06 ± 0 bc	0.07 ± 0 ab	0.07 ± 0 a	0.06 ± 0 c
L-lysine	0.15 ± 0.01 C	0.28 ± 0.01 A	0.22 ± 0.01 B	0.26 ± 0.01 A	0.11 ± 0.01 a	0.11 ± 0 ab	0.1 ± 0 ab	0.09 ± 0.01 b
Putrescine	0.07 ± 0 C	0.1 ± 0.01 B	0.1 ± 0.01 B	0.13 ± 0.01 A	0.12 ± 0.01 a	0.11 ± 0 ab	0.07 ± 0.01 c	0.1 ± 0 b
Total	4.7 ± 0.1 D	8.6 ± 0.3 A	6.7 ± 0.3 C	7.9 ± 0.3 B	3.5 ± 0.1 a	3.7 ± 0.2 ab	3.2 ± 0.2 bc	3.05 ± 0.04 c

WIR Verm.: Vermicompost of wine industry residues; WIR + SS Verm.: Vermicompost of wine industry residues and sewage sludge. Different letters indicate significant differences at $p < 0.05$. Different capital letters indicate significant differences ($p < 0.05$) in rainfed vineyard. Different lower-case letters indicate significant differences ($p < 0.05$) in deficit irrigation vineyard.

The availability and concentration of specific amino acids can significantly impact the outcome of fermentation. A balanced amino acid profile promotes robust yeast growth and efficient fermentation. Conversely, deficiencies or imbalances can result in sluggish or stuck fermentations, as well as the production of undesirable compounds. For instance, insufficient methionine levels have been linked to elevated hydrogen sulfide production, resulting in off-flavors [72]. The concentration of this amino acid must be between 1 and 3 mg/L. In our case, all analyzed samples reach this concentration.

Other key amino acids are glutamine and glutamic acid, which are central to nitrogen metabolism and are consumed quickly; arginine is important for polyamine synthesis, and leucine, isoleucine, and valine are precursors to higher alcohols, such as isoamyl alcohol and isobutanol. Phenylalanine contributes to the formation of aromatic compounds. The lowest values for all these amino acids are found in the control assay in rainfed conditions, whereas the highest values are reached with chemical fertilizer and vermicompost from wine industry residues plus sewage sludge. In deficit irrigation assays, there are few differences among them.

Figures 4 and 5 show cluster-normalized heatmaps, with amino acid content used as the classifying variable. In the case of the rainfed treatments (Figure 4), there is a clear separation between the control and fertilized trials. All the amino acids have negative values, indicating that the lowest concentrations are found in this trial. Conversely, conventional fertilizer and the vermicompost sludge treatment show positive values for most amino acids, with both trials presenting a similar profile.

In the irrigation treatments, two well-differentiated groups are observed: the first comprises the control and conventional treatments, with the latter generally exhibiting the highest values; the vermicompost treatments exhibit the lowest values. However, as mentioned above, the differences in amino acid concentration are much smaller under these conditions.

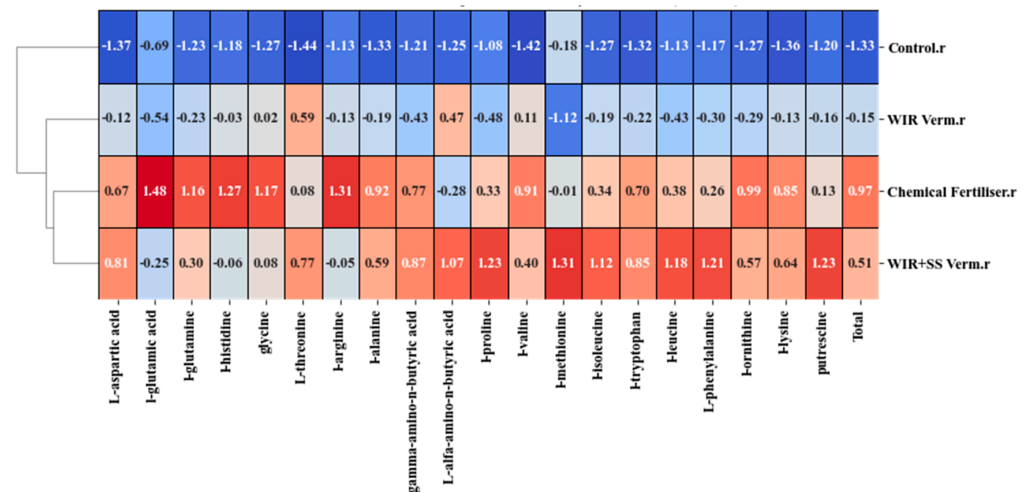


Figure 4. Normalized amino acid profile heatmap with Cluster (Rainfed vineyard); WIR Verm.: Vermicompost of wine industry residues; WIR + SS Verm.: Vermicompost of wine industry residues and sewage sludge. Blue colors indicate negative correlation. Red colors indicate positive correlation.

