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A Comparison of Static Aeration and Conventional Turning Windrow Techniques: Physicochemical and Microbial Dynamics in Wine Residue Composting

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Abstract: Chile, one of the top global wine producers, produces a significant quantity of grape pomace waste, composed primarily of peels and seeds, of which their management includes many environmental challenges. Composting offers a sustainable waste management solution, converting organic waste into a rich nutrient and beneficial microorganisms for soil amendment. This study compared traditional turning and static forced aeration composting systems using a mix of grape pomace (70 m^3), wheat straw (15 m^3), and manure (15 m^3). The results show no significant differences in the final compost chemical quality between the two systems. Nevertheless, forced aeration (T1) influenced the bacterial community, particularly during the thermophilic stage, leading to a major differentiation compared to traditional composting (T0). Similar Shannon index values for bacterial diversity across stages suggest that both composting methods support comparable levels of bacterial diversity. However, the fungal communities exhibited more variability, likely due to the differences in temperature and aeration conditions between the windrows, which are known to affect fungal growth and activity. While both composting methods met the Chilean regulatory standards and achieved high-quality compost, the forced aeration system demonstrated advantages in temperature control, microbial diversity, and pathogen suppression, suggesting its potential for more efficient composting in similar agricultural contexts.

Keywords: composting; forced aeration; wine residues; microbial communities; wine industry

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1. Introduction

Grape wine is one of the most popular alcoholic drinks worldwide, with Chile being among the ten largest wine producers around the world, producing around 1200 million liters of wine in 2023 [1]. The regions of Maule and Libertador Bernardo O'Higgins alone

account for 72% of the country's wine producing area [2]. This high level of wine production also generates considerable environmental impacts due to the accumulation of winemaking residues, primarily grape peels and seeds, which constitute approximately 20% of the processed grapes [3]. Currently, this waste is poorly managed and often ends up in landfills, where it undergoes anaerobic degradation, emitting greenhouse gases and contributing to global warming [4].

Organic agriculture emphasizes environmental respect by utilizing natural products and reducing the use of agrochemicals, aiming to minimize pollution and the exploitation of non-renewable resources [5]. Soil management, fertilization, conservation, and fertility management are principles of organic production designed to enhance crop resistance to pests and diseases [6]. Among the techniques used in organic agriculture, composting is one of the most efficient options for the revalorization of biowastes [7]. Composting refers to the natural decomposition of organic matter by establishing optimal parameters for the process such as moisture content, carbon-to-nitrogen ratio (C/N), pH, and temperature [8]. This process transforms organic waste into compost through the action of microorganisms, a natural soil amendment that provides nutrients, organic matter, and microorganisms beneficial to both soil and vineyards [9]. The composting process facilitates the microbiological decomposition and stabilization of organic substrates under aerobic conditions, with specific parameters such as humidity and temperature, that allow microorganisms to degrade organic matter into a stable, pathogen-free compost with a diverse microbiological population [2,10,11].

The composition of the initial raw materials for compost needs specific physicochemical characteristics, such as an ideal C/N for the development of an efficient microbial community and a balanced porosity to ensure good oxygenation and moisture distribution throughout the process [4]. Humidity plays a crucial role in the microbiological activity of the process, which diminishes when moisture levels fall below 40% of the total pile volume. Conversely, excess humidity or poor porosity can hinder oxygen transfer, reducing aerobic microbial activity [12]. pH is also an essential parameter, affecting microbial presence and serving as an indicator of anaerobic conditions. Thus, the pH of the composting process should be within an optimal range [2,13].

The composting process is divided into four main stages, mesophilic, thermophilic, stabilization, and maturation, each defined by their differences in temperature [14]. In the mesophilic stage, microorganisms begin to biodegrade organic matter, excluding complex molecules like lipids [15]. The decomposition activity generates energy that is released as heat, increasing the temperature. The thermophilic stage, characterized by high temperatures, involves thermophilic organisms degrading fats, proteins, and sugar molecules, This rise in temperature (above 70 °C) eliminates pathogenic microorganisms [11,16,17]. There is also high oxygen consumption due to high microbial activity [18]. During the stabilization stage, as the temperature drops, mesophilic microorganisms reappear, completing the decomposition of remaining biodegradable matter [19]. In the maturation stage, microbial activity decreases, and the compost temperatures return to ambient levels [20].

