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Composting Waste from the White Wine Industry

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Abstract: The wine industry generates a large amount of waste, and composting is an alternative for recycling these residues with agronomic and environmental advantages. With this aim, grape marc and grape stalks were composted in static and turned piles, with three and six turns, to investigate the effects of pile conditions during composting in order to improve final compost quality. Thermophilic temperatures were attained soon after pile construction, and the highest maximum temperatures were achieved in the turned piles (70.5–71.8 °C). However, pile moisture content decreased below the recommended values after day 42 in these piles. The extremely high temperatures and low moisture content in the turned piles hampered organic matter mineralization rates and the amount of potentially mineralizable organic matter (OM_0) (391–407 g kg^{-1}), whereas the structure of the static pile provided adequate porosity to increase organic matter decomposition and OM_0 (568 g kg^{-1}). This study shows that composting grape marc with stalks, for a period of 140 days, resulted in stabilized and matured compost (NH_4^+-N/NO_3^--N < 0.5) with good chemical characteristics for applications as soil organic amendment, without the need for rewetting or turning the piles, thus reducing the agronomic and environmental cost of the composting process.

Keywords: compost quality; grape marc; grape stalks; organic matter mineralization

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1. Introduction

Mediterranean vineyards are threatened by serious risks of soil deterioration due to loss of organic matter, loss of biodiversity, erosion, fertilizer contamination and compaction [1–3]. In addition, water availability will decrease due to the impact of climate change, which imposes more severe warm and drought conditions on the vineyards [4–6]. Low soil moisture content due to heatwaves during the summer may have serious consequences on the quantity and quality of wines produced [7]. Under this scenario, sustainable soil management practices are crucial to improve soil quality and increase soil water content [8,9].

It is widely recognized that soil influences wine grape quality. Soil biological activity rules the nutrients' availability and influence wine grape composition [10]. For example, excessive nitrogen availability may increase grapevine vigor, leading to loss of grape quality, and influence the amount of yeast in the grapes, which has implications on wine quality [11]. Moreover, soil microorganisms have the potential to colonize the microbial community of the grapes and indirectly influence wine characteristics [12]. Of all soil properties, soil water content has the most influence on vine growth and the subsequent effects on wine quality [10]. The scarcity of water in the soil has a negative impact in photosynthesis, which reduces the weight of the grape and increases the concentration of sugar, phenol compounds and anthocyanins, changing the wine quality traits [13]. Recently, several authors have studied the effect of vineyard compost applications to minimize threats such as extended drought or soil degradation [14,15]. The major role of organic matter in the formation of stable aggregates was described, as well as its effects on water holding capacity, aeration and resistance to root growth [16]. Badalikova et al. [15], for example, reported that bulk density decreased (2–10%) and porosity and soil moisture content consequently increased 2 years after the incorporation of 30 t ha^{-1} compost into the vines in furrows 25–30 cm deep. In addition, to enhance the structure of soils and thereby improve water availability, compost application reduces soil-borne pathogens and increases biodiversity and nutrient use efficiency [2,17].

Composting is defined as a biological process that degrades organic matter under conditions that allow the development of thermophilic temperatures, resulting in a stabilized and sanitized product free of weed seeds and pathogenic microorganisms [18]. The OM degradation depends on the composition of the feedstock, but also on environmental conditions such as moisture content or oxygen levels [19,20]. Excess moisture restricts the oxygen movement, and anaerobic conditions may decrease the speed of composting. For this reason, the moisture content values for efficient composting are in the range of 50–60% [21]. Turning the composting piles during the bio-oxidative phase provides oxygen to the decomposition process, but also increases nutrient losses [22]. For this reason, the construction of composting piles with materials that provide the adequate aeration contributes to decreasing the number of turnings and consequently increases the agronomic value of the compost [20].

Winery waste is a major environmental problem for the wine industry because the winemaking process involves the generation of a significant amount of waste [9,23]. For example, Portugal, with a wine production of 736 ML [24], processes roughly 1030 ML of waste (between 1.3 and 1.5 kg of waste per liter of wine [9]). The primary white winery waste is grape marc obtained after the pressing process. Usually, stalks are separated from the grapes by being fed into a de-stemmer. After pressing, grape marc without stalks have approximately 58% of skins and 42% of seeds (w/w) [25]. Wine lees are produced after the fermentation and clarification steps, and sludge obtained from the wastewater is used for the cleaning process of the wine machinery after being dewatered aerobically in a wastewater treatment plant.