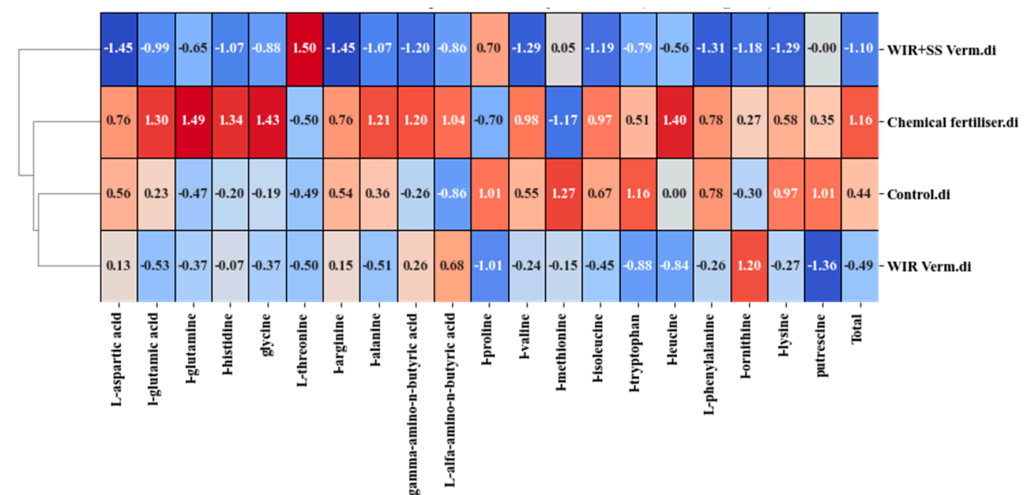


Figure 5. Normalized amino acid profile heatmap with Cluster (Deficit irrigation vineyard). WIR Verm.: Vermicompost of wine industry residues; WIR + SS Verm.: Vermicompost of wine industry residues and sewage sludge. Blue colors indicate negative correlation. Red colors indicate positive correlation.

3.6. Cluster and Principal Component Analysis

Cluster analysis is a multivariate statistical technique that classifies observed subjects into groups based on their degree of similarity. As this analysis is descriptive in nature, it does not seek to explain causal relationships; therefore, the interpretation of the resulting groups is at the analyst's discretion. The proximity with which subjects are grouped together is expressed by a dimensionless measure called 'distance', which reflects how similar they are to each other. Several techniques exist for this type of analysis. In this study, Ward's method was used, which is considered the most appropriate for clearly identifying and defining the different levels of grouping [73], combined with a heat map representing the values obtained from standardizing the data to improve understanding and provide an interpretative overview of the results. Here, we used the oenological parameters of the musts (probable ethanol, pH, titratable acidity, ammonium, and YAN) and the macronutrient content (N, P, K, and Mg), as determined at flowering and veraison.

In the case of the rainfed trials (Figure 6), there is clear differentiation between the control and the other trials. There are also differences between the assays with vermicompost

and conventional fertilizer. Clear trends emerge in the fertilized trials, with an increase in macronutrient content (N, K, and Mg) in the foliar samples at veraison, and in NFA, NH_4 , and probable ethanol content in the musts, compared to the control. Regarding the analysis of foliar samples at flowering, P, K, and Mg contents of the assays fertilized with vermicompost derived from wine-growing waste and sludge is notable.

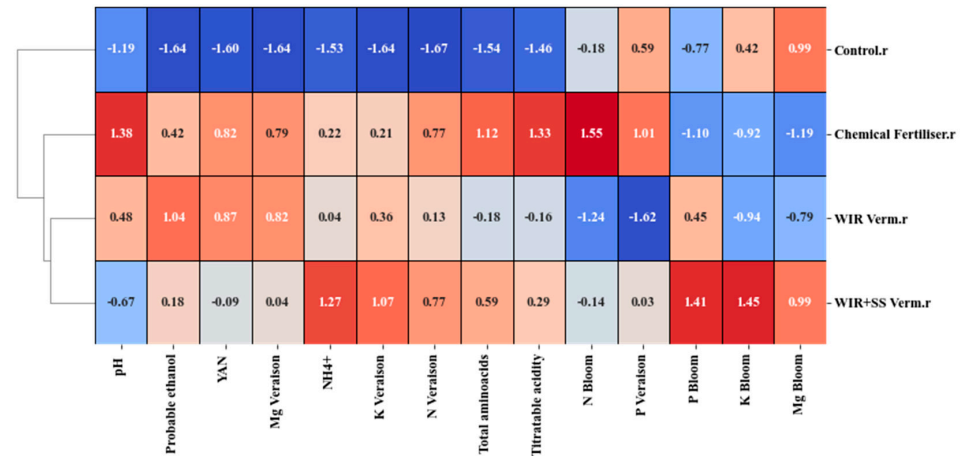


Figure 6. Cluster and heatmap of rainfed trials. WIR Verm.: Vermicompost of wine industry residues; WIR + SS Verm.: Vermicompost of wine industry residues and sewage sludge. Blue colors indicate negative correlation. Red colors indicate positive correlation.

In the deficit irrigated trials (Figure 7), the trends are less clear, as the water supply minimizes the differences. Once again, vermicompost-fertilizer form a distinct group, with P and K content at flowering, Mg and N at flowering and veraison, standing out in samples obtained from wine industry residues plus sewage sludge. The rest of the parameters, together with K and N at flowering, stand out in the case of fertilization with conventional fertilizer.