Throughout the composting process, various groups of microorganisms, including bacteria, actinomycetes, fungi, and protozoa, play significant roles, varying in abundance during different stages [21]. During the decomposition phase, diverse populations of fungi and bacteria break down organic matter, raising the temperature of the windrows and allowing thermophilic microorganisms to thrive [20]. During the thermophilic stage, the increase in temperature activates resistance mechanisms, leading them to form spores [22], as the temperature decreases at the end of this phase, most microorganisms return to their active forms along with the addition of protozoa, myriapods, nematodes, etc. [21], initiating the compost maturation phase [20].

This is a low-cost and environmentally friendly method, emerging as a highly useful technique for agricultural waste management [23]. Among the available approaches, two main composting systems are commonly used: the traditional windrow method with material turning and the forced aeration system. The windrow technique is the most basic and also the slowest, relying on periodic turning to maintain adequate aeration, especially in the center of the pile [8]. This method requires specialized machinery for large-scale turning. In contrast, the composting system with forced aeration involves active ventilation and temperature monitoring through a fan and corrosion-resistant piping systems beneath the pile to distribute the air [24]. This system uses static [25] or can be integrated with periodic turning to improve aeration, humidity, texture, and microorganism distribution [26].

Windrow composting with forced aeration offers an effective solution for managing large volumes of agro-industrial waste under controlled conditions, producing high-quality compost for vineyards in a shorter timeframe. However, its implementation depends on the costs of setup, maintenance, and process optimization [24]. Studies have shown that aeration systems significantly influence temperature increase, often leading to substantial water loss—an important limitation of this method [24]. Recent research, however, suggests that lower aeration rates may improve microbial activity and reduce moisture loss by maintaining more stable temperatures [25,27].

Previous studies have demonstrated the effectiveness of composting with forced aeration systems and explored their impact on temperature and moisture dynamics [24,25]; furthermore, there is limited research evaluating their performance specifically in the composting of wine industry residues. Moreover, most studies focus on optimizing aeration parameters, but few compare the overall compost quality and microbial composition between static forced aeration systems and traditional turning methods. Consequently, the objective of this study is to compare two composting systems by assessing whether a static forced aeration system may reduce composting time by achieving comparable physicochemical quality while enhancing beneficial microbial populations and reducing pathogenic microorganisms in the final compost produced. This research provides valuable insights for optimizing sustainable waste management in viticulture with potential applications in large-scale organic farming systems.

2. Materials and Methods

2.1. Raw Materials

The composting windrows were assembled at Las Palmeras, Nancahua, region Libertador Bernardo O'Higgins (S 34°40′29.1″; W 71°12′10.5″), property of Viñedos Emiliana S.A during the 2022. The physical and chemical analyzes were carried out in the laboratory of Biotechnology of Natural Resources (CENbio) of the Catholic University of Maule. The material to be composted (grape pomace, straw, and manure) were provided by Viñedos Emiliana, and the chemical properties are shown in Table 1. The microbiological analyzes were carried out at the Concha y Toro Viña Research and Innovation Center (CII).

Table 1. Chemical characterization of the initial wine residue mix with the average value of each chemical with their corresponding standard error.