Stalks and sludge may be recycled and valorized through the composting process [26]. Grape marc and lees are considered products with value, and wineries can benefit from distillation to produce ethanol or use them to recover phenolic compounds and extract oil from seeds [27]. However, the potential use of winery waste to produce these substances depends on the market value related to the management cost of the waste from the winery. Disposal may also be a solution depending on the disposal fee [23]. Alternatively, composting has gained interest due to the poverty of many soils in organic matter and susceptibility to erosion, and because of its advantage to minimize mineral fertilization and reduce transportation costs. Moreover, several studies indicated that soil amendment with compost from winery wastes increases soil organic matter content and microbial diversity, providing a slow release of nutrients and high to moderate values of potassium, which is considered a quality factor in vines [28,29]. Therefore, composting can be a suitable way to improve winery waste characteristics and to reintroduce them into the soil according to the principles of a circular economy, which is considered a climate change mitigation strategy [14,23].

Grape marc as a soil amendment shows some disadvantages such as low pH and the presence of phytotoxic compounds such as ethanol and polyphenols which may inhibit root growth [30,31]. However, grape marc is an interesting soil fertilizer due to its richness in potassium and high organic matter content [32]. A suitable option is composting to reduce the presence of phytotoxic compounds [25]. However, the decomposition of grape marc alone may be hampered by the low pH that negatively affects microbial activity [27]. A better option is to mix grape marc with grape stalks to act as a bulking agent and improve the porosity of the composting piles [33]. These authors reported that grape marc and stalks composted in the proportion of 25%:75% (grape marc: stalk, w:w) stayed in the thermophilic phase time enough to satisfy sanitation requirements, achieving a high quality compost.

The Vinho Verde Region located in the NW of Portugal is the largest wine region in Portugal with 16022 ha. Wine tourism has a fundamental role in the development of the Vinho Verde Region, and sustainability is pointed out as being important to improve wine tourism as wine consumers increasingly appreciate environmentally friendly practices [34]. However, the vineyard industry has not implemented strategies to promote a circular approach. Indeed, there is a lack of knowledge in wine industries about the composting process and application of winery waste compost in the vineyards. This requires an additional effort of growers and technical advisers. Therefore, composting experiments at the industrial scale are very important to develop winery waste management strategies. With this purpose, this work aims to investigate the composting process of grape marc with grape stalks, under field conditions, for compost applications in vineyards as soil organic amendments.

2. Materials and Methods

Composting was carried out at Quinta da Torre (42°01′ N; 8°29′ O) from October 2021 to March 2022, with white wine waste from the Anselmo Mendes winery located in the Vinho Verde Region (NW of Portugal). Grape stalks after destemming, and grape marc (skin and seeds) obtained after pressing the juice, were collected in the same container before the fermentation process. At the composting site, this feedstock material was turned over with a backhoe loader to thoroughly mix the grape marc and stalks. Subsequently, three composting piles were built outdoors to approximately 2 m wide, 1.6 m high and 8 m long and covered with TenCate Toptex ®(GEOSIN) to both avoid rainfall and allow gas exchange. The composting process was carried out for a period of 140 days. Composting treatments included turning piles with a backhoe loader after 7, 28 and 56 days (PT3), after 7, 14, 28, 42, 56 and 84 days (PT6) from the beginning of the composting process, and a static pile (PT0). The pile cover was removed 56 days after the commencement of the composting process to allow rain to wet the piles.

Environmental air temperature was automatically measured with a thermistor below a reflector board at 80 cm height and composting pile temperatures were monitored with thermistors placed in the core of three different parts of each pile. The temperatures were recorded every hour with a Data Logger DL2 from Delta Devices. Four replicate samples of each pile were collected for chemical analysis at the start of the process and at 7, 14, 28, 42, 56, 84 and 140 days after the beginning of composting.

Fresh samples were used to determine dry matter content (DM), pH and electrical conductivity (EC) by standard procedures [35]. Mineral N was extracted from 100 g of fresh compost using KCl 1:5 solution, and NH_4^+-N and NO_3^--N content were determined by molecular absorption spectrophotometry with a segmented flow analyzer (SanPlus System, Skalar, Breda, the Netherlands). The samples were dried at 65 °C until constant weight and were subsequently milled using a rotor mill with a 2 mm sieve to determine organic matter (OM), total N, P, K, Ca and Mg. The OM content was determined by the loss of mass at 550 °C for 6 h using a muffle furnace. The C content in the soil was calculated by dividing OM content by a factor of 1.8 [22]. Total N was determined using the modified Kjeldahl method based on a sulfuric acid digestion with a copper selenium catalyst, using a Kjeldahl digestion unit and a compact distillation unit. The total P was measured by UV visible spectrophotometry (UV visible espectro, Thermo Scientific) after digestion with sulfuric acid, and the total K, Ca and Mg were quantified by atomic spectrophotometry (Analyst 200, Perkin Elmer) after nitro-perchloric acid digestion.