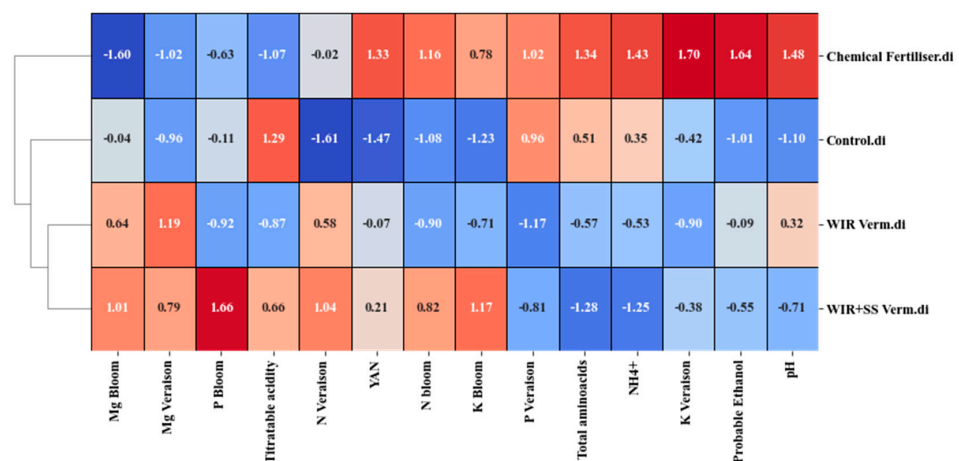


Figure 7. Cluster and heatmap of deficit irrigated trials. WIR Verm.: Vermicompost of wine industry residues; WIR + SS Verm.: Vermicompost of wine industry residues and sewage sludge. Blue colors indicate negative correlation. Red colors indicate positive correlation.

Finally, a heatmap was created to analyze the correlation between the nutritional status of the plant (macronutrient content in foliar analyses) and must parameters (see Figures 8 and 9). The graph represents the Pearson correlation coefficient between each pair of variables, ranging from -1 (blue) to 1 (red). This shows the direction of the correlation (positive or negative) and its accuracy: values close to 0 represent a poor correlation.

Furthermore, the variables have been automatically arranged to enhance visualization and to categorize variables with similar correlations.

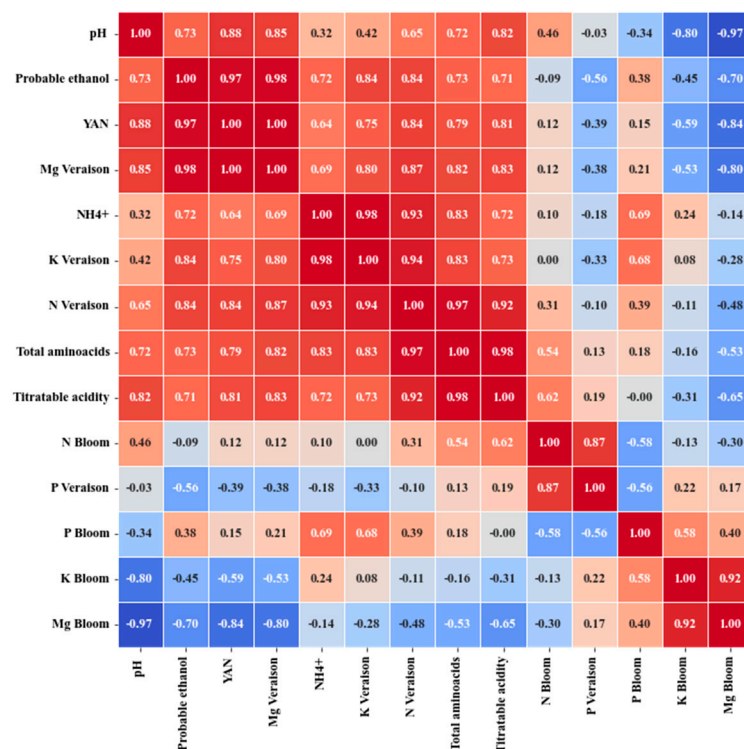


Figure 8. Heatmap of agronomic and must parameters of rainfed trials. Blue colors indicate negative correlation. Red colors indicate positive correlation.

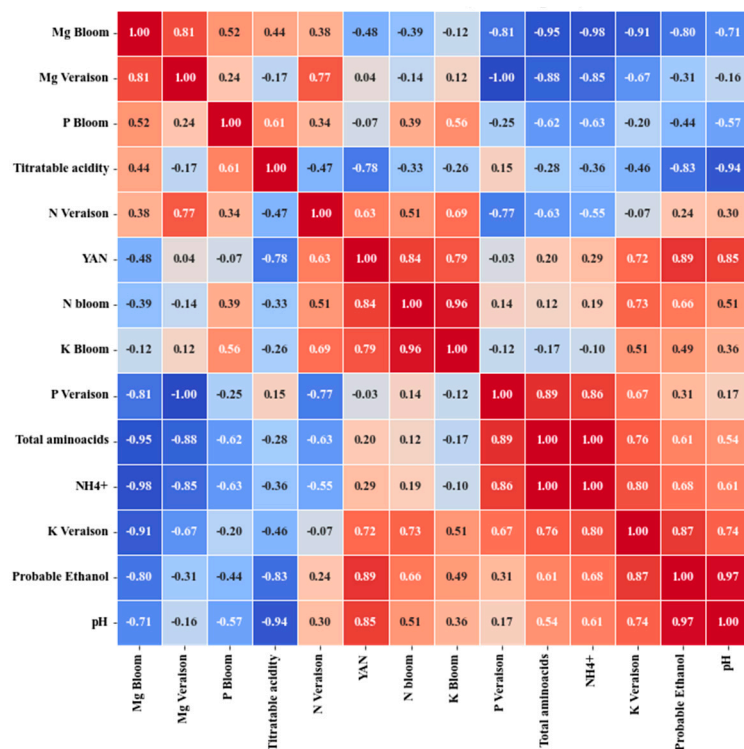


Figure 9. Heatmap of agronomic and must parameters of deficit irrigated trials. Blue colors indicate negative correlation. Red colors indicate positive correlation.