Treatment	pH	Organic Matter (%)	C/N	NH_4/NO_3	N (%)	P_2O_5 (%)	K_2O (%)	NH_4 (mg/kg)	NO_3 (mg/kg)
T0	5.9 ± 0.2	78.6 ± 1.2	27.2 ± 2.3	3.1 ± 0.7	1.6 ± 0.1	1 ± 0	2.7 ± 0.1	425 ± 76	142 ± 10
T1	5.6 ± 0	82.6 ± 0.7	28.0 ± 1	2.3 ± 0.2	1.6 ± 0	0.9 ± 0	2.6 ± 0	353 ± 57	151 ± 30

2.2. Composting Process and Experimental Design

Two composting windrows, each with a volume of 100 m^3, were established for the experiment. The first windrow (T0 or control) followed traditional composting with monthly turning, while the second windrow (T1) utilized a static forced aeration system. The pipes for the forced aeration system were covered with a layer of wheat straw to prevent the clogging of ventilation pores. The initial raw materials were then mixed and evenly divided between the two windrows. The composition of each windrow was 15 m^3 of manure, 15 m^3 of wheat straw, and 70 m^3 of red wine pomace (Figure 1). Throughout the experiment, both windrows were covered with a semipermeable TOPTEX fabric (Figure 1). To monitor the temperatures of the T1 windrow, three sensors of different lengths were placed in the windrows, providing real-time measurements that could be accessed remotely through a virtual interface provided by Ewon [28]. In contrast, the T0 windrow's temperatures were obtained with a thermometer (TEL-TRU), with an average of 6 readings each 15 days, 2 readings for each sector within the stack (top, middle, and bottom). Each treatment (T1 and T1) pile had a width ranging from 4.5 to 4.7 m, a height from 1.7 to 1.8 m, and a length of approximately 13.2 m. For each treatment, piles were divided into 3 different sections equivalent to the three replicates (R1, R2, and R3) (Figure 2).