The germination test was performed with 5 repetitions according to a modified procedure based on Zucconi et al. [36]. The compost extracts were prepared by shaking a mechanically composted sample with distilled water at a mixing rate of 1:10 w/v for 1 h and then filtering (VWR 413). Radish (*Raphanus sativus* L.) and cress (*Lepidium sativum* L.) seeds were placed in Petri dishes on a layer of filter paper with 5 mL of each compost sample extract. Germination and root length percentage were measured after an incubation period of 96 h at 25 °C. The germination index was calculated by multiplying relative seed germination (%) and relative root growth (%).

Total boron content was determined by Azomthine-H method after being boiled at 550 °C. The heavy metals (Cu, Zn, Pb, Cd, Cr and Ni) were extracted by digestion with aqua regia and measured by ICP-OES method (EN 14084). Total Hg was determined by USA method (EPA 7473). Prevalence of *Salmonella* spp. and *Escherichia* coli were detected according to ISO 6579 and ISO 16649 [37,38], respectively.

Losses of OM and mass reduction were calculated according to Equation (1) [39] and Equation (2) [40], respectively.

$$\text{OM loss } (\text{g kg}^{-1}) = 1000 - 1000\ [x_1(1000 - x_2)]/[x_2(1000 - x_1)] \quad (1)$$

$$\text{Mass reduction } \left(\text{g kg}^{-1}\right) = (1 - x_1/x_2) \times 1000 \quad (2)$$

where x_1 and x_2 are the initial and final ash content (g kg^{-1}), respectively.

The first order kinetic model (Equation (3)) was fitted to OM mineralization determined by the OM lost [39].

$$\text{OM}_\text{m} = \text{OM}_0 \left(1 - \text{e}^{-\text{kt}}\right) \quad (3)$$

where OM_m is the estimated mineralized OM (g kg^{-1} DM) at time t (day), OM_0 is the amount of potentially mineralizable OM, and k is the mineralization constant rate (day^{-1}).

Analysis of variance (ANOVA) was performed using the general linear model procedure. A probability level of p = 0.05 was applied to assess differences between mean chemical characteristics from each composting treatment. All statistical calculations were performed using SPSS v. 17.0 for windows (SPSS Inc.).

3. Results and Discussion

3.1. Temperature

After pile construction, the temperature of the composting material rose quickly due to the rapid breakdown of the readily available OM. All composting piles reached thermophilic temperatures (> 50 °C) in the second day of composting, and these temperatures were maintained for approximately 50 days during the composting process (Figure 1). Turning promoted aeration, increasing oxygen levels and causing microorganisms to improve their activity. Therefore, composting progressed faster and the piles' temperature increased after turning [41]. The maximum temperatures of 70.5 °C and 71.8 °C were registered on day 28 for PT3 and PT6, respectively. The temperature was over 60 °C for 18 days in the turned piles. In contrast, PT0 temperature did not exceed 62.2 °C. The maximum temperatures measured on the turned piles were similar to previous published results with winery wastes [26,42,43]. For example, Carmona et al. [43] registered maximum temperatures between 65 and 73 °C in composting piles with grape marc and grape stalks.

The temperature was above 55 °C at least 31 days in all compost treatments. The sanitation requirements of 28 days at 55 °C with the pile turned 3 times [44] was fulfilled for PT3 and PT6. The temperatures returned to thermophilic values within 1 to 3 days after the turnings on days 7, 14, 28 and 42. However, the lag time period for the temperatures to rise increased to 9 and 13 days after the turnings on days 56 and 84, respectively, because the composting piles became more recalcitrant to decomposition [45]. After the thermophilic phase, the OM became more stabilized, microbial activity decreased and the temperature approached ambient levels approximately 100 days after starting composting, except for PT6, where temperatures remained above ambient air temperature for another month.