Notably, there is a high positive correlation between foliar N at veraison and the increase in must N content in the form of YAN and NH_4^+ , titratable acidity and probable ethanol, particularly in the rainfed trials. This may be because a higher N content in the vine induces the synthesis of more chlorophyll, resulting in a higher photosynthetic rate [58]. Foliar K content at veraison also correlates with YAN and probable ethanol content because K regulates osmotic potential and the transport of water and solutes (e.g., nutrients and hormones) within the plant. The capacity of accumulate sugars also depends largely on K content [58].

It has also been observed that the nutritional status of the plant at the time of flowering has a lesser effect on the oenological parameters of the must, as the correlations are not as strong. Good correlations are found between must parameters and the leaf content of N, which is preferentially absorbed from before flowering until veraison [51], for both veraison and flowering. Conversely, for other macronutrients, such as K, Mg, and P, which are absorbed at their highest rate between flowering and veraison [51], a higher correlation is found between must parameters and the leaf content of these nutrients at veraison, rather than at flowering. This is because the foliar content of these macronutrients at flowering comes mainly from the plant's reserves rather than from absorption of the nutrients by the plant from the soil; therefore, fertilizer does not have a clear effect [51].

In irrigated vineyards, however, the correlations are less clear. This may be because the absorption of nutrients is facilitated by the higher water content of the soil, which also favors transport through the plant [74]. This minimizes the possible differences between the amount of nutrients available, and the amount absorbed by the plant. However, there is a high correlation between potassium content at veraison and some must parameters, such as probable ethanol, pH, and YAN.

In short, fertilization affects the nutrient content of the vines' leaves, which in turn affects the must parameters at harvest. There is a greater correlation in dry conditions with leaf analysis at veraison.

4. Conclusions

The vermicomposting process, when applied to wine industry residues with or without sewage sludge, successfully produced materials that met legal standards for agricultural use. However, significant differences were observed in the performance of *Eisenia fetida*: reproduction rates, biomass accumulation, and overall population dynamics were all higher in the treatment involving only wine residues. This treatment also produced vermicompost with superior agronomic properties, including a higher organic matter content and a germination index exceeding 100%, indicating advanced maturity and the absence of phytotoxicity. In contrast, although the inclusion of sewage sludge was compliant with legal heavy metal limits, it introduced elevated levels of elements such as Na, Mg, Zn, and Pb, which could affect its suitability for certain agricultural uses.

When applied to vineyards, vermicompost made solely from wine residues improved soil fertility, increased nitrogen availability and enhanced plant nutrition, particularly under rainfed conditions compared to the no-fertilizer trial and the chemical fertilizer trial. This resulted in greater vegetative growth, higher grape yields, and improved must quality, including higher YAN levels and a richer amino acid profile, which is essential for fermentation. The correlations observed between foliar nitrogen and potassium content at veraison and must composition emphasize the importance of nutrient timing and availability. Overall, the data suggest that vermicompost derived solely from wine industry residues has the potential to be a safer and possibly more effective organic fertilizer, in line with the principles of sustainability and the circular economy in viticulture. However, considering that the results correspond to a single growing season developed under climatic

conditions characterized by below-average precipitation and above-average temperatures, a multi-year follow-up will be necessary to validate and consolidate these findings.

Author Contributions: Conceptualization, A.R. and R.A.P.; methodology, M.d.V.P., F.S.-S., A.R. and R.A.P. validation, M.d.V.P., F.S.-S., A.R. and R.A.P.; formal analysis, C.C.-V., I.M.S.-D., V.M.R.-M., M.d.V.P. and F.S.-S.; investigation, M.d.V.P., F.S.-S., A.R. and R.A.P.; C.C.-V., I.M.S.-D., V.M.R.-M., M.d.V.P. and F.S.-S., writing—original draft preparation, M.d.V.P., F.S.-S., A.R. and R.A.P.; writing—review and editing, M.d.V.P., F.S.-S., A.R. and R.A.P.; supervision, A.R. and R.A.P.; funding acquisition, A.R. and R.A.P. All authors have read and agreed to the published version of the manuscript.

Funding: The authors are grateful for the funding received through Project TED2021-129208B-100 by MICIU/AEI/10, 13039/501100011033 and by the European Union Next Generation.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding authors.

Acknowledgments: We are grateful for the help and availability of the vineyard of José María Sánchez for this study, as well as for the help with fertilizer application. Authors also like to thank the collaboration of the Municipal Water Company of Seville (EMASESA), Alvear S.A. and Viñas de Alange S.A. wineries.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

DEEM	Ethoxymethylenmalonate
DMPP	3,4-Dimethylpyrazole Phosphate
DTPA	Diethylenetriaminepentaacetic acid
OM	Organic Matter
OIV	International Organisation of Vine and Wine
SA	Exposed Surface Area
UV	Ultraviolet
YAN	Yeast assimilable Nitrogen
WIR Verm	Vermicompost of wine industry residues
WIR + SS Verm	Vermicompost of wine industry residues and sewage sludge
WWTP	Urban Wastewater Treatment Plant

