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Composting from organic municipal solid waste: a sustainable tool for the environment and to improve grape quality

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Abstract

Composting from organic municipal solid waste (MSW), such as a separate waste collection, is a valid tool for eliminating a considerable amount of waste that would otherwise be destined for landfills and incinerators, thus representing an effective complement to traditional forms of recycling. It allows organic substance to be recovered and reintegrated into the soil, thus preventing erosion phenomena, increasing the biological fertility of the soil and contributing significantly to the restoration of impoverished sites. Modern winegrowing must address the issue of vineyard fertility in the sustainability context. The goal of this study was to assess the advantages of distributing a sustainable product to the vineyard that can achieve vine balance (vegetative and productive equilibrium). In a *Vitis vinifera* L. Sangiovese cv., vineyard, four soil treatments were applied (three compost rates and a control): municipal solid waste compost (40 tons per hectare – MSW40, 15 tons per hectare – MSW15, 2.5 tons per hectare – MSW2.5), and no compost (CTRL). The vine physiology (leaf gas exchange and water potential) and berry compositions (phenolic and technological maturity) were studied during the 2018–2019 growing seasons in the Sieci area, Italy. The results of this experiment provide some general insights showing that MSW compost options can be expected to reduce water stress, balanced vine performance and provide sustainable recirculation of organic matter. MSW compost is a true agronomic and environmental resource.

Introduction

In the soil, organic matter has a fundamental role in the formation and advancement of soil physical properties, such as its bulk density, water retention capacity and molecular aggregation capacity (Angst *et al.*, 2021). The organic substance has an amending function and is necessary to preserve the fertility of the soil, understood as a complex of chemical, physical, biological and mechanical characteristics favourable to the physiological functions of plants (Schröder *et al.*, 2018; Picariello *et al.*, 2020).

The use of composted soil improvers favours an increase in soil porosity, structural stability, water retention and the reduction of erosion as well as an increase in organic matter content and providing a source of nutrients for production (Gurmu, 2019; Usharani *et al.*, 2019; Aytenew and Bore, 2020). In the land destined for the cultivation of vines, anthropic interventions, such as trenching and excavation, that involve the displacement of large quantities of land, often induced a loss of fertility due to a reduction in the presence of microbial populations (Costantini *et al.*, 2018; Garcia *et al.*, 2018; Pandey *et al.*, 2019; Jakšić *et al.*, 2020).

The conventional agriculture trend to maximize yields, through intensive cultivation techniques, together with the use of chemical fertilizers, has progressively compromised the fertility of agricultural land (Bonanomi *et al.*, 2020; Saffeullah *et al.*, 2021). Furthermore, the separation of livestock activities from cultivation has reduced the availability of organic matter, such as manure, within farms (Takahashi *et al.*, 2020; Valve *et al.*, 2020).

Modern winegrowing must address the issue of vineyard fertility in the sustainability context (Burg *et al.*, 2019). Currently greater attention is being paid to replacing conventional and synthetic fertilizers, such as urea, mineral superphosphate and potassium chloride (Roig *et al.*, 2018; Ollanazarovich, 2021; Pisciotta *et al.*, 2021) with different types of fertilizers (source of organic matter) in the form of compost, organic manure or digestate (Ronga *et al.*, 2019; Pizzeghello *et al.*, 2021). The new trends aimed at sustainable vineyard management lead to safeguarding soil fertility by preserving non-renewable resources and making the most of territorial resources (Cataldo *et al.*, 2021*a*; Rusch *et al.*, 2022). Viticulture conducted without the use of synthetic chemicals is based on agronomic management that observes the physiology and phenological rhythms of plants, in order to make them less demanding and less susceptible to pathogen attacks, as well as making the agroecosystem more resilient. Furthermore, a vineyard that is correctly stabilized from the point of view of additional contributions to the soil allows harmonious berry ripening without imbalances deriving from biotic (pathogenic attacks) or abiotic (climate change) factors (Tangolar *et al*., 2020; Cataldo *et al*., 2021*b*; Hooper and Grieshop, 2021).

It has been shown that a recycling integrated system recuperates nutrients and energy from the waste flow and decreases landfill disposal of recyclable and organic waste by reducing greenhouse gas (GHG) emissions, in comparison with conventional landfill disposal (Menikpura *et al*., 2013). In addition, the effect of soil organic matter on soil respiration has not only agronomic but also environmental relevance due to their contribution to both emissions and removals of GHGs (carbon fluxes) (Montanaro *et al*., 2021). Composting from organic municipal solid waste (MSW), such as a separate waste collection, is a valid tool for eliminating a considerable amount of waste that would otherwise be destined for landfills and incinerators, thus representing an effective complement to traditional forms of recycling (Richard 1992; Garcıa-Gil *et al*., 2000). It allows the recovery of organic substance to reintegrate it into the soil, thus preventing erosion phenomena, increasing the biological fertility of the soil and contributing significantly to the restoration of impoverished sites (Farrell and Jones, 2009).

However, it is well known that the addition of composted soil improvers can block the loss of organic matter and restore soil fertility by compensating for humus deficit, improving soil structure even in the long term and increasing plant performance through a better balance of the source-sink ratio (Sánchez-Monedero *et al*., 2019).

In vineyards, the use of MSW and composted sewage sludge has been a source of research and monitoring (Siles-Castellano *et al*., 2021). However, owing to the poor quality of the compost deriving from MSW (i.e. heavy metals, glass and plastic), alarm for the health of living beings and the environment and related marketing issues have occurred over time (Wei *et al*., 2017).

For this reason, MSW composting was embellished by an arrangement in which organic waste is divided at the beginning (source) and stockpiled independently before being composted to guarantee better compost production (fewer impurities and contamination) (Stunzenas and Kliopova, 2018; Edo *et al*., 2022).

Organic waste (MSW) contains a high amount of organic carbon (30–50%) and easily available nitrogen (N) and thus can be efficiently used in viticulture (Weber *et al*., 2014). On one hand, during the composting process, organic matter undergoes stabilization, humification and the matured compost (final product) is described as a good amendment to enhance the physicochemical and biological soil properties (Yu *et al*., 2015). But on the other hand, MSW compost may contain different concentrations of potentially harmful elements, such as metals and metalloids (subjected to limitations by law) causing adverse effects on the environment (i.e. soil and water contamination and phytotoxicity to plants) (Illera *et al*., 2000; Dercová *et al*., 2005). In fact, most studies point to the MSW composting process and degree of maturity of the final product as basic conditions for its safe utilization, indicating its components and criticalities (Jamroz *et al*., 2020).

The aim of the work was to improve knowledge of MSW composting in viticulture through the study of its application on grapevines soil analysing the main parameters of leaf gas exchange and the quality of the grapes.

Materials and methods

Temperature, experiment location and compost analysis

The experiment was carried out in the municipality of Pontassieve in the Sieci area (43°47′18.49″N–11°23′40.02″E). The area is located along the banks of the Arno River, at the point where the Sieci stream of the same name enters (4 km), on the slopes of the Remole hill (249 m a.s.l.). The climatic zone for the Pontassieve territory (assigned by Decree of the President of the Republic n. 412 of 26 August 1993 and subsequent updates until 31 October 2009) is D with 1928 degree days.

Vitis vinifera L. Sangiovese cv./SO4 was planted in 2013. Vines were planted at 2.8 m × 1 m (row × vine) spacing in north-south orientated rows. All the vines were trained on a vertical upward single cordon positioning system. The vineyard was managed under a semi-mechanized management system.