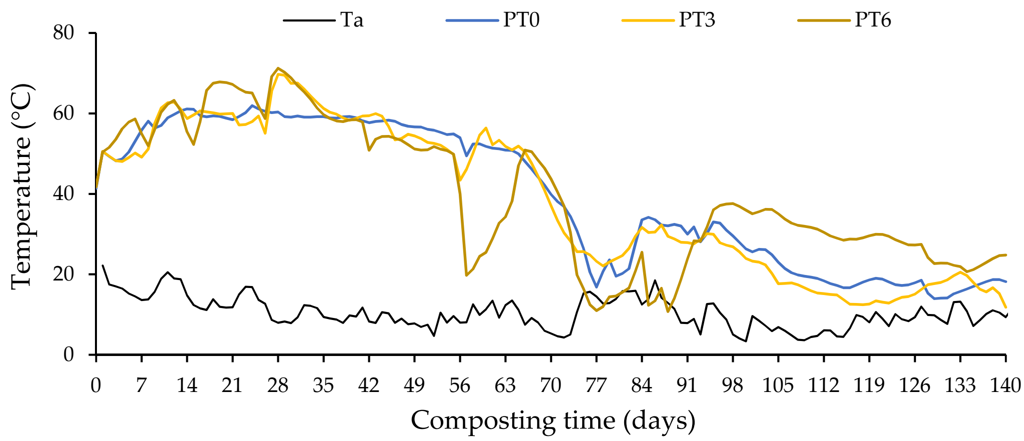

Figure 1. Temperature during composting of grape stalks and grape marc for the static pile (PT0), pile turned 3 times (PT3), and pile turned 6 times (PT6). Ta is the ambient air temperature.

3.2. Moisture Content

The moisture content (MC) was initially slightly above 600 g kg^{-1} in all piles (Table 1), and remained between 487 g kg^{-1} and 621 g kg^{-1} during the composting process in PT0. However, the MC of PT3 and PT6 decreased to 417 g kg^{-1} and 335 g kg^{-1}, respectively, 56 days after composting commencement because of increased evaporative water losses in the turned piles compared to the static piles [46,47]. The wet conditions allowed the MC value for PT0 to persist within an adequate range for optimal composting of 500–600 g kg^{-1} [21] without the need of rewetting. However, the MC in turned piles decreased to values below or near 400 g kg^{-1}, decreasing microbial activity. A similar decrease in moisture content below 400 g kg^{-1} on the turned piles after 60 days of composting was reported when composting the solid fraction of dairy cattle slurry [48]. Therefore, it may be recommendable to reduce pile turning because pile rewetting requires the availability of water resources and increases the process complexity and cost of the turned piles. Moreover, turning increases fossil energy use and may increase the emissions of pollutant gases such as ammonia and nitrous oxide [21,49].

Table 1. Moisture content (MC), pH and electrical conductivity (EC) during composting of grape stalks and grape marc in the static pile (PT0), pile turned 3 times (PT3), and pile turned 6 times (PT6).

Characteristics (Unit)	**Pile**	**Sample Day**							
		0	**7**	**14**	**28**	**42**	**56**	**84**	**140**
MC (g kg^{-1})	PT0	621	581	609	563	611	487	611	567
	PT3	621	638	577	585	481	417	440	422
	PT6	621	606	552	530	439	335	402	408
	LSD	0	17	57	27	66	61	43	13
pH	PT0	3.9	5.3	4.6	5.0	4.4	7.8	8.0	7.7
	PT3	3.9	4.2	4.4	4.4	6.2	6.8	7.8	7.8
	PT6	3.9	5.0	5.5	5.6	7.3	7.7	8.1	8.1
	LSD	0.0	0.7	1.3	0.7	0.8	0.1	0.2	0.1
EC (dS m^{-1})	PT0	2.2	1.8	2.0	2.0	2.7	1.6	1.1	1.5
	PT3	2.2	2,0	1.9	2.1	2.3	1.7	1.6	1.6
	PT6	2.2	2.2	2.2	2.3	2.0	1.7	1.6	1.3
	LSD	0.0	0.2	0.5	0.2	0.4	0.2	0.2	0.1

LSD = least significant difference ($p < 0.05$) between mean values within columns

3.3. pH and Electrical Conductivity

The pH value of the raw material increased during 84 days, probably due to the degradation of organic acid compounds [50] and the degradation of organic N, leading to the formation of amines and ammonia [51]. During the first 42 days of composting, the pH value was generally low, decreasing the risk of NH_3 volatilization during the thermophilic phase of composting [52,53]. After 28 days of composting, the pH value was significantly lower for PT0 compared to PT3 and PT6, probably due to low oxygen levels that delayed the breakdown of organic acids in PT0 [47]. The final pH values were similar for all piles (7.7–8.1), and similar to the pH values reported by other authors after composting grape marc with different biowastes [25,28,33].