References

1. OIV State of the World Vine and Wine Sector in 2024. Available online: https://www.oiv.int/sites/default/files/2025-04/OIV-State_of_the_World_Vine-and-Wine-Sector-in-2024.pdf (accessed on 21 April 2025).
2. Giorgi, F.; Lionello, P. Climate Change Projections for the Mediterranean Region. *Glob. Planet. Change* **2008**, *63*, 90–104. [CrossRef]
3. Gaitán, E.; Pino-Otín, M.R. Using Bioclimatic Indicators to Assess Climate Change Impacts on the Spanish Wine Sector. *Atmos. Res.* **2023**, *286*, 106660. [CrossRef]
4. Fraga, H. Viticulture and Winemaking under Climate Change. *Agronomy* **2019**, *9*, 783. [CrossRef]
5. Bucur, G.M.; Dejeu, L. Research on Adaptation Measures of Viticulture to Climate Change: Overview. *Sci. Pap. Ser. B Hortic.* **2022**, *66*, 177–190.
6. van Leeuwen, C.; Sgubin, G.; Bois, B.; Ollat, N.; Swingedouw, D.; Zito, S.; Gambetta, G.A. Climate Change Impacts and Adaptations of Wine Production. *Nat. Rev. Earth Environ.* **2024**, *5*, 258–275. [CrossRef]
7. Fraga, H.; García de Cortázar Atauri, I.; Malheiro, A.C.; Santos, J.A. Modelling Climate Change Impacts on Viticultural Yield, Phenology and Stress Conditions in Europe. *Glob. Change Biol.* **2016**, *22*, 3774–3788. [CrossRef] [PubMed]

8. van Leeuwen, C.; Darriet, P. The Impact of Climate Change on Viticulture and Wine Quality. *J. Wine Econ.* **2016**, *11*, 150–167. [CrossRef]
9. Allamy, L.; Van Leeuwen, C.; Pons, A. Impact of Harvest Date on Aroma Compound Composition of Merlot and Cabernet-Sauvignon Must and Wine in a Context of Climate Change: A Focus on Cooked Fruit Molecular Markers. *OENO One* **2023**, *57*, 99–112. [CrossRef]
10. Milazzo, F.; Fernández, P.; Peña, A.; Vanwalleghem, T. The Resilience of Soil Erosion Rates under Historical Land Use Change in Agroecosystems of Southern Spain. *Sci. Total Environ.* **2022**, *822*, 153672. [CrossRef] [PubMed]
11. Arellano, B.; Zheng, Q.; Roca, J. Analysis of Climate Change Effects on Precipitation and Temperature Trends in Spain. *Land* **2025**, *14*, 85. [CrossRef]
12. Selmy, S.A.H.; Abd Al-Aziz, S.H.; Jiménez-Ballesta, R.; García-Navarro, F.J.; Fadl, M.E. Modeling and Assessing Potential Soil Erosion Hazards Using USLE and Wind Erosion Models in Integration with GIS Techniques: Dakhla Oasis, Egypt. *Agriculture* **2021**, *11*, 1124. [CrossRef]
13. Lucchetta, M.; Romano, A.; Alzate Zuluaga, M.Y.; Fornasier, F.; Monterisi, S.; Pii, Y.; Marcuzzo, P.; Lovat, L.; Gaiotti, F. Compost Application Boosts Soil Restoration in Highly Disturbed Hillslope Vineyard. *Front. Plant Sci.* **2023**, *14*, 1289288. [CrossRef] [PubMed]
14. Gaiotti, F.; Marcuzzo, P.; Belfiore, N.; Lovat, L.; Fornasier, F.; Tomasi, D. Influence of Compost Addition on Soil Properties, Root Growth and Vine Performances of Vitis Vinifera Cv Cabernet Sauvignon. *Sci. Hortic.* **2017**, *225*, 88–95. [CrossRef]
15. Burg, P.; Badalíková, B.; Mašán, V.; Csáki, Š.; Burgová, J.; Turan, J.; Matwijczuk, A. Evaluation of the Effect of Deep Compost Application in the Areas around Vineyard Tree Trunks on Selected Soil Chemical Properties and the Vegetative Growth of the Vine. *Processes* **2023**, *11*, 632. [CrossRef]
16. Ho, T.T.K.; Tra, V.T.; Le, T.H.; Nguyen, N.-K.-Q.; Tran, C.-S.; Nguyen, P.-T.; Vo, T.-D.-H.; Thai, V.-N.; Bui, X.-T. Compost to Improve Sustainable Soil Cultivation and Crop Productivity. *Case Stud. Chem. Environ. Eng.* **2022**, *6*, 100211. [CrossRef]