The geological material underlying the soil is a group of calcareous sands, silts and argillites originating from the Myocene. Red calcareous argillites are interspersed with isolated sand levels. Generally speaking, the vineyard soil had a high pH (over 8.3), carbonate content (over 37%) and active lime content of over 13.30% with some rock fragments (Dane and Topp, 2020; Sparks *et al*., 2020). The physico-chemical analysis of the soil was performed by an external laboratory (Table 1) (Demetra di Landi Stefano & Baroncelli Paolo SNC, Pescia, PT, Italy).

An automated weather station (Ecotech, Germany) located in the vineyard, was used to record total rainfall (mm) and maximum, mean and minimum air temperature (°C). The climate was the semiarid Mediterranean according to the Papadakis classification (Arshad and Rawayau, 2016), with a mean annual rainfall of 760 mm and a mean annual temperature of 13.5°C. Climatic conditions varied during the two vintages studied: the 2019 vintage was slightly dry (740 mm) and the 2018 was exceptionally wet with respect to the average (1290 mm).

The experiment was arranged with a complete randomized block design, consisting of five experimental plots and one factor (soil treatment). Each experimental plot consisted of three parallel rows per treatment, with only the central row sampled to limit edge effects. Four soil treatments were applied (three compost

Table 1. Physical (sand, silt and clay) and chemical (total nitrogen, assimilable phosphorus, exchangeable potassium, exchangeable calcium, exchangeable magnesium, assimilable ferrum, organic substance, C/N ratio, total limestone, active limestone and cation exchange capacity) analysis of vineyard soil

Physical analysis of the soil	
Sand	34.5%
Silt	28.7%
Clay	36.8%
Chemical analysis of the soil	
Total nitrogen (N)	1.3 N%0
Assimilable phosphorus (P)	6 P_2O_5 ppm
Exchangeable potassium (K)	146 K_2O ppm
Exchangeable calcium (Ca)	5045 Ca ppm
Exchangeable magnesium (Mg)	123 Mg ppm
Ferrum assimilable	138 Fe ppm
Organic substance (SO)	1.84%
C/N	8.2
Total limestone	24.5%
Active limestone	3.9%
Cation exchange capacity	26.6 meq/100 g

Table 2. MSW compost analysis

Biological parameters		Agronomic characteristics	
Salmonella spp.	–	Humidity	55%
Total Enterobacteriaceae	$< 1 \times 10^2$ UFC/ g	N	2.79% s.s.
Streptococcus faecalis	–	P (P_2O_5)	2.13% s.s.
Nematoda, Cestoda, Trematoda	–	K (K_2O) (% s.s.)	1.26% s.s.
Unwanted materials (% s.s.)	Organic carbon	25% s.s.	
Plastic materials (≤3.33 mm)	< 0.31	pH	8.15
Plastic materials (>3.33 × ≤ 10 mm)	< 0.05	Conductivity	3730 μS/cm
Other inert materials (≤3.33 mm)	< 0.3	Mg (MgO)	1.53%
Other inert materials (>3.33 × ≤ 10 mm)	< 0.1	Mn	360 mg/kg s.s.
Plastic and inert materials (>10 mm)	–	Fe	13 850 mg/kg s.s.
Heavy metals (ppm s.s.)	Bulk density	400 g/l	
Zinc (Zn)	350	Total porosity	82.34% vol/vol
Copper (Cu)	150	Water available (H_2O)	13.88% vol/vol
Lead (Pb)	100		
Nickel (Ni)	45		
Mercury (Hg)	1.2		
Cadmium (Cd)	0.4		
Chromium (Cr)	–		

Biological parameters (*Salmonella* spp., total Enterobacteriaceae, *Streptococcus faecalis*, Nematoda, Cestoda and Trematoda), unwanted materials (plastic materials ≤ 3.33 mm, plastic materials > 3.33 × ≤ 10 mm, other inert materials ≤ 3.33 mm, other inert materials > 3.33 × ≤ 10 mm and plastic and inert materials > 10 mm), heavy metals (Zn, Cu, Pb, Ni, Hg, Cd and Cr) and agronomic characteristics (humidity, N, P, K, organic carbon, pH, conductivity, Mg, Mn, Fe, bulk density, total porosity and H_2O)

rates and a control): municipal solid waste compost (40 tons per hectare – MSW40), municipal solid waste compost (15 tons per hectare – MSW15), municipal solid waste compost (2.5 tons per hectare – MSW2.5) and no compost (CTRL). The vines had received basic fertilization during the installation of the vineyard (50 tons of manure; 300 kg K; 200 kg P; 200 kg Mg; 10 kg B); during the following years, no fertilization was applied to the soil. The treatments were applied in autumn 2017 and autumn 2018 with a manure spreader machine. Compost was applied on a per hectare basis, with a single application in bands that were lightly incorporated (10–20 cm) into the soil directly under the interrow (Wilson *et al.*, 2021).

At the composting Center of Faltona (Alia Servizi Ambientali SpA, Borgo San Lorenzo, Italy), with the technical and scientific supervision of the Agricultural School (DAGRI, University of Florence, Italy), in a specially set up area tests were carried out to obtain quality compost, derived from organic waste matrices selected from separate collection from MSW, agri-food waste, etc. The obtained compost was subjected to analysis (Table 2), by an external laboratory, for the verification of the qualitative standard parameters required by current legislation on fertilizers, before being used for agronomic experimentation.

Briefly, the composting plant in Faltona foresees three macro phases (Diaz *et al.*, 2020; Miller, 2020; Siles-Castellano *et al.*, 2020):

(i) Mechanical treatment of incoming materials and preparation of the mixture; shredding and/or screening and/or mixing in order to first remove foreign materials, to obtain the correct porosity and humidity of the mixture, and to balance the nutrients.
(ii) Biostabilization of the mixture; series of technologies (temperature control, oxygen level, humidity) to obtain the optimal conditions for microorganisms in order to stabilize the organic substance, accelerating natural processes and eliminating potential pathogens.
(iii) Final refining of the stabilized material (screening and iron removal), for the definitive removal of foreign materials to obtain a compost that fully complies with the standard (annex 2 of Legislative Decree 75/10), which can be used directly in the field or in the production of other fertilizers.

Shoot growth, number of leaves per sprout, stomatal conductance, net photosynthesis, transpiration, and water use efficiency, midday stem water potential and chemical analysis of leaves.

Shoot growth and leaves number per shoot were measured every 2 weeks until the vegetative canopy was mechanically topped by sampling ten shoots per treatment chosen in the tagged vines. Leaf gas exchange measurements were taken to assess leaf photosynthetic activities by using a portable infrared gas analyser CIRAS-3 (PP Systems, Amesbury, MA, USA). The measurements were assessed three times per season (full bloom: 25 May 2018–24 May 2019, veraison: 13 August 2018–7 August 2019 and harvest: 15 September 2018–10 September 2019). Ten sun-exposed leaves were selected from the main shoot axis in each experimental unit. Gas exchange measurements were taken when the sunlight condition was close to saturating in both years (average PARi = 1728 ± 211 $\mu mol/m^2s$ in 2018, 1742 ± 236 $\mu mol/m^2s$ in 2019). The relative humidity was set at 40%, the reference CO_2 concentration was set at 400 µmol CO_2/mol as the standard environmental condition setting in CIRAS-3. Net carbon assimilation rate (Pn, µmol CO_2/m^2s), transpiration (E, mmol H_2O/m^2s) and stomatal conductance (*gs*, mmol H_2O/m^2s) were obtained. Intrinsic water use efficiency (WUEi) was calculated as the proportion of Pn over *gs* (µmol CO_2/mmol H_2O). Extrinsic water use efficiency (WUEe) was calculated as the proportion of Pn over E (µmol CO_2/mmol H_2O) (Yu and Kurtural, 2020).