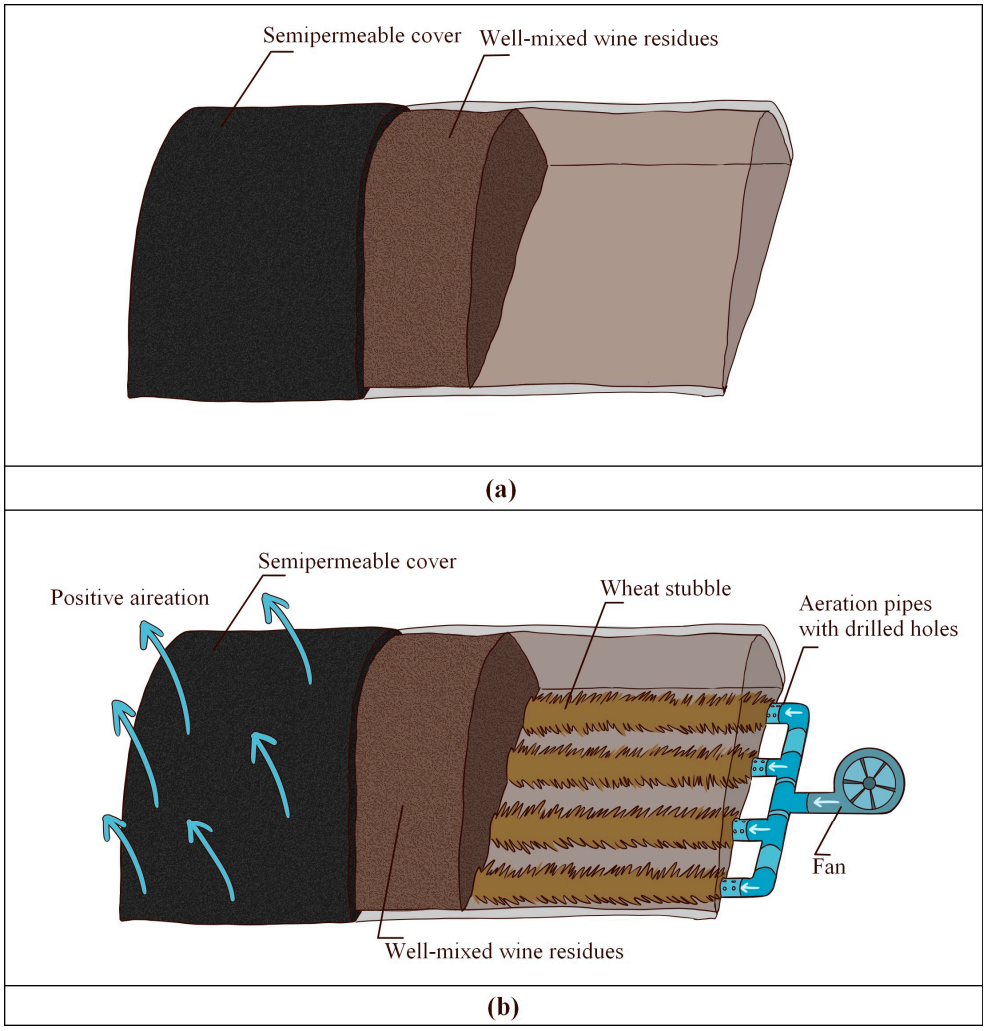


Figure 1. Internal construction of both windrows. (**a**) Conventional turning windrow (T0) and (**b**) static forced aeration compost windrow (T1). The semipermeable cover permits the flow of air through the pile, when the fan is pumping air through the aeration pipes, which have holes for the air to flow, while the wheat straw protects the aeration pipes from clogging with percolates.

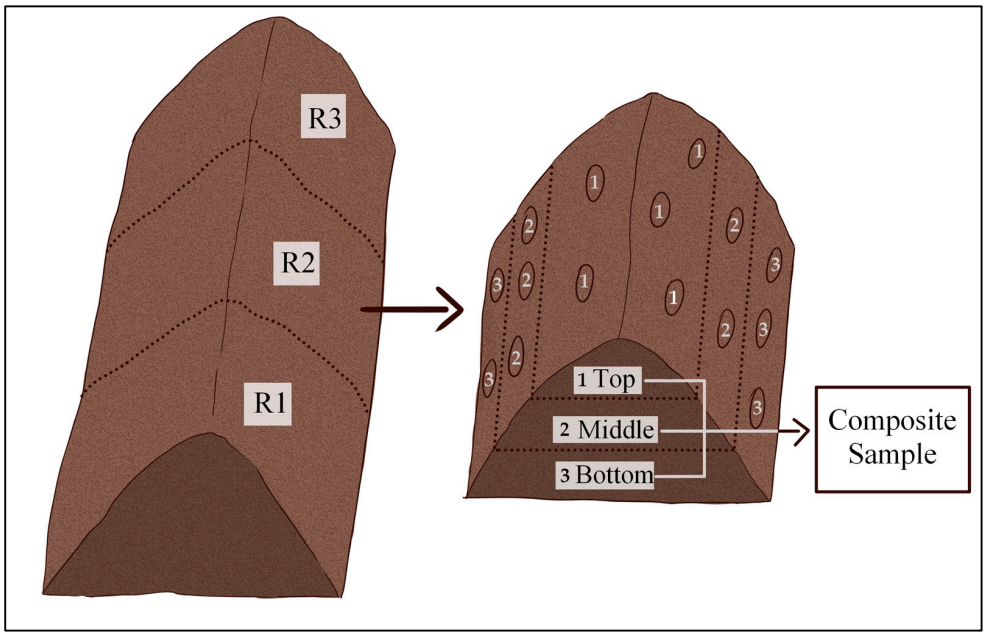


Figure 2. Sampling process for each replicate (R1, R2, and R3) for both treatments (T0 and T1).

2.3. Sampling

The sampling protocol followed the Chilean Composting Standard 2880 [29] based on the TMECC method [30], with modifications. Each windrow was divided into three sectors (R1, R2, and R3), and 5 holes were dug from the top, middle, and bottom of the pile, obtaining 15 subsamples per replicate. (Figure 2). A common container (20 L plastic bucket) was used to collect subsamples, which were mixed thoroughly with a shovel. A composite sample of 1.5 kg was extracted from this mixture for physicochemical analysis for each replicate. Four physicochemical analyses for each replicate were conducted for each treatment at different stages of the process: initial or stage 1 (day 0), thermophilic or stage 2 (day 62), final forced aeration or stage 3 (day 125), and beginning of the late mesophilic or stage 4 (day 232). We obtained a total of 36 samples, which were stored at 4 °C and −80 °C for chemical analysis and microbiological analysis, respectively. In addition, during the last two stages, the chemical analyses were complemented with a SOLVITA test, which measures CO_2 and NH_3 (ammonia) emissions from compost samples using colorimetric gel paddles to determine compost maturation [31].