17. EC—European Commission. *Circular Economy Action Plan—The European Green Deal*; Publications Office: Brussels, Belgium, 2020.
18. Wesseler, J. The EU 's Farm-to-fork Strategy: An Assessment from the Perspective of Agricultural Economics. *Appl. Econ. Perspect. Policy* **2022**, *44*, 1826–1843. [CrossRef]
19. Rodrigues, R.P.; Gando-Ferreira, L.M.; Quina, M.J. Increasing Value of Winery Residues through Integrated Biorefinery Processes: A Review. *Molecules* **2022**, *27*, 4709. [CrossRef] [PubMed]
20. Rodrigues Machado, A.; Attoprak, T.; Santos, J.; Alexandre, E.M.C.; Pintado, M.E.; Paiva, J.A.P.; Nunes, J. Potentialities of the Extraction Technologies and Use of Bioactive Compounds from Winery By-Products: A Review from a Circular Bioeconomy Perspective. *Appl. Sci.* **2023**, *13*, 7754. [CrossRef]
21. Gouvínhas, I.; Barros, A. Winery By-Products as Source of Bioactive Compounds for Pharmaceutical and Cosmetic Industries. In *Innovation in the Food Sector Through the Valorization of Food and Agro-Food By-Products*; IntechOpen: London, UK, 2021.
22. Nascimento-Gonçalves, E.; Azevedo, T.; Lopes, H.; Sousa, J.R.; Oliveira, P.A.; Roboredo, M.; Coimbra, A.M.; Morais, M.C. Vermicomposting as a Valorization Solution to the Winery Sector By-Products. *Agronomy* **2024**, *14*, 1111. [CrossRef]
23. Nogales, R.; Fernández-Gómez, M.J.; Delgado-Moreno, L.; Castillo-Díaz, J.M.; Romero, E. Eco-Friendly Vermitechnological Winery Waste Management: A Pilot-Scale Study. *SN Appl. Sci.* **2020**, *2*, 653. [CrossRef]
24. Paradelo, R.; Moldes, A.B.; Barral, M.T. Properties of Slate Mining Wastes Incubated with Grape Marc Compost under Laboratory Conditions. *Waste Manag.* **2009**, *29*, 579–584. [CrossRef] [PubMed]
25. Gómez-Brandón, M.; Martínez-Cordeiro, H.; Domínguez, J. Changes in the Nutrient Dynamics and Microbiological Properties of Grape Marc in a Continuous-Feeding Vermicomposting System. *Waste Manag.* **2021**, *135*, 1–10. [CrossRef] [PubMed]
26. Nogales, R.; Cifuentes, C.; Benítez, E. Vermicomposting of Winery Wastes: A Laboratory Study. *J. Environ. Sci. Health Part B* **2005**, *40*, 659–673. [CrossRef] [PubMed]
27. Domínguez, J.; Gómez-Brandón, M. Life Cycles of Vermicomposting Earthworms. *Acta Zool. Mex.* **2010**, *26*, 309–320.
28. Ndegwa, P.M.; Thompson, S.A.; Das, K.C. Effects of Stocking Density and Feeding Rate on Vermicomposting of Biosolids. *Bioresour. Technol.* **2000**, *71*, 5–12. [CrossRef]
29. Hidalgo Fernández-Cano, L.; Hidalgo Togores, J. *Tratado de Viticultura*; Mundi Prensas: Madrid, Spain, 2019; Volume I and II.
30. Consejería de Medio Ambiente y Rural, P.A. y Territorio. J. de E.E. Red de Asesoramiento al Regante de Extremadura (REDAREX). Available online: <https://redarexplus.juntaex.es/RedarexPlus/> (accessed on 10 May 2025).
31. Rosal, A. Caracterización y Mejora de La Calidad En El Compostaje de Residuos Municipales. Ph.D. Thesis, Universidad de Córdoba, Córdoba, Spain, 2007.
32. Olsen, S.R.; Cole, C.V.; Watanabe, F.S. *Estimation of Available Phosphorus in Soils by Extraction with Sodium Bicarbonate*; USDA Circular No. 939; US Government Printing Office: Washington, DC, USA, 1954.
33. Lindsay, W.L.; Norvell, W.A. Development of a DTPA Soil Test for Zinc, Iron, Manganese, and Copper. *Soil. Sci. Soc. Am. J.* **1978**, *42*, 421–428. [CrossRef]