In parallel with leaf gas exchange measurements, at the same dates and phenological stages, midday stem water potential (Ψstem) was measured in 2018 and 2019 to assess plant water status. Ten leaves in the shade were selected from the main shoot axis on the grapevines and were concealed in pinch-sealed dark Mylar® bags for about 1.30 h prior to the measurements in each experimental unit. A pressure chamber (Model 615D, PMS Instrument Company, Albany, OR, USA) was used to take the measurements.

The leaf samples (five samples per treatment chosen in the tagged vines) for determining the concentrations of microelements (Fe, B, Cu, Zn, Mn and Mo) and trace elements (Al, Ba, Cd, Cr, Pb and Ni) of grapevines were taken from the opposite sides of clusters at veraison times (13 August 2018–7 August 2019) and their leaf blades were used in the analysis (Ozdemir *et al*., 2008). Plant samples were washed in distilled water before forced-air oven drying at 60°C. Samples were ground before extraction. After wet microwave digestion in HNO_3 (CANDY – MIC 201 EX, 1000 watt microwave), the samples were analysed using the ICP-OES technique (Prodigy Teledyne, Leeman Labs. spectrometer, Mason, OH, USA) (Domagala-Swiatkiewicz and Gastol, 2013).

Berry analysis and production data

Ten samples of 100 berries per treatment were taken at veraison (13 August 2018 and 7 August 2019), full maturation (31 August 2018 and 28 August 2019) and harvest (15 September 2018 and 10 September 2019) for technological analysis. Berry weight was determined with a digital scale (Pts3000-Bs Pesola, Schindellegi, Switzerland). The berries were hand-pressed in a stainless-steel juicer to yield about 30 ml of juice that was centrifuged at 1800 g for 3 min and used for pH, titratable acidity and °Brix determination. The pH was measured using Seven Compact pH/Ion meter S220 (Mettler Toledo, MI, Italy). Titratable acidity was automatically titrated (Mettler Toledo ET18 titrator, Mettler Toledo Instruments) with a solution of 0.05 M NaOH to a final pH of 7.0, expressed as g/l of tartaric acid (Shi *et al*., 2017). °Brix was determined from the juice of 10 ml per sample per treatment, using a 55586-Refractometer (Fernox, NO, Italy).

The procedure for anthocyanins and polyphenols extraction developed by Glories (1984 was implemented with the method by Kontoudakis *et al*. (2010). Briefly, 100 g of berries were put into a kitchen blender (BOSCH MMB6141S, 1200 watt, MI, Italy) and blended on a low pulsed level to homogenize pulp and skin. Two different pH solutions were prepared:

(A) a pH 1 solution with 0.3M $C_2H_2O_4$ (oxalic acid) adjusted with HCl (hydrochloric acid);
(B) a pH 3.2 solution with 0.3M H_3PO_4 (phosphoric acid) adjusted with 10 M NaOH (sodium hydroxide).

Solution A (50 ml) was added to grape mash (50 g) and solution B (50 ml) was added to the remaining 50 g of the grape mash. These were incubated for 4 h at ambient temperature with agitation every 35 min and centrifuged at 4200 RPM for 8 min.

Extraction solvent (21 ml comprising 5 ml ethanol + 16.7 ml 12% HCl in 100 ml H_2O) was added to 1 ml of each pH sample supernatant. In total, 4 ml of a 15% (w/w) SO_2 were added to 10 ml of each sample (sulphured samples), while 4 ml H_2O were added to an additional 10 ml of each sample (native samples). All samples were incubated for 15 min and analysed at 520 nm against the dilution solution (C_2H_6O + HCl in H_2O) as a blank reagent. Extractable and total anthocyanins were calculated using the following formulas (Sommer and Cohen, 2018):

(a) Potential anthocyanins (mg/L) $= [\text{A520 (pH 1)} - \text{A520 (pH 1; } SO_2)] \times 875$
(b) Extractable anthocyanins (mg/L) $= [\text{A520 (pH 3.2)} - \text{A520 (pH 3.2; } SO_2)] \times 875$

Ten samples of 100 berries per treatment were taken at veraison (13 August 2018 and 7 August 2019), full maturation (31 August 2018 and 28 August 2019) and harvest (15 September 2018 and 10 September 2019) and frozen at −20°C. In order to thaw for spectrophotometric analysis (Spectrophotometer UV/VIS Mettler-Toledo S.p.A., MI, Italy), they were left at 4°C for 24 h.

Statistical analyses

Laboratory and field data were analysed with a one-way analysis of variance to test treatment effects. In all analyses, means were separated by Tukey's honest significant difference for post hoc comparisons where significant effects were observed. All analyses were conducted in R version 3.4.0 (R Foundation for Statistical Computing, Vienna, Austria) using a $P < 0.05$ significance level.

Results

The overall weather of the vineyard: temperature and rainfall

The climate during the 2 years of the experiment was characterized by Mediterranean trends; from the point of view of precipitation, there were considerable differences (Fig. 1). The 2018 season (March–October 1297.1 mm) was characterized by a uniform rain distribution with a dry period in September. The 2019 season (March–October 747.1 mm) was characterized by an uneven distribution of rain, in particular there was a peak during May month (243.0 mm of rain) and a dry period in June (10.0 mm of rain) and July (76.0 mm of rain).

As reported in Fig. 1, maximum temperatures exceeded 32°C on the following days (2018 season): from 30 June to 2 July (181–183 day of the year (DOY)), from 13 to 15 July (194–196 DOY), from 18 to 21 July (199–202 DOY), from 24 July to 12 August (205–224 DOY), from 17 to 24 August (229–236 DOY), 29 August (241 DOY), 11 September (254 DOY). In addition, maximum temperatures exceeded 32°C on the following days (2019 season): from 7 to 14 June (158–165), from 18 to 21 June (169–172), from 24 July to 6 July (175–187 DOY), from 8 to 9 July (189–190 DOY), from 17 to 27 July (198–208 DOY), from 1 to 7 August (213–219 DOY), from 9 to 13 August (221–225 DOY), from 16 to 21 August (228–233 DOY), from 26 to 27 August (238–239 DOY), from 25 August to 1 September (241–244 DOY).

Furthermore, while only 3 days were with extreme temperatures in 2018 (1 August 38°C, 5 August 37°C and 7 August