2.4. Physicochemical Analysis

Similarly to Echeverría et al., 2024 [11], the physicochemical properties, such as bulk density, temperature, electrical conductivity (EEc), pH, organic matter (OM), C content, N content, C:N ratio, ammonium and nitrate (NH_4 and NO_3) contents, NH_4:NO_3 ratio, P, and K, were analyzed for each of treatment at each stage according to the test method for the examination of composting and compost [30]. In summary, EEc was measured in an aqueous extract from a 1/5 mixture of compost and distilled water at ambient temperature; OM was calculated from the values for the combusted solid material and the original oven-dried sample; C was calculated based on the OM fraction; N was obtained by using the classical Kjeldahl procedure; NH_4 and NO_3 were estimated by colorimetric methods; and P and K were determined using inductively coupled plasma (ICP). Compost maturation was evaluated using the Solvita test [31]. Statistical analyses were performed with InfoStat software (https://www.infostat.com.ar/), using a Kruskal–Wallis test with a significance level of 0.05; this method was used due to the low number of replicates of each treatment.

2.5. DNA Extraction and Sequencing

The samples for microbiological analysis were stored at −80° C. DNA extraction was carried out following the protocol of the DNeasy PowerSoil Pro kit [32], homogenizing the samples, and 500 mg was resampled for DNA extraction and subsequent sequencing. The quality of the DNA obtained was measured using the NanoQuant plate. Subsequently, the samples were sent for the amplicon sequencing of the V3–V4 region of 16 s rRNA genes for the bacterial community using the primers 341f (CCTACGGGNGGCWGCAG) and 805r (GACTACHVGGGTATCTAATCC). For the fungal community, the ITS primers ITS1F (CTTGGTCATTTAGAGGAAGTAA) and ITS2R (GCTGCGTTCTTCATCGATGC) were used.

2.6. Microbiological Data Processing

The QIIME.V.2 software [33] was used to clean the raw sequences and perform a taxonomic assignment using the UNITE database ver_9 dynamic (29 November 2022) [34,35] for ITS fungi and SILVA 138-SSU-NR99 [36,37] for 16S bacteria.

A literature review was conducted to classify the microbial genera (bacteria and fungi) as either beneficial or pathogenic. This database was used to classify the microorganisms sequenced from the compost samples, yielding the total number of beneficial and pathogens microorganisms present in the sequenced compost samples.

Bioinformatics analysis was performed using the PRIMER 6 software [38], evaluating the differences between the composting systems and their stages. The bacterial count data were normalized using a fourth root to mitigate the effect of extremely high values. Sample similarity was calculated using the Bray–Curtis algorithm and used for cluster analysis, grouping the samples according to common patterns. Non-metric Multidimensional Scaling (nMDS) was employed to visualize the similarity between the samples in a 2D graph, where the distances represent the degree of similarity based on the similarity table. Finally, a multivariate permutational analysis of variance (PERMANOVA) was performed to analyze the differences between microbial communities across the different treatments, considering the factors "Aeration type" and "Stage" of the composting process. Total diversity was also evaluated using the Shannon–Wiener index with a Log(e) base.

3. Results

3.1. Physicochemical

Temperature monitoring showed that the T1 windrow, which utilized forced aeration, maintained temperatures approximately 13% higher than the T0 windrow until the aeration system was removed on day 125 (Figure 3). Both windrows experienced a decrease in moisture content, reaching around 30% by the end of the experiment (Figure 4a). The pH levels in both treatments increased significantly 60 days after the composting process began, exceeding pH 7.5 (Figure 4b). By day 232, the SOLVITA test indicated that the substrate in both windrows had entered the stabilization phase.