34. Duan, Z.; Zhu, Y.; Xia, H.; Huang, K.; Peng, L. A Novel Strategy for Eliminating Antibiotic Resistance Genes during Fertilization of Dewatered Sludge by Earthworms: Vermicomposting Practice Using Chinese Herbal Residues Derived from Lianhua Qingwen as a Bulking Material. *J. Environ. Manag.* **2024**, *349*, 119444. [[CrossRef](#)] [[PubMed](#)]
35. Palenzuela, M.d.V.; López de Lerma, N.; Sánchez-Suárez, F.; Martínez-García, R.; Peinado, R.A.; Rosal, A. Aroma Composition of Wines Produced from Grapes Treated with Organic Amendments. *Appl. Sci.* **2023**, *13*, 8001. [[CrossRef](#)]
36. RD 506/2013 RD 506/2013; Productos Fertilizantes. Boletín Oficial Del Estado. Ministerio de La Presidencia: Madrid, Spain, 2013.
37. Sánchez-de-Miguel, P.; Baeza, P.; Junquera, P.; Lissarrague, J.R. Vegetative Development: Total Leaf Area and Surface Area Indexes. In *Methodologies and Results in Grapevine Research*; Springer: Dordrecht, The Netherlands, 2010; pp. 31–44.
38. International Organisation of Vine and Wine. *Compendium of International Methods of Wine and Must Analysis*; International Organisation of Vine and Wine: Dijon, France, 2023; ISBN 9782850380686.
39. Shively, C.E.; Henick-Kling, T. Comparison of Two Procedures for Assay of Free Amino Nitrogen. *Am. J. Enol. Vitic.* **2001**, *52*, 400–401. [[CrossRef](#)]
40. Gómez-Alonso, S.; Hermosín-Gutiérrez, I.; García-Romero, E. Simultaneous HPLC Analysis of Biogenic Amines, Amino Acids, and Ammonium Ion as Aminoenone Derivatives in Wine and Beer Samples. *J. Agric. Food Chem.* **2007**, *55*, 608–613. [[CrossRef](#)] [[PubMed](#)]
41. Gómez-Brandón, M.; Fornasier, F.; de Andrade, N.; Domínguez, J. Influence of Earthworms on the Microbial Properties and Extracellular Enzyme Activities during Vermicomposting of Raw and Distilled Grape Marc. *J. Environ. Manag.* **2022**, *319*, 115654. [[CrossRef](#)] [[PubMed](#)]
42. Castillo-González, E.; Giraldo-Díaz, M.R.; De Medina-Salas, L.; Sánchez-Castillo, M.P. Pre-Composting and Vermicomposting of Pineapple (*Ananas Comosus*) and Vegetable Waste. *Appl. Sci.* **2019**, *9*, 3564. [[CrossRef](#)]
43. Tabassum-Abbasi, Khamrang, C.; Abbasi, T.; Abbasi, S.A. The Fecundity and the Vermicomposting Efficiency of Three Generations of Four Earthworm Species in High-Rate Vermireactors Fed with the Pernicious Aquatic Weed *Salvinia*. *Environ. Sci. Pollut. Res.* **2022**, *30*, 27382–27393. [[CrossRef](#)] [[PubMed](#)]
44. Santana, N.A.; Jacques, R.J.S.; Antonioli, Z.I.; Martínez-Cordeiro, H.; Domínguez, J. Changes in the Chemical and Biological Characteristics of Grape Marc Vermicompost during a Two-Year Production Period. *Appl. Soil Ecol.* **2020**, *154*, 103587. [[CrossRef](#)]
45. Domínguez, J.; Martínez-Cordeiro, H.; Álvarez-Casas, M.; Lores, M. Vermicomposting Grape Marc Yields High Quality Organic Biofertiliser and Bioactive Polyphenols. *Waste Manag. Res. J. Sustain. Circ. Econ.* **2014**, *32*, 1235–1240. [[CrossRef](#)] [[PubMed](#)]
46. Gómez-Brandón, M.; Lores, M.; Martínez-Cordeiro, H.; Domínguez, J. Effectiveness of Vermicomposting for Bioconversion of Grape Marc Derived from Red Winemaking into a Value-Added Product. *Environ. Sci. Pollut. Res.* **2020**, *27*, 33438–33445. [[CrossRef](#)] [[PubMed](#)]
47. Villar, I.; Alves, D.; Pérez-Díaz, D.; Mato, S. Changes in Microbial Dynamics during Vermicomposting of Fresh and Composted Sewage Sludge. *Waste Manag.* **2016**, *48*, 409–417. [[CrossRef](#)] [[PubMed](#)]
48. Luo, G.; Li, L.; Friman, V.-P.; Guo, J.; Guo, S.; Shen, Q.; Ling, N. Organic Amendments Increase Crop Yields by Improving Microbe-Mediated Soil Functioning of Agroecosystems: A Meta-Analysis. *Soil. Biol. Biochem.* **2018**, *124*, 105–115. [[CrossRef](#)]
49. Cidre-González, A.; Ruiz-Gómez, F.J.; Bonet, F.J.; González-Moreno, P. Forecasting the Risk of *Phytophthora Cinnamomi* Related-Dieback in Mediterranean Forest Ecosystems under Climate Change Scenarios. *Ecol. Modell.* **2025**, *505*, 111115. [[CrossRef](#)]
50. Priya, E.; Sarkar, S.; Maji, P.K. A Review on Slow-Release Fertilizer: Nutrient Release Mechanism and Agricultural Sustainability. *J. Environ. Chem. Eng.* **2024**, *12*, 113211. [[CrossRef](#)]
51. Schreiner, R.P. Nutrient Uptake and Distribution in Young Pinot Noir Grapevines over Two Seasons. *Am. J. Enol. Vitic.* **2016**, *67*, 436–448. [[CrossRef](#)]
52. Cocco, A.; Mercenaro, L.; Muscas, E.; Mura, A.; Nieddu, G.; Lentini, A. Multiple Effects of Nitrogen Fertilization on Grape Vegetative Growth, Berry Quality and Pest Development in Mediterranean Vineyards. *Horticulturae* **2021**, *7*, 530. [[CrossRef](#)]
53. MPELASOKA, B.S.; SCHACHTMAN, D.P.; TREEBY, M.T.; THOMAS, M.R. A Review of Potassium Nutrition in Grapevines with Special Emphasis on Berry Accumulation. *Aust. J. Grape Wine Res.* **2003**, *9*, 154–168. [[CrossRef](#)]
54. Bai, R.; Liu, H.; Liu, Y.; Yong, J.W.H. Effects of Foliar Application of Magnesium Fertilizer on Photosynthesis and Growth in Grapes. *Agronomy* **2024**, *14*, 2659. [[CrossRef](#)]
55. Dhaliwal, S.S.; Naresh, R.K.; Mandal, A.; Singh, R.; Dhaliwal, M.K. Dynamics and Transformations of Micronutrients in Agricultural Soils as Influenced by Organic Matter Build-up: A Review. *Environ. Sustain. Indic.* **2019**, *1–2*, 100007. [[CrossRef](#)]
56. Chtouki, M.; Laaziz, F.; Naciri, R.; Garré, S.; Nguyen, F.; Oukarroum, A. Interactive Effect of Soil Moisture Content and Phosphorus Fertilizer Form on Chickpea Growth, Photosynthesis, and Nutrient Uptake. *Sci. Rep.* **2022**, *12*, 6671. [[CrossRef](#)] [[PubMed](#)]
57. Martínez-Vidaurre, J.M.; Pérez-Álvarez, E.P.; García-Escudero, E.; Peregrina, F. Effects of Soil Water-Holding Capacity and Soil N-NO₃ and K on the Nutrient Content, Vigour and Yield of Cv. Tempranillo Vine and the Composition of Its Must and Wine. *OENO One* **2023**, *57*, 447–466. [[CrossRef](#)]
58. Keller, M. *The Science of Grapevines*; Elsevier: Amsterdam, The Netherlands, 2020; ISBN 9780128163658.