High salt concentration may cause phytotoxicity problems on seed germination, seedling emergence and root growth. Therefore, the EC value of compost is important in evaluating the suitability and safety of compost for agricultural purposes. The EC values of the composting piles ranged from 1.3 dS m^{-1} to 2.7 dS m^{-1} during the composting process, with a trend towards a slight decrease in EC after 42 days of composting. This trend may be related to the transformation of OM into humic substances, increasing the cation exchange capacity (CEC) and, therefore, causing a reduction of the EC because it quantifies the non-adsorbed and soluble salts [54]. The final compost EC values (1.4–1.6 dS m^{-1}) were in the range of EC values reported by Patti et al. [55] for grape marc composts from four different vineyards (1.2–2.9 dS m^{-1}), and were well below the maximum value of 3 dS m^{-1} recommended for application to soil [56].

3.4. Organic Matter Decomposition

Organic matter was gradually decomposed and mineralized as the available C and N sources were used by microorganisms to produce energy (60–70%) and to incorporate into their cells (30–40%) [57]. Here, mineralization of OM during composting, determined by the OM lost, was fitted to a first-order kinetic model (Figure 2) used to describe OM biodegradation by numerous researchers [32,39]. This model shows that 60–70% of the total mineralization of OM occurred during the thermophilic period (56 days). The highest OM mineralization rate was found for the static pile (k = 0.0191 day^{-1}). In contrast, the slowest rate of composting (k = 0.0118 day^{-1}) occurred in PT6. Thus, the largest amount of potentially mineralizable OM (OM_0) was found for PT0 (568 g kg^{-1}), whereas for PT3 and PT6, it decreased to 407 g kg^{-1} and 391 g kg^{-1}, respectively.

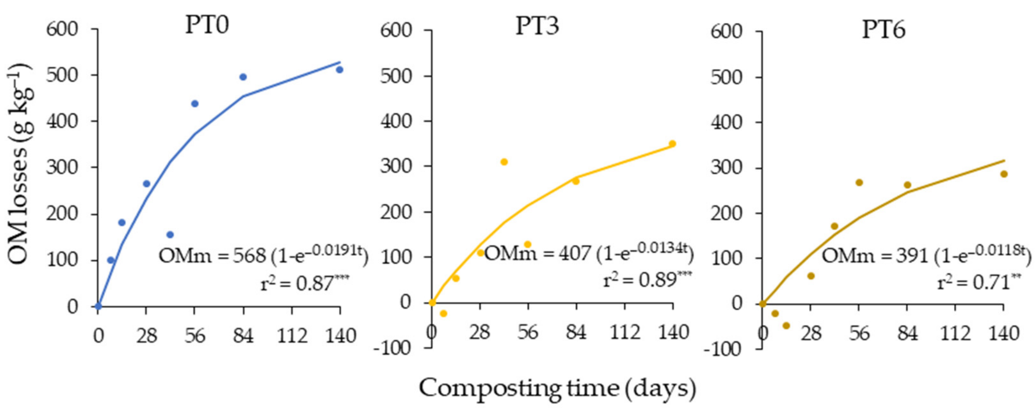

Figure 2. Organic matter (OM) losses (g kg^{-1}) during composting of grape stalks and grape marc for the static pile (PT0), pile turned 3 times (PT3) and pile turned 6 times (PT6). ** $p < 0.01$; *** $p < 0.001$.

After 140 days of composting, the estimated mineralized OM (OM_m) was relatively higher for PT0 (529 g kg^{-1}) compared to PT3 (345 g kg^{-1}) and PT6 (316 g kg^{-1}). Consequently, maximum overall feedstock mass reduction after 140 days of composting was found for PT0 (490 g kg^{-1}), compared to PT3 (317 g kg^{-1}) and PT6 (284 g kg^{-1}).

Although different raw materials with different characteristics such as moisture content and C/N ratio have different effects on OM mineralization rates [58], OM losses are usually above the values found here for PT3 and PT6. For example, OM losses between 520 and 600 g kg^{-1} were found during the co-composting of dairy cattle slurry with straw and gorse [59], and reached 670 g kg^{-1} for cattle manure and 720 g kg^{-1} for pig manure [21]. The lower composting rates found here are explained by the large amount of cellulose, hemi-celluloses and lignin resistant to microbial biodegradation of both grape marc and stalks.