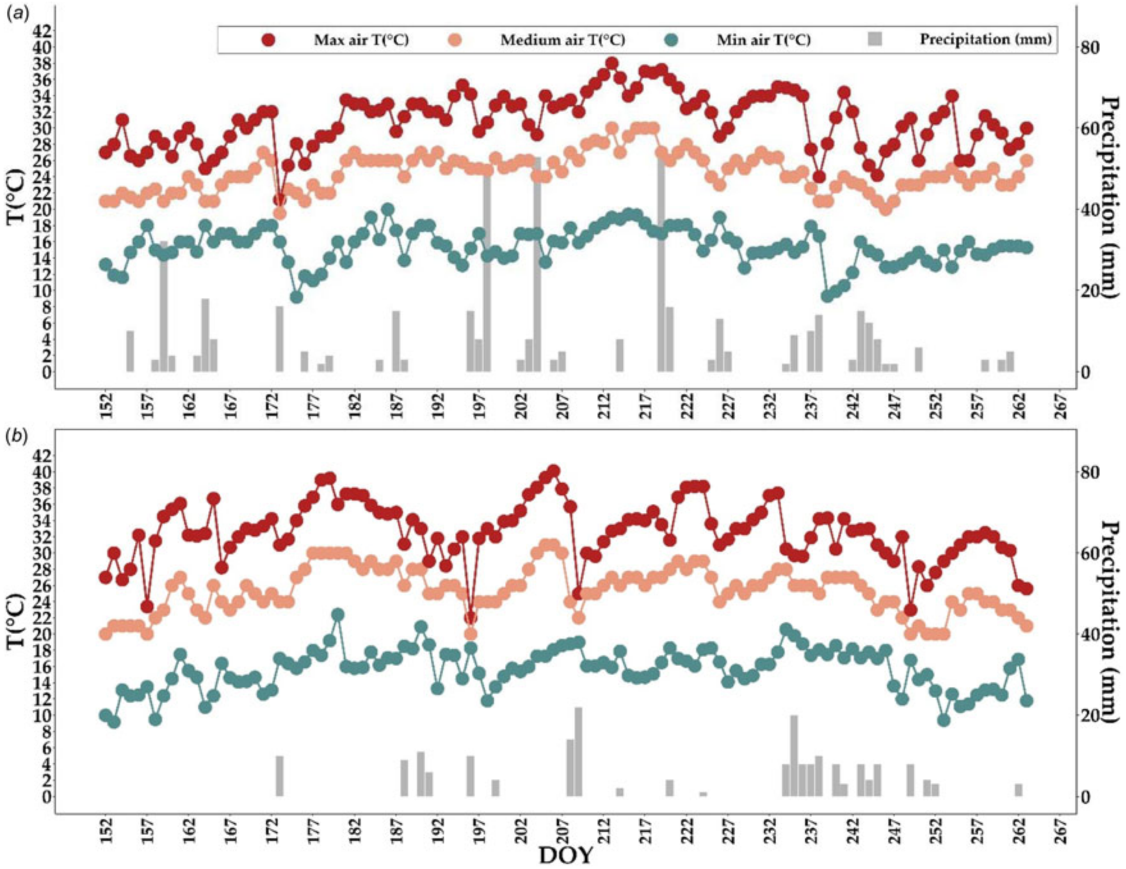

Fig. 1. Colour online. The overall weather of the vineyard. Daily total rainfall (mm) and mean, maximum, minimum temperature (°C) of 2018 (*a*) and 2019 (*b*). All data refer to the hottest central months of each year (from June to September). The days are expressed in day of the year (DOY) as follows: June 2018 (152–181), July 2018 (182–212), August 2018 (213–243), September 2018 (244–263) and June 2019 (152–181), July 2019 (182–212), August 2019 (213–243), September 2019 (244–263).

37.2°C), in 2019 15 days with severe temperatures were recorded (26 June 39°C, 28 June 39.2°C, 30 June 37.3°C, 1 July 37.3°C, 2 July 37.1°C, 22 July 37.2°C, 23 July 38.1°C, 24 July 39.3°C, 25 July 40.1°C, 26 July 37.9°C, 10 August 38.1°C, 11 August 38.2°C, 12 August 38.2°C, 20 August 37.1°C and 21 August 37.4°C).

Shoot growth, number of leaves per shoot, stomatal conductance, net photosynthesis, transpiration, water use efficiency, midday stem water potential and chemical analysis of leaves

The shoot length of grapevines was significantly affected ($P < 0.05$) by the MSW applications in both years (Tables 3 and 4). MSW40 treatment significantly reduced the shoot length, which was 112.00 cm in the 2019 season (by failing to reach the last wire of the plant system). Prior to topping, MSW2.5 and MSW15 treatments turned out a greater length and number of leaves (i.e. on 29 May 123.22 and 126.45 respectively).

Single leaf net CO_2 assimilation at saturating light (Pn) decreased during the season from values ranging between 8 and 10 μmol/m^{2}s to values between 2 and 6 μmol/m^{2}s in treatments (Fig. 2). Leaf net assimilation was significantly influenced by MSW treatment. MSW40 treatment showed significantly lower values (i.e. 3.07 μmol m^2/s on 15 September 2018 and 3.35 μmol/m^{2}s on 10 September 2019). In most cases, the reduction in photosynthesis was due to a stomatal mechanism as emerges from the comparison with the stem water potential data.

Leaf stomatal conductance (*gs*) also decreased during the hottest 2019 season from maximum morning values ranging between 110 and 180 mmol/m^{2}s to values between 70 and 120 mmol/ m^{2}s in treatments. The *gs* drop was quite consistent in MSW40 treatment that not fully recovered to the *gs* levels recorded in the previous season (i.e. 104.00 mmol/m^{2}s on 15 September 2018 *v.* 75.00 mmol/m^{2}s on 10 September 2019).

Leaf water potential (Ψ) was significantly affected by temperature, seasonal rainfall and MSW treatment. As shown in Table 3, during the hottest days (13 August 2018, 7 August 2019 and 10 September 2019), MSW2.5 and MSW15 plants showed higher mean values (no water stress) than MSW40 and CTRL plants. The mean values of Ψ for MSW2.5 were between −1.20 and −1.55 MPa while those for MSW15 were between −1.17 and −1.39 MPa.

Leaf boron (B) and manganese (Mn) concentrations showed an increasing trend during the two seasons in treated vines (Tables 5 and 6). Soil application of 40 q/ha MSW enhanced the negative effect of accumulation on the leaf of copper (Cu), nickel (Ni) and lead (Pb); the concentration of these elements was higher in MSW40-treated vines compared to untreated plants (i.e. during 2019 season Cu 22.71 mg/kg *v.* 10.03 mg/kg; Pb 3.10 mg/kg *v.* 1.25 mg/kg; Ni 2.33 mg/kg *v.* 2.00 mg/kg). No difference was found in both years for the concentrations of chromium (Cr) and cadmium (Cd).

Table 3. Sprout growth (cm) and number of leaves per sprout (2018 season)

	MSW40	MSW15	MSW2.5	CTRL
2018 – Sprout growth (cm)				
13 April	4.7 ± 0.35a	4.7 ± 0.40a	4.7 ± 0.90a	4.7 ± 0.33a
4 May	41.5 ± 3.50a	44.1 ± 3.32a	41.1 ± 5.32a	39.3 ± 5.75a
14 May	92.5 ± 5.58a	84.1 ± 5.82b	81.0 ± 4.51b	86.5 ± 5.21b
25 May	105.1 ± 8.54b	114.9 ± 9.33a	117.5 ± 8.42a	104.1 ± 8.74b
5 June	120.0 ± 0.00a	120.0 ± 0.00a	120.0 ± 0.00a	120.0 ± 0.00a
2018 – Number of leaves per sprout				
13 April	3.0 ± 0.00a	3.0 ± 0.00a	3.0 ± 0.00a	3.0 ± 0.00a
4 May	7.0 ± 0.00a	7.0 ± 0.00a	6.0 ± 0.00b	7.0 ± 0.00a
14 May	11.0 ± 0.50a	11.0 ± 0.50a	9.0 ± 0.00b	9.0 ± 0.00b
25 May	15.0 ± 0.50a	14.0 ± 0.50b	14.0 ± 0.50b	15.0 ± 0.50a
5 June	15.0 ± 0.50a	15.0 ± 0.00a	14.0 ± 0.50b	15.0 ± 0.50a

Data (mean ± s.e., $n = 10$) were subjected to one-way ANOVA. Different letters within the same day and rows indicate significant differences among treatments (LSD test, $P \leq 0.05$).