59. Badalíková, B.; Burg, P.; Mašán, V.; Prudil, J.; Jobbágy, J.; Čížková, A.; Krištof, K.; Vašinka, M. Deep Placement of Compost into Vineyard Soil Affecting Physical Properties of Soils, Yield and Quality of Grapes. *Sustainability* **2022**, *14*, 7823. [\[CrossRef\]](#)
60. Guilpart, N.; Metay, A.; Gary, C. Grapevine Bud Fertility and Number of Berries per Bunch Are Determined by Water and Nitrogen Stress around Flowering in the Previous Year. *Eur. J. Agron.* **2014**, *54*, 9–20. [\[CrossRef\]](#)
61. Verdenal, T.; Spangenberg, J.E.; Zufferey, V.; Lorenzini, F.; Dienes-Nagy, A.; Gindro, K.; Spring, J.-L.; Viret, O. Leaf-to-Fruit Ratio Affects the Impact of Foliar-Applied Nitrogen on N Accumulation in the Grape Must. *OENO One* **2016**, *50*, 23. [\[CrossRef\]](#)
62. Martínez-Lüscher, J.; Kurtural, S.K. Same Season and Carry-Over Effects of Source-Sink Adjustments on Grapevine Yields and Non-Structural Carbohydrates. *Front. Plant Sci.* **2021**, *12*, 695319. [\[CrossRef\]](#) [\[PubMed\]](#)
63. Peanusaha, S.; Pourreza, A.; Kamiya, Y.; Fidelibus, M.W.; Chakraborty, M. Nitrogen Retrieval in Grapevine (*Vitis vinifera* L.) Leaves by Hyperspectral Sensing. *Remote Sens. Environ.* **2024**, *302*, 113966. [\[CrossRef\]](#)
64. Rogiers, S.Y.; Coetzee, Z.A.; Walker, R.R.; Deloire, A.; Tyerman, S.D. Potassium in the Grape (*Vitis vinifera* L.) Berry: Transport and Function. *Front. Plant Sci.* **2017**, *8*, 1629. [\[CrossRef\]](#) [\[PubMed\]](#)
65. Moreno, J.J.; Peinado, R.A. *Enological Chemistry*; Academic Press: Boston, MA, USA, 2012.
66. Forino, M.; Picariello, L.; Rinaldi, A.; Moio, L.; Gambuti, A. How Must PH Affects the Level of Red Wine Phenols. *LWT* **2020**, *129*, 109546. [\[CrossRef\]](#)
67. Miliordos, D.E.; Kanapitsas, A.; Lola, D.; Goulioti, E.; Kontoudakis, N.; Leventis, G.; Tsiknia, M.; Kotseridis, Y. Effect of Nitrogen Fertilization on Savvatio (*Vitis vinifera* L.) Grape and Wine Composition. *Beverages* **2022**, *8*, 29. [\[CrossRef\]](#)
68. Gobert, A.; Tourdot-Maréchal, R.; Sparrow, C.; Morge, C.; Alexandre, H. Influence of Nitrogen Status in Wine Alcoholic Fermentation. *Food Microbiol.* **2019**, *83*, 71–85. [\[CrossRef\]](#) [\[PubMed\]](#)
69. Bisson, L.F. Stuck and Sluggish Fermentations. *Am. J. Enol. Vitic.* **1999**, *50*, 107–119. [\[CrossRef\]](#)
70. Ralser, M.; Wamelink, M.M.; Kowald, A.; Gerisch, B.; Heeren, G.; Struys, E.A.; Klipp, E.; Jakobs, C.; Breitenbach, M.; Lehrach, H.; et al. Dynamic Rerouting of the Carbohydrate Flux Is Key to Counteracting Oxidative Stress. *J. Biol.* **2007**, *6*, 10. [\[CrossRef\]](#) [\[PubMed\]](#)
71. Hazelwood, L.A.; Daran, J.-M.; van Maris, A.J.A.; Pronk, J.T.; Dickinson, J.R. The Ehrlich Pathway for Fusel Alcohol Production: A Century of Research on *Saccharomyces cerevisiae* Metabolism. *Appl. Environ. Microbiol.* **2008**, *74*, 2259–2266. [\[CrossRef\]](#) [\[PubMed\]](#)
72. Linderholm, A.L.; Findleton, C.L.; Kumar, G.; Hong, Y.; Bisson, L.F. Identification of Genes Affecting Hydrogen Sulfide Formation in *Saccharomyces cerevisiae*. *Appl. Environ. Microbiol.* **2008**, *74*, 1418–1427. [\[CrossRef\]](#) [\[PubMed\]](#)
73. Gutiérrez, R.; González, A.; Torres, F.; Gallardo, J.A. *Técnicas de Análisis de Datos Multivariable. Tratamiento Computacional*; Universidad de Granada: Granada, Spain, 1994.
74. Dayer, S.; Peña, J.P.; Gindro, K.; Torregrosa, L.; Voinesco, F.; Martínez, L.; Prieto, J.A.; Zufferey, V. Changes in Leaf Stomatal Conductance, Petiole Hydraulics and Vessel Morphology in Grapevine (*Vitis vinifera* Cv. Chasselas) under Different Light and Irrigation Regimes. *Funct. Plant Biol.* **2017**, *44*, 679. [\[CrossRef\]](#) [\[PubMed\]](#)

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