The pH analysis showed similar trends for both windrows, but with large differences in temperatures. Temperatures for T1 consistently were between 60 °C and 70 °C from day 33, while T0 only reached these temperatures by day 84 (Figure 3). The highest pH readings were recorded on day 64, with T0 reaching 7.64 and T1 reaching 8.57 (Figure 4b).

Bulk density increased in both windrows (Figure 4c) as the composting process progressed, which is consistent with observations from other studies [24,39–41].

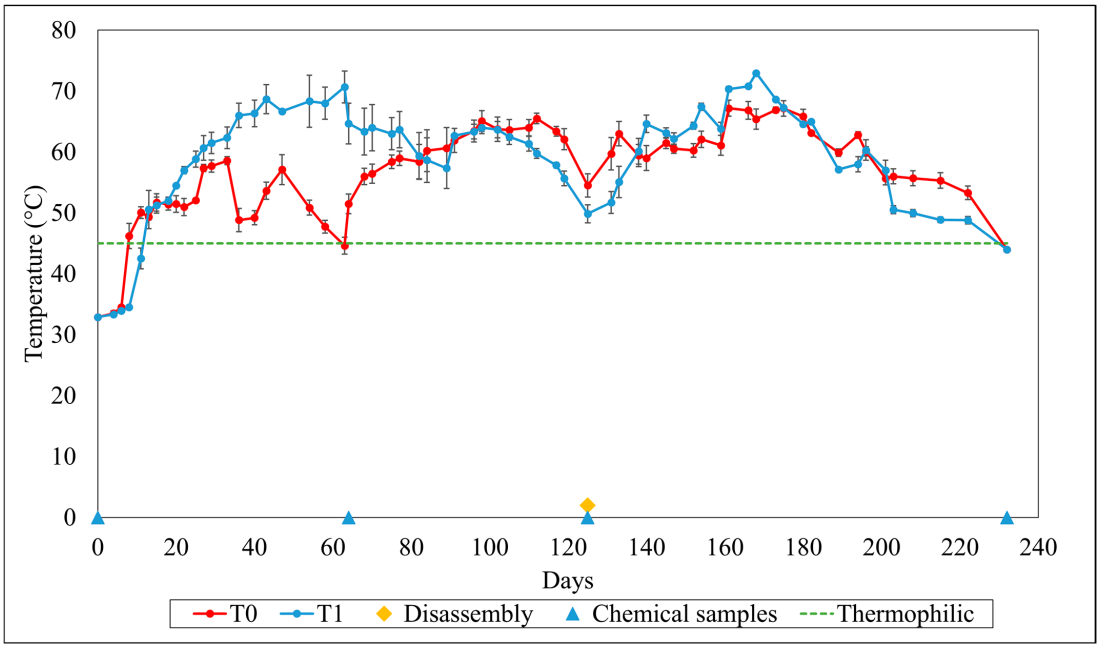


Figure 3. Temperature trend of each treatment throughout the composting process. Each point represents the average of triplicate values; the standard error ranged between 0 and 3.9. Triangles indicate the times of sample collection, and the diamond indicates the disassembly of the forced aeration system.