Table 4. Sprout growth (cm) and number of leaves per sprout (2019 season)

	MSW40	MSW15	MSW2.5	CTRL
2019 – Sprout growth (cm)				
9 April	3.3 ± 0.10b	5.1 ± 0.44a	5.0 ± 0.12a	4.7 ± 0.35a
29 April	35.2 ± 2.10d	52.5 ± 3.14a	49.8 ± 5.02b	39.2 ± 4.35c
14 May	73.5 ± 7.12c	73.4 ± 5.82c	85.8 ± 4.51a	77.8 ± 5.21b
29 May	92.7 ± 6.32c	126.4 ± 10.56a	123.2 ± 9.11a	110.0 ± 7.32b
5 June	112.0 ± 7.43b	120.0 ± 0.00a	120.0 ± 0.00a	120.0 ± 0.00a
2019 – Number of leaves per sprout				
9 April	2.0 ± 0.00b	3.0 ± 0.00a	3.0 ± 0.00a	3.0 ± 0.00a
29 April	5.0 ± 0.00b	7.0 ± 0.00a	5.0 ± 0.00a	7.0 ± 0.00a
14 May	9.0 ± 0.50c	13.0 ± 0.00a	12.0 ± 0.50b	9.0 ± 0.50c
29 May	11.0 ± 0.00d	18.0 ± 0.50a	17.0 ± 0.00b	14.0 ± 0.50c
5 June	11.0 ± 0.50c	14.0 ± 0.00a	14.0 ± 0.50a	13.0 ± 0.50b

Data (mean ± s.e., $n = 10$) were subjected to one-way ANOVA. Different letters within the same day and rows indicate significant differences among treatments (LSD test, $P \leq 0.05$).

Berry analysis and production data

Figure 3 indicates the Sangiovese grape's composition under four different soil management approaches in the 2018 and 2019 years in terms of technological maturity. During the 2018 season, significant differences at mid-maturation and harvest were noted in sugar content while during the 2019 season, significant differences at all stages were noted in sugar content. CTRL had the highest values of °Brix than other treatments. Furthermore, at harvests, lower acidity values were found for the CTRL treatment.

As shown in Fig. 4, significant differences in phenolic maturity were found (extractable and total anthocyanins). As for the 2018 season, at full maturation and harvest, CTRL berries showed significantly higher total anthocyanin content compared to treated grapes. The lowest values in extractable anthocyanins were recorded for the MSW40 treatment at harvest stages. Optimal and balanced parameters were found in MSW15 treatment (i.e. at 2018 harvest 701.75 mg/l and at 2019 harvest 929.83 mg/l).

At the 2019 harvest, no differences in total polyphenols were found, while during the 2018 harvest CTRL berries showed significantly higher total polyphenol content compared to the other treatments. In both seasons, significant differences were found in the production parameters at harvest (Table 7). MSW15 and MSW2.5 treatments, in general, had a higher weight of the bunches and yield per plant compared to MSW40 treatment and CTRL.

Discussion

The threats to the vineyard (e.g. soil compaction or erosion, reduced fertility and lower agricultural productivity) are

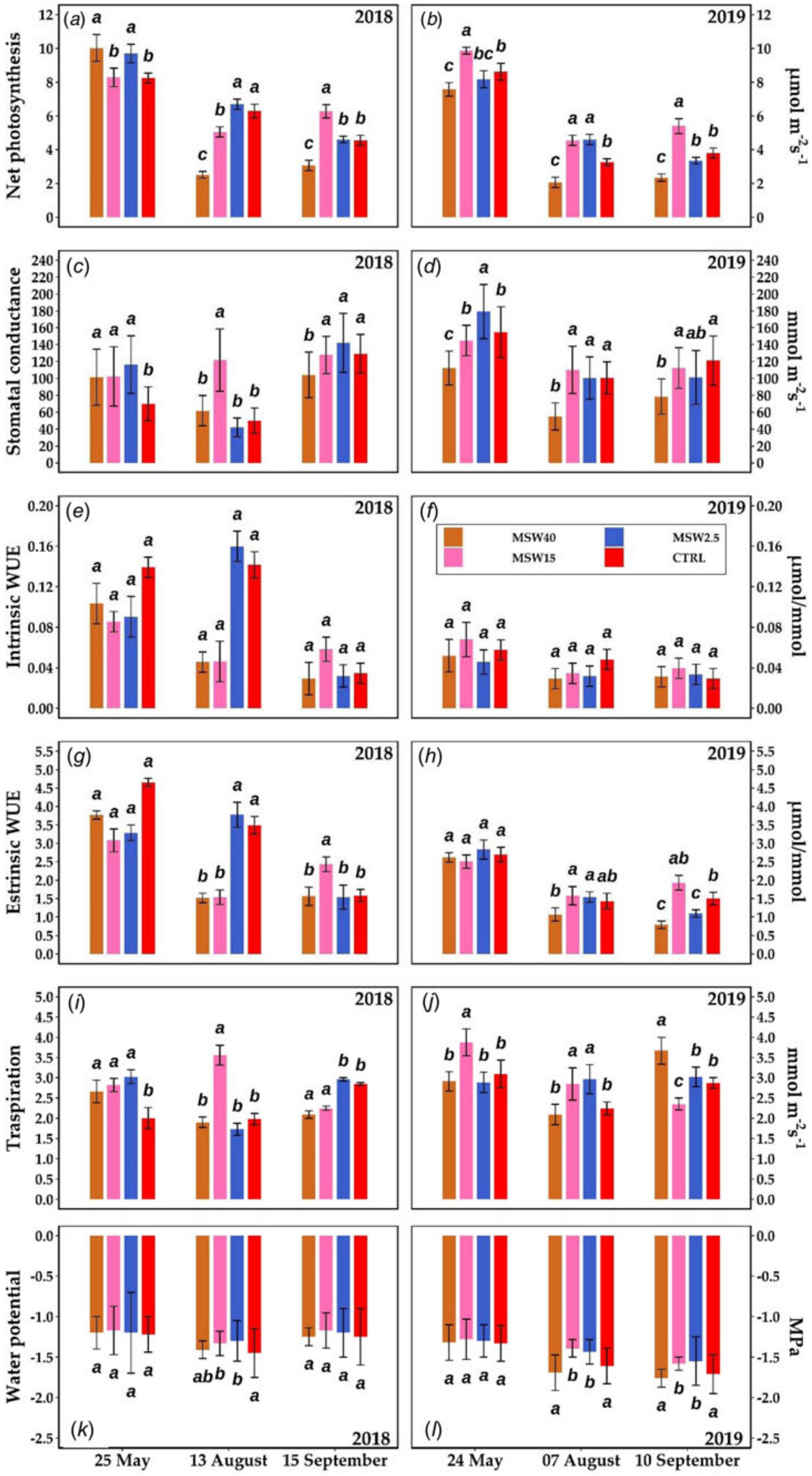

Fig. 2. Colour online. Net photosynthesis (Pn) (*a–b* 2018–2019), stomatal conductance (gs) (*c–d* 2018–2019), intrinsic water use efficiency (iWUE) (*e–f* 2018–2019), extrinsic water use efficiency (eWUE) (*g–h* 2018–2019), transpiration (E) (*i–l* 2018–2019) and midday stem water potential (Ψstem) (*m–n* 2018–2019) of Sangiovese vines treated with three compost rates and a control: municipal solid waste compost (40 tons per hectare – MSW40), municipal solid waste compost (15 tons per hectare – MSW15), municipal solid waste compost (2.5 tons per hectare – MSW2.5) and no compost (CTRL). Data (mean ± S.E., *n* = 10) were subjected to one-way ANOVA. Different letters within the same parameter and columns indicate significant differences (LSD test, $P \leq 0.05$).