It is commonly accepted that the rate of OM mineralization increases for turned piles compared to static piles because the turned piles have higher oxygen levels, causing the microorganisms to increase their activity [41,53]. However, here, OM mineralization increased for the static pile compared to the turned piles because of the extremely high temperatures during the thermophilic phase of composting and lower moisture content of the turned piles. The temperatures generated during the composting in the turned piles largely exceeded the adequate values of 45–55 °C for maximum decomposition rates [60]. Therefore, slower mineralization rates in the turned piles may be associated with high thermophilic temperatures, which may have caused a reduction in microbial activity [61]. Moreover, Bueno et al. [62] indicated that the OM decomposition is less influenced by the aeration than by the moisture content, and the moisture content of the turned piles, after 42 days of composting (<500 g kg^{-1}), was a limiting factor for the biodegradation of the grape marc residues. These results indicate that the structure of the static pile provided adequate porosity to support aerobic decomposition and to increase the decomposition rates of the feedstock material compared to the turned piles under the climatic conditions of the experimental site.

3.5. Nitrogen Transformations

Total N increased in the composting piles from 15.8 g kg^{-1} to 21.7–22.8 g kg^{-1} after 140 days (Figure 3), which is important from an agricultural point of view in terms of N fertilizer. These results are close to those reported by Bustamante et al. [63] during composting of grape marc with grape stalk (from 14.5 to 23.7 g kg^{-1}). The final N content slightly increased in the static pile (22.8 g kg^{-1}) in comparison to the turned piles (21.7 g kg^{-1}). This increase in N content is explained by increased OM losses in the static pile compared to turned piles because the higher rate of C loss compared to N loss increases final compost N content [57].

The C/N ratio declined from 32 at the beginning of the composting process to values of 21 to 23 in the final composts (Figure 3). It is generally recognized that the final C/N values < 20 indicate that the composts reached an acceptable degree of stability [29,64]. However, the C/N ratio is not always a good indicator of stability because it depends on the type of raw material. In the case of grape marc, which is made up mainly by recalcitrant compounds such as cellulose, hemi-celluloses and lignin [65], a final C/N value for composts greater than 20 is expected because the increased proportion of lignin reduces the availability of organic carbon in the composting process [22]. The relatively high C/N ratio at the beginning of the composting process may have contributed to the retention of NH_4^+ released by OM decomposition [19,21] and to decrease NH_3 volatilization [52,66].

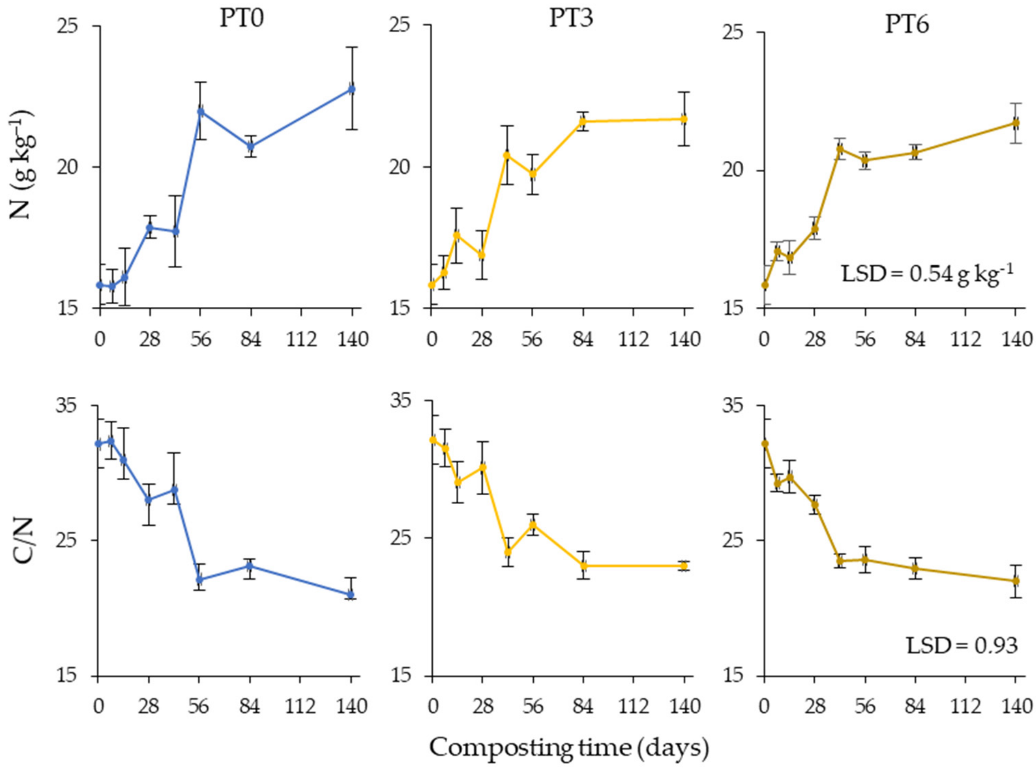

Figure 3. Total N and C/N ratio during composting of grape stalks and grape marc in the static pile (PT0), pile turned 3 times (PT3) and pile turned 6 times (PT6). LSD = least significant difference ($p < 0.05$) between mean values for each characteristic. Vertical bars indicate standard deviation of mean.