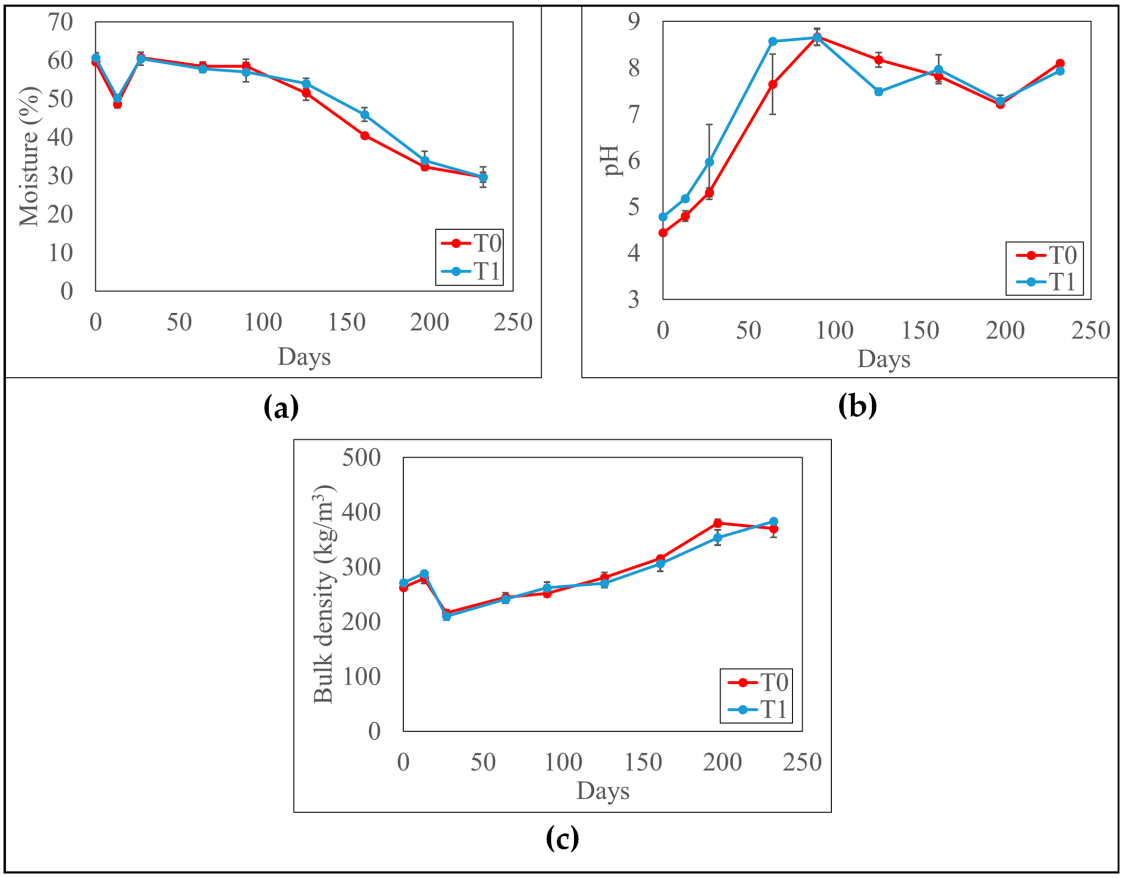


Figure 4. Changes in the physicochemical properties of compost over time. (**a**) Percentage of moisture content. (**b**) pH level. (**c**) Bulk density of the windrows. The error bars show the standard error of triplicate measurements for each treatment. Each sampling point has its respective standard error.

The compost produced by both systems met most of the parameters established by the Chilean Composting Standard 2880. The nitrogen reached 2.5% in T0 and 2.4% in T1 (Table 2). Moisture content remained above 30% (Figure 4b), and the C/N ratio was below the maximum limit of 30, with values of 12.7 and 13.5 for T0 and T1, respectively. The pH level stayed within the acceptable range of 5.5 to 8.5, with values of 8.1 for T0 and 7.63 for T1. Additionally, the organic matter content surpassed the required 20% of the compost Chilean standard, showing an increase in both treatments—56.17% in T0 and 58.33% in T1—indicating the degradation of the raw materials during the process. However, the NH_4^+/NO_3^- ratio exceeded the standard limit of $\leq$3, with values of 3.3 for T0 and 5.3 for T1 (Table 2). The ammonium (NH_4^+) concentration in T0 complied with the standard of $\leq$500 mg/kg, reaching 459.7 mg/kg. In contrast, the concentration in T1 was slightly higher than the recommended limit, at 575.3 mg/kg. Although these differences were observed, the Kruskal–Wallis statistical analysis did not show significant differences between the two treatments in each phase (Table 2).

Table 2. Results of the average (with standard error) of the chemical analysis of the treatments throughout the composting process during the different phases of the process (M: mesophilic; T: thermophilic; S: stabilization; and L: maturation); error bars represent the average of triplicates. No statistical differences were found between treatments in each phase.