Table 5. Content of micro-elements (B, Cu, Fe, Zn, Mn and Mo; mg/kg d.m.) and trace elements in the leaves (Al, Ba, Cd, Cr, Ni and Pb; mg/kg d.m.) (2018 veraison)

	MSW40	MSW15	MSW2.5	CTRL
2018 – Micro element (mg/kg d.m.)				
B	20.1 ± 1.54b	32.8 ± 1.99a	23.0 ± 1.22b	29.1 ± 1.54ab
Cu	10.9 ± 1.32a	9.1 ± 1.18b	9.0 ± 1.12b	9.1 ± 1.30b
Fe	119.8 ± 8.50a	99.2 ± 8.22b	87.2 ± 6.31c	95.6 ± 6.62a
Zn	29.0 ± 3.08a	30.4 ± 2.83a	29.7 ± 2.57a	27.0 ± 1.26b
Mn	158.7 ± 11.37b	160.1 ± 9.25b	175.6 ± 10.28a	170.3 ± 10.74a
Mo	0.0 ± 0.00a	0.0 ± 0.00a	0.0 ± 0.00a	0.0 ± 0.00a
2018 – Trace element (mg/kg d.m.)				
Al	24.1 ± 1.88b	30.1 ± 1.43a	27.1 ± 1.92ab	29.5 ± 2.00a
Ba	13.9 ± 1.50a	12.3 ± 1.21b	13.7 ± 1.98b	17.2 ± 1.93a
Cd	0.1 ± 0.01a	0.1 ± 0.01a	0.1 ± 0.01a	0.1 ± 0.01a
Cr	0.1 ± 0.01a	0.1 ± 0.01a	0.2 ± 0.01a	0.1 ± 0.01a
Ni	3.0 ± 0.54a	2.8 ± 0.16a	2.1 ± 0.63a	2.5 ± 0.32a
Pb	1.4 ± 0.08a	1.4 ± 0.05a	1.1 ± 0.05a	1.2 ± 0.05a

associated with climate change's negative effects (e.g. extreme weather events, droughts, frosts and increases in temperature) (Hamidov *et al.*, 2018). These climate-related risks raise major concerns regarding the vineyard ecosystem as a balanced resource for wine production. This study emphasizes the importance of compost application in the Mediterranean vineyard for maintaining and progressively increasing organic fertility in order to obtain a balanced and qualitatively satisfactory production.

The length and number of leaves were influenced by the amount of compost provided. The control together with the MSW40 treatment recorded lower values compared to doses 2.5 and 15 t/ha. This is probably due to the more abundant presence of copper (Cu) in the MSW400 treatment. Copper element converts the toxicity above a threshold level based on the type of crop plants (An, 2006); on average 1 kg of dry plant tissue contains around 10 mg of Cu (Rawat *et al.*, 2018). The toxic effects of Cu on cultivated crop plants such as mungbean (*Vigna radiate* L.), rice (*Oryza sativa* L.), lettuce (*Lactuca sativa* L.), mustard (*Brassica nigra* L.) and kidneybean (*Phaseolus vulgaris* L.) are denoted by inhibiting seed germination, decreases in the shoot and root lengths and morphological as well enzymatic changes; in addition, Cu toxicity has been shown to reduce the content of macronutrients in the shoot (Ca, Mg, K and P) most likely due to an interference with the uptake and translocation of the ions (Shaw and Hossain, 2013; Gopalakrishnan Nair *et al.*, 2014; Mustafa *et al.*, 2017; Zafar *et al.*, 2017; Shams *et al.*, 2018; Marastoni *et al.*, 2019*a*, 2019*b*).

Table 6. Content of micro-elements (B, Cu, Fe, Zn, Mn and Mo; mg/kg d.m.) and trace elements (Al, Ba, Cd, Cr, Ni and Pb; mg/kg d.m.) in the leaves (2019 veraison)

	MSW40	MSW15	MSW2.5	CTRL
2019 – Micro element (mg/kg d.m.)				
B	35.2 ± 2.45b	39.8 ± 1.98a	25.0 ± 1.43c	29.2 ± 1.09c
Cu	22.7 ± 1.87a	12.4 ± 1.27b	9.9 ± 1.23b	10.0 ± 1.10b
Fe	139.1 ± 8.77a	120.1 ± 7.13b	119.2 ± 7.98bc	98.1 ± 9.66c
Zn	57.2 ± 4.67a	52.4 ± 2.29a	49.6 ± 2.99ab	44.0 ± 3.21b
Mn	237.4 ± 34.11c	320.5 ± 28.93a	276.5 ± 20.66b	312.3 ± 36.86a
Mo	0.0 ± 0.01a	0.0 ± 0.01a	0.0 ± 0.01a	0.0 ± 0.01a
2019 – Trace element (mg/kg d.m.)				
Al	35.3 ± 2.89a	33.4 ± 2.21a	29.2 ± 1.04b	30.1 ± 2.53b
Ba	14.0 ± 2.25b	18.5 ± 1.95a	13.9 ± 1.67b	17.1 ± 1.43a
Cd	0.3 ± 0.01a	0.3 ± 0.01a	0.1 ± 0.01a	0.1 ± 0.01a
Cr	0.1 ± 0.03a	0.2 ± 0.01a	0.2 ± 0.01a	0.1 ± 0.01a
Ni	2.3 ± 0.08a	2.5 ± 0.10a	2.8 ± 0.54a	2.0 ± 0.32a
Pb	3.1 ± 0.03a	1.9 ± 0.02b	1.3 ± 0.03b	1.2 ± 0.01b