The mineral N was only 1.1% of the total N in the raw material. During the thermophilic phase of composting, the NH_4^+-N content increased (Figure 4) due to the transformation of organic N into ammonium N [21,67]. The highest content of NH_4^+-N (314–418 mg kg^{-1} DM) occurred 56 and 84 days after the start of composting in the static and turned piles, respectively. The nitrification was detected by the formation of NO_3^--N approximately 84 days after the beginning of the composting process when the temperature reached approximately 35 °C. Indeed, the nitrification process takes place mostly below 35 °C [51,67] because the nitrifying bacteria are suppressed at temperatures above 40 °C [68]. After 140 days of composting, the lower content of NH_4^+-N (84 mg kg^{-1}) in PT0 compared to the turned piles (222–280 mg kg^{-1}) indicated a more dynamic N transformation in PT0 during the nitrification period (Figure 4). The increased nitrification in PT0 compared to the turned piles may be explained by the reduced moisture content in PT3 (42–44%) and PT6 (40–41%) compared to PT0 (57–61%), which impaired the activity of nitrifying microorganisms [69,70].

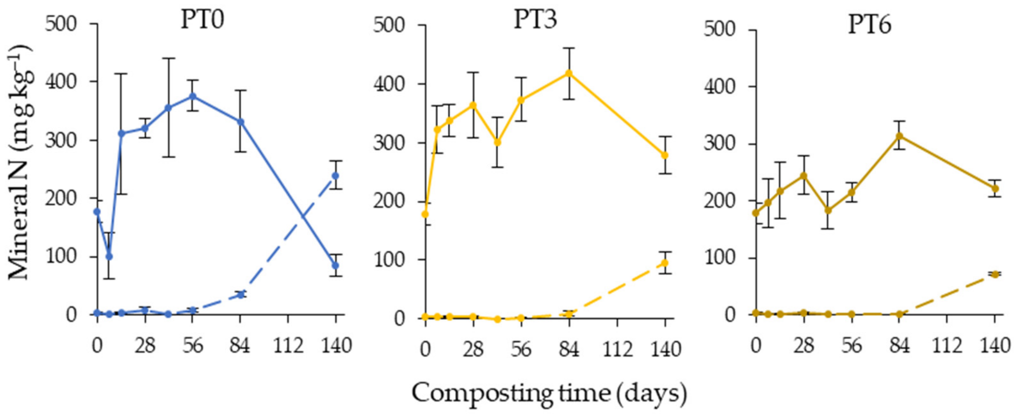

Figure 4. Mineral N contents during composting of grape stalks and grape marc in the pile static pile (PT0), pile turned 3 times (PT3) and pile turned 6 times (PT6). Vertical bars indicate standard deviation of mean.

3.6. Compost Quality

The main criteria for compost quality includes compost maturation and stability, chemical characteristics such as pH, EC, OM and nutrient contents, absence of phytotoxicity, and low levels of toxic compounds such as heavy metals [21]. Compost stability is related to the degree of OM decomposition. Labile organic compounds are degraded and, as composting progresses, other more recalcitrant compounds are partially broken down and humified, leading to the formation of stable compounds responsible for the organic fertility of the soil [71]. Here, final composts showed a high level of stability 140 days after the start of composting, as suggested by the stable temperatures near ambient levels at the end of the composting process [64] in addition to NH_4^+-N contents, which were well below the maximum recommended value of 400 mg kg^{-1} for stabilized composts [72]. However, the lower limit for OM losses of 420 g kg^{-1} recommended for mature composts [73] suggests that whereas composts from PT0 (529 g kg^{-1}) achieved a high degree of stabilization, the same was not true for PT3 (345 g kg^{-1}) and PT6 (316 g kg^{-1}).

The nitrification activity is an important indicator of compost maturation since the nitrifying bacteria are mainly active during the maturation stage [20,66]. Therefore, the ratio NH_4^+-N/NO_3^--N is a useful index of compost maturation, with values under 0.5 indicating mature composts [74]. Here, the ratio NH_4^+-N/NO_3^--N below the upper limit value of 0.5 was only achieved for the static pile (0.35) 140 days after composting because the OM mineralization in the turned piles was delayed compared to the static pile.