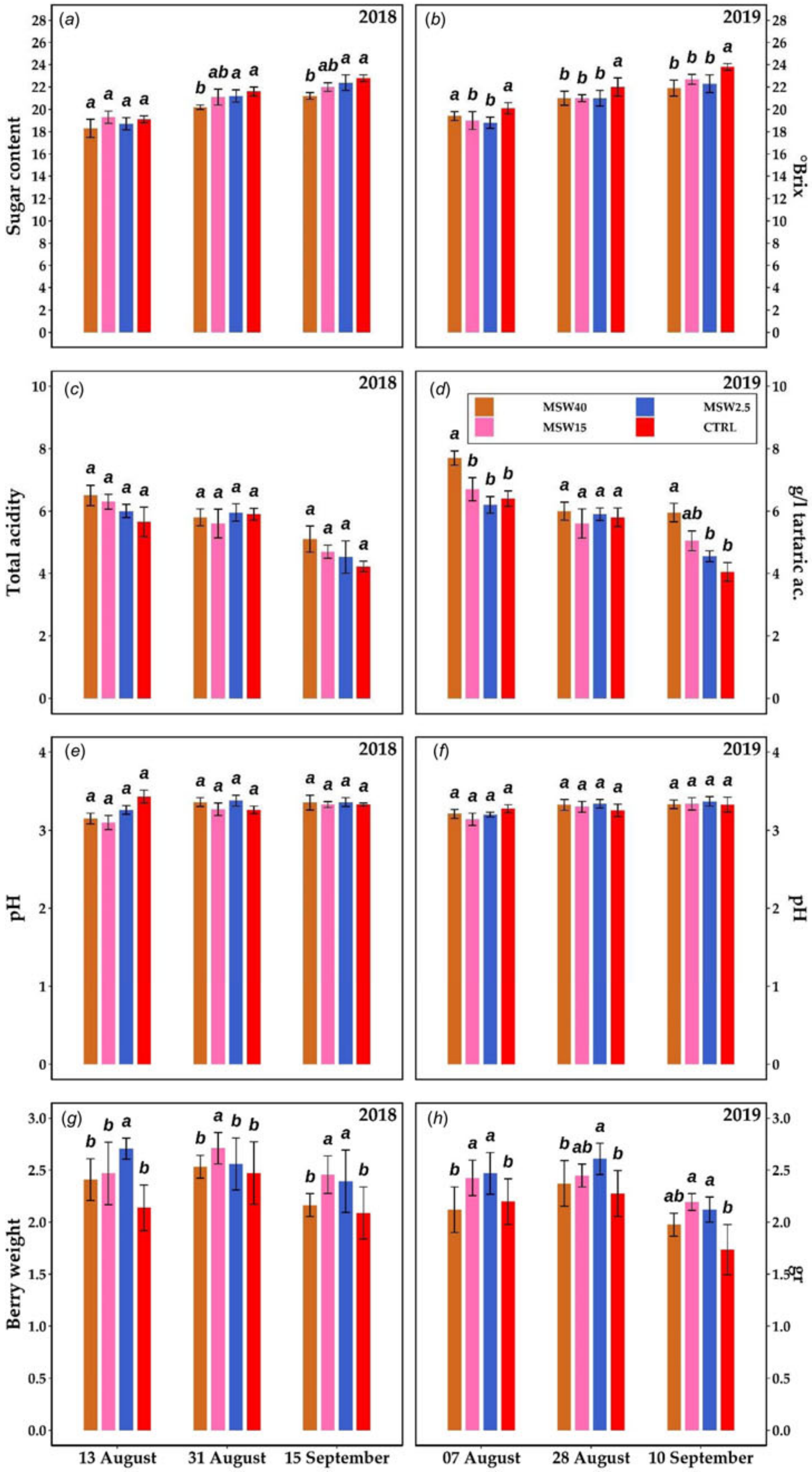

Fig. 3. Colour online. Technological maturity of the grapes. Sugar content (°Brix) (*a*–*b* 2018–2019), titratable acidity (TA) (*c*–*d* 2018–2019), pH (*e*–*f* 2018–2019) and berry weight (*g*–*h* 2018–2019) of Sangiovese berries treated with three compost rates and a control: municipal solid waste compost (40 tons per hectare – MSW40), municipal solid waste compost (15 tons per hectare – MSW15), municipal solid waste compost (2.5 tons per hectare – MSW2.5) and no compost (CTRL). Data (mean ± S.E., *n* = 10) were subjected to one-way ANOVA. Different letters within the same parameter and columns indicate significant differences (LSD test, $P \leq 0.05$).

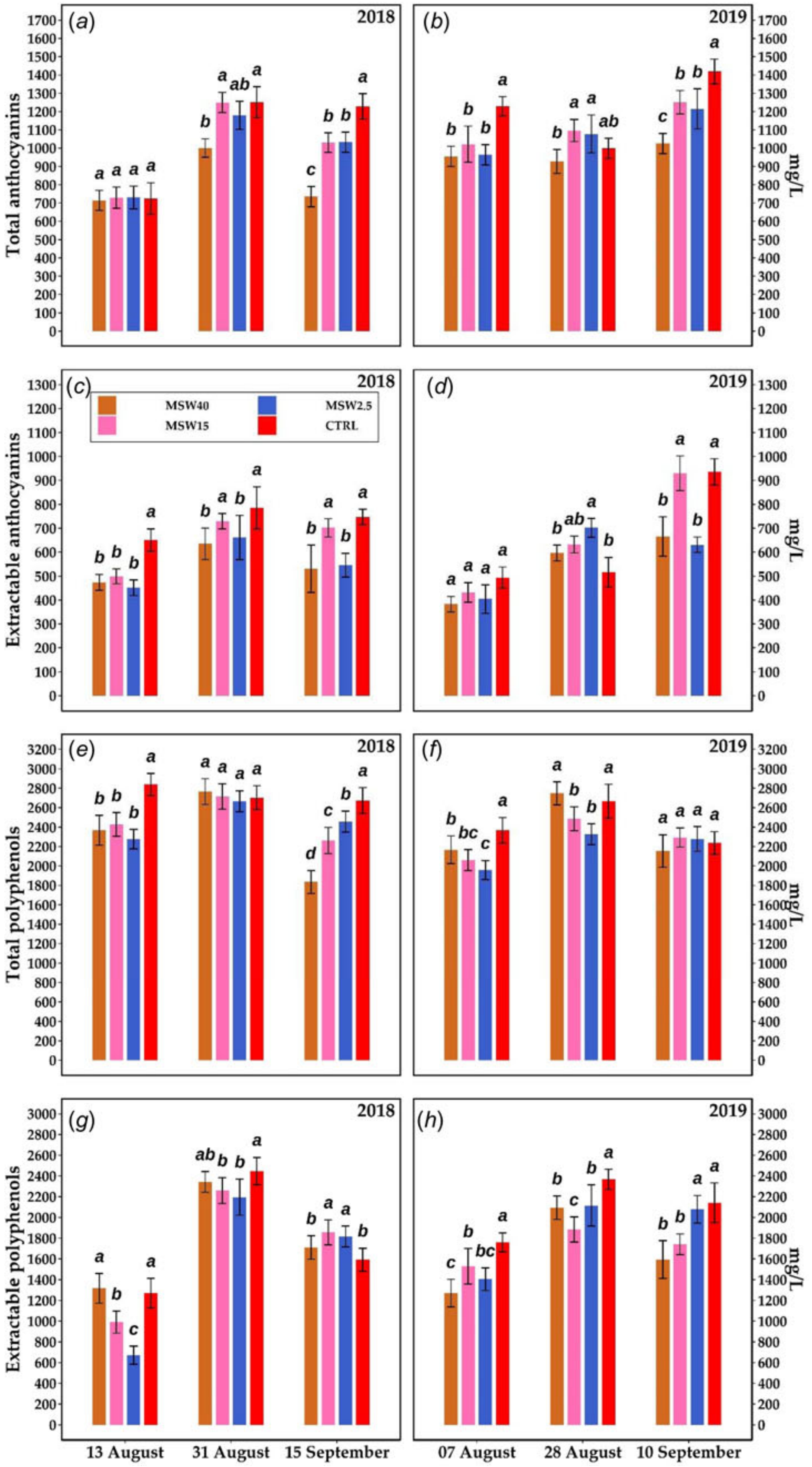

Fig. 4. Colour online. Phenolic maturity of the grapes. Total (*a*–*b* 2018–2019) and extractable (*c*–*d* 2018–2019) anthocyanins, total (*e*–*f* 2018–2019) and extractable (*g*–*h* 2018–2019) polyphenols of Sangiovese berries treated with three compost rates and a control: municipal solid waste compost (40 tons per hectare – MSW40), municipal solid waste compost (15 tons per hectare – MSW15), municipal solid waste compost (2.5 tons per hectare – MSW2.5) and no compost (CTRL). Data (mean ± s.e., *n* = 10) were subjected to one-way ANOVA. Different letters within the same parameter and columns indicate significant differences (LSD test, $P \leq 0.05$).

Table 7. Harvest production data (15 September 2018 and 10 September 2019)

	MSW40	MSW15	MSW2.5	CTRL
2018 – Harvest				
Yield per vine (kg)	3.05 ± 0.41b	4.55 ± 1.85a	4.38 ± 0.73a	3.19 ± 1.55b
No. of bunch	7.6 ± 1.71a	8.00 ± 2.74a	7.90 ± 1.44a	7.60 ± 1.71a
Bunch weight (kg)	0.41 ± 0.06b	0.56 ± 0.13a	0.57 ± 0.15a	0.46 ± 0.25b
2019 – Harvest				
Yield per vine (kg)	2.81 ± 0.38b	4.05 ± 1.22a	3.88 ± 0.89a	2.99 ± 1.16b
No. of bunch	7.00 ± 1.50b	8.00 ± 1.70a	8.00 ± 1.23a	7.60 ± 1.93ab
Bunch weight	0.40 ± 0.05b	0.52 ± 0.13a	0.49 ± 0.14a	0.43 ± 0.23ab

Data (mean ± s.e., $n = 10$) were subjected to one-way ANOVA. Different letters within the same day and rows indicate significant differences among treatments (LSD test, $P \leq 0.05$).

The vines subjected to MSW2.5 and MSW15 treatments benefited from the contribution of compost and showed an increase in the growth of the sprout, similar to the results reported by Machado *et al.* (2021). The amendment had a substantial influence on shoot biomass, which underwent an increase of about 12.53% in 2018 and 14.54% in 2019. A similar effect of promoting biomass accumulation was also observed by Garau *et al.* (2021) on the *Cynara cardunculus*.

The concentration of the leaf element levels was influenced by the treatments, especially in the second year of the experiment. Significant differences were found between soil fertility treatments for Fe, Cu and Zn in treated vines. In the 2 years, the highest rates of MSW compost produced the highest levels of leaf Cu, Fe and Zn.

The fertilizer plots induced less Mn uptake in the plant probably through the effect of fertilizer additions which increased the soil pH and reduced the availability of Mn (Warman *et al.*, 2009). In fact, although the soil type has some influence, exchangeable Mn is generally the dominant below pH 5.2, while at higher pH values Fe-oxide bound forms are dominant (Sims, 1986). As found for tomato crops by Radin and Warman (2011), no significant differences in heavy-metal (Ni, Cr and Cd) tissue concentrations were found among treatments.

From the point of view of net photosynthesis, the treatment with 40 t/ha underwent a decrease in photosynthesis in both seasons compared to the CTRL (−60.00% on 13 August 2018, −32.41% on 15 September 2018, −12.07% on 24 May 2019, −36.64% on 7 August 2019 and −38.16% on 10 September 2019). Probably due to its functions as a reducing (Cu^{1+}) or oxidizing (Cu^{2+}) agent in biochemical reactions, Cu becomes potentially toxic as Cu ions which can catalyse the production of free radicals (Ivask *et al.*, 2010), induce oxidative stress (Thounaojam *et al.*, 2012) and convert as genotoxic substances (Chelomin *et al.*, 2017) altering the process of photosynthesis, transpiration rate and enhancing chromatin condensation and lipid peroxidation (Rajput *et al.*, 2018). MSW2.5 and MSW15 treatments increased the photosynthetic efficiency of the monitored plants probably owing to an increase in all chlorophyll fluorescence indices (Qui *et al.*, 2020), as demonstrated by Srivastava *et al.*, (2018) where a Pn increase of 14–15% was recorded at a 40–100 t/ha application rate, followed by a progressive decline in total chlorophyll content at higher doses (200 or 300 t/ha).

It was found that the addition of MSW compost surcharged the soil water holding capacity without an enhancement in the estimated available water (Mamo *et al.*, 2000). This is in accordance with this study where MSW compost application (2.5 and 15 t/ha) dwindled the water stress in vines. The two intermediate treatments both reduced water stress compared to the control during the hottest days; with the MSW2.5 treatment, there was a reduction of 11.53% on 13 August 2018, 12.58% on 7 August 2019 and 10.32% on 10 September 2019 while with the MSW15 treatment, there was a reduction of 9.02% on 13 August 2018, 15.83% on 7 August 2019 and 8.23% on 10 September 2019. This effect was probably associated with compost incorporation, which increases water retention, carbon mineralization and most enzyme activities (Paradelo *et al.*, 2019).

During 2018, significant differences in maturation and harvest were found in sugar content, whilst during 2019, significant differences in veraison, maturation and harvest were distinguished in sugar content. The CTRL treatment had the highest values compared to all treatments. At the time of harvest, CTRL increased the °Brix by 7.55% in 2018 and 8.68% in 2019 compared to MSW40. We hypothesize that the higher sugar content of control-treated plants was due to their berry size (dehydration accumulation; Jamaly *et al.*, 2021) and to a productive shift towards vegetative growth by the treated vines (Oliveira *et al.*, 2003).

The berry size (enhanced in MSW2.5 and MSW15 treatments) is probably ascribed to the uptake of mineral nutrients upgrade by the grapevines (Ferrara Brunetti, 2010) and to the possible hydration activity enhanced by the best vine water status (Sadras *et al.*, 2008).

No statistical differences were observed in both years for the pH parameter.

Regarding phenolic maturity, differences were found in the composition of total and extractable anthocyanins. In fact, it was demonstrated that the total anthocyanins were directly related to sugars in the must and closely related to the derivatives of peonidin, and the sugars in the skin were closely correlated to each of the anthocyanins and to the other phenolic compounds present in the skin (González-Sanjosé and Diez, 1992). Additionally, phosphate deprivation can enhance the dihydroflavonol 4-reductase (DFR) activity significantly and correspondingly increase anthocyanin accumulation (He *et al.*, 2010). At harvest, CTRL berries showed significantly higher extractable and total anthocyanins content compared to other treatments (2018–19). However, MSW15 treatment noted optimum values compared with a view to quality red winemaking (1250.25 mg/l total anthocyanins and 929.83 mg/l extractable anthocyanins on 10 September 2019).

During the 2019 season, no differences in total polyphenols at harvest were found. At the 2018 harvest, MSW2.5 and MSW15 treatments showed significantly higher extractable polyphenol content, while at the 2019 harvest MSW2.5 and CTRL treatments showed significantly higher extractable polyphenol content compared to the other applications.

Significant differences ($P \leq 0.05$) were found in the production parameters at harvest (Ponchia *et al.*, 2010). MSW15 and MSW2.5 treatments had generally increased the weight of bunches, yield by vine (2018, 2019) and their number (2019) (higher crop production), reducing evaporation and increasing nutrient uptake by plants (Nguyen *et al.*, 2013).

In general, the data were consistent with the climatic trend; the 2018 season was characterized by greater rainfall which could have influenced the increase in production and berry size, creating a dilution effect in °Brix and anthocyanins (lower skin-to-pulp ratio), while the 2019 season was characterized by less rainfall and higher temperatures which led to concentration sugar and colour with less production (higher skin-to-pulp ratio) (Santesteban and Royo, 2006).

Conclusion

Incorrect fertilization is a major threat that could lead to an unbalanced yield in viticultural production. Adaptation and soil management are important to manage the risks and utilize the benefits of climate change. The results of this experiment provide some general insights showing that MSW compost options are expected to reduce water stress, improve vine performance and provide sustainable recirculation of organic matter. MSW compost is a true agronomic and environmental resource. Its application improves the structure and workability of the soil, allowing less energy for ploughing and complementary tillage, increases the water retention capacity of the soil with less energy consumption for irrigation, and improves soil aggregation (lower soil loss due to erosion). The production of compost from the organic fraction of the waste represents an effective recovery of matter, which can be considered a valid tool for a balanced vineyard.

However, more studies are needed in the future to support this strategy given the uncertainties inherent to the market, stakeholders, climate change, long-term soil process dynamics and the multiple interacting factors affecting the agricultural practices.

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