The presence or absence of phytotoxic compounds on composts is usually assessed by germination tests that quantify seed growth [71]. Several types of seeds have been used in germination tests, with cress being the most common [75]. Conversely, Komilis et al. [76] studied the interaction between different types of seeds and composts and concluded that a germination test with radish is a valid test to assess compost stability and phytotoxicity. Here, two germination tests were set up with cress and radish to assess the presence of phytotoxic compounds on grape marc compost (Table 2). Differences between PT0, PT3 and PT6 on relative seed germination (RSG), relative root growth (RRG) and germination index (GI) with cress or radish were not significant, except for radish RSG between PT6 and PT0. The GI above 80% found for composts with cress indicated the absence of phytotoxicity [36]. These results are in agreement with [25], who found GI values over 80% with grape marc compost with or without stalks during a bioassay with cress. In contrast, the high GI (113–118%) found for composts with radishes indicated a beneficial effect on seed growth, which is in line with Moldes et al. [25], who found GI values above 125% for composted grape marc with or without stalks during a germination test with rye grass seeds. Therefore, the metabolic degradation of the phytotoxic compounds of grape marc such as ethanol, acetic acid or lactic acid during composting enables the grape marc to be used as soil fertilizer, unlike the raw grape marc [25]. Moreover, the absence of *Salmonella* spp. evaluated in 25 g compost samples and the counting of *Escherichia coli* < 1000 UFC g^{-1} meet the sanitation requirements for the final composts [44].

Table 2. Relative seed germination (RSG; %), relative root growth (RRG; %); and germination index (GI; %) of final composts.

		RSG (%)	RRG (%)	GI (%)
Cress	TP0	101	86	87
	TP3	94	87	82
	TP6	102	78	82
	LSD	11	24	24
Radish	TP0	96	118	113
	TP3	102	113	115
	TP6	106	118	125
	LSD	7	17	20

GI (%) = RSG (%) × RRG (%).

Final compost nutrient contents (Table 3) indicate nutrient rich composts similar to values previously reported for winery waste composts by other authors [28,55,77]. This, in addition to high compost OM content (860–884 g kg^{-1}), suitable pH value (7.7–8.1), low electrical conductivity (1.35–1.58 dS m^{-1}) and low heavy metal contents (Table 4) below the Portuguese and the European limits established for compost [44,78], indicates good quality compost. The humified nature of mature compost that promotes water retention and the slow release of N, and the balance between nutrients in the final grape marc composts, suggests their suitability as soil amendments for vineyards [26,79]. However, it is crucial to ensure a suitable moisture content during the composting process that does not harm microbial activity and, consequently, does not slow down the composting process.

Table 3. Chemical characteristics of final composts.

Pile	OM	N	C/N	NH_4^+-N	NO_3^--N	P	K	Ca	Mg
	(g kg^{-1})	(g kg^{-1})		(mg kg^{-1})	(mg kg^{-1})	(g kg^{-1})			
PT0	860	22.8	21	84.1	239.7	4.3	24.5	6.7	2.3
PT3	884	21.7	23	279.7	96.2	3.5	20.9	6.6	2.1
PT6	869	21.7	22	221.8	71.4	3.5	24.9	5.3	2.2

Nutrient content is expressed on a dry matter basis.

Table 4. Heavy metal content of final composts.

Pile	B	Cu	Zn	Pb	Cd	Cr	Ni	Hg
	(mg kg^{-1})	(mg kg^{-1})	(mg kg^{-1})	(mg kg^{-1})	(mg kg^{-1})	(mg kg^{-1})	(mg kg^{-1})	(mg kg^{-1})
PT0	24.0	46.9	21.8	0.27	0.11	1.85	0.66	0.003
PT3	22.9	45.7	20.7	0.28	0.15	1.88	0.64	0.003
PT6	25.2	38.7	23.3	0.31	0.12	4.93	1.52	0.003
*LVR	-	100	200	100	0.7	100	50	0.7

Nutrient content is expressed on a dry matter basis. *LVR: limit values allowed by Portuguese regulation [44].

4. Conclusions

The mixture of grape marc with grape stalks has sufficient structure and porosity to support aerobic composting activity on an industrial scale without the need for turning strategies or rewetting. Maximum rates of organic matter destruction were found for static piles compared to turned piles because the high thermophilic temperatures (>65 °C) and low moisture content (<500 g kg^{-1}) in the turned piles hampered organic matter decomposition. This compost, produced with minimal intervention, was stabilized and matured, rich in nutrients, has good chemical characteristics and is suitable for application as an organic soil amendment to improve soil fertility according to circular economy principles. This is particularly relevant for wine producers to implement strategies to reduce the complexity and cost of the composting process with agronomic and environmental benefits.

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