P	T	pH	C:N	N (%)	P (%)	K (%)	NH_4 (mg/kg)	NO_3 (mg/kg)	NH_4:NO_3
M	T0	6 ± 0.2	27.2 ± 2.4	1.6 ± 0.2	1 ± 0.1	2.8 ± 0.1	452.7 ± 76.6	142 ± 10.7	3.1 ± 0.8
	T1	5.7 ± 0.1	28 ± 1.1	1.6 ± 0.1	0.9 ± 0	2.6 ± 0.1	353.7 ± 57.7	151 ± 30.8	2.4 ± 0.2
T	T0	9.1 ± 0.1	24.3 ± 2.4	1.7 ± 0.1	1 ± 0.1	2.2 ± 0.1	374.7 ± 33	237 ± 8.9	1.6 ± 0.2
	T1	8.9 ± 0.1	18.9 ± 0.4	2.2 ± 0.1	1.1 ± 0.1	2.9 ± 0.2	482.3 ± 48.5	305.3 ± 16.6	1.6 ± 0.3
L	T0	8.7 ± 0.1	15.3 ± 0.6	2.4 ± 0	1.5 ± 0	3.1 ± 0	460.7 ± 98.2	243.7 ± 25.4	1.9 ± 0.4
	T1	8.5 ± 0.1	17.1 ± 1.5	2.3 ± 0.1	1.2 ± 0.1	3.1 ± 0	328.3 ± 31.4	242.7 ± 13	1.4 ± 0.2
S	T0	8.1 ± 0.1	12.7 ± 0.2	2.5 ± 0	2 ± 0.1	3.1 ± 0.1	459.7 ± 24.8	142.3 ± 14.4	3.3 ± 0.6
	T1	7.9 ± 0.1	13.5 ± 0.5	2.4 ± 0	1.9 ± 0	3.1 ± 0.1	575.3 ± 73.2	113 ± 12.5	5.3 ± 1.2

3.2. Microorganisms

The Shannon index showed similar bacterial diversity across the four stages, while the fungal community exhibited a high dominance (low evenness) and less diversity at the initial stages (Table 3).

Table 3. Shannon index (H' loge) for bacterial and fungal communities along the composting process for both treatments. T0—traditional composting; T1—forced aeration system, through the four stages of composting: mesophilic (S1), thermophilic (S2), stabilization (S3), and maturation (S4).

Treatment	Bacteria	Fungi
T0S1	4.59 ± 0.01	0.54 ± 0.31
T1S1	4.68 ± 0.07	0.70 ± 0.10
T0S2	4.57 ± 0.25	2.50 ± 0.37
T1S2	4.38 ± 0.42	2.32 ± 0.67
T0S3	4.43 ± 0.28	2.27 ± 0.41
T1S3	5.09 ± 0.16	1.94 ± 0.16
T0S4	4.49 ± 0.48	1.75 ± 0.31
T1S4	4.33 ± 0.38	1.95 ± 0.65

Significant differences in the composition of the bacterial and fungal community were detected between the windrows in stages 2 and 3 (PERMANOVA, $p < 0.05$). However,

no significant differences were observed in stage 4 for both groups, indicating similar community composition through the thermophilic stage (Figure 5). *Acetobacter* was the only pathogenic bacteria found in small quantities at the initial stage; however, it was not detected during the rest of the composting stages (Figure 6a). Noticeable high quantities of beneficial bacteria, such as *Bacillus* and *Ureibacillus* followed by *Streptomyces* and *Pseudomonas*, were identified along the entire process (Figure 6a). Pathogenic fungi such as *Penicillium* was found in small quantities (<1%) along the different composting stages and treatments; however, in the forced aeration system, it was detected in even smaller quantities (<0.01%). Beneficial fungi such as *Saccharomyces* (25%) was only found at the first stage, and *Thermomyces* (27%) were the most abundant fungi at the final stages (Figure 6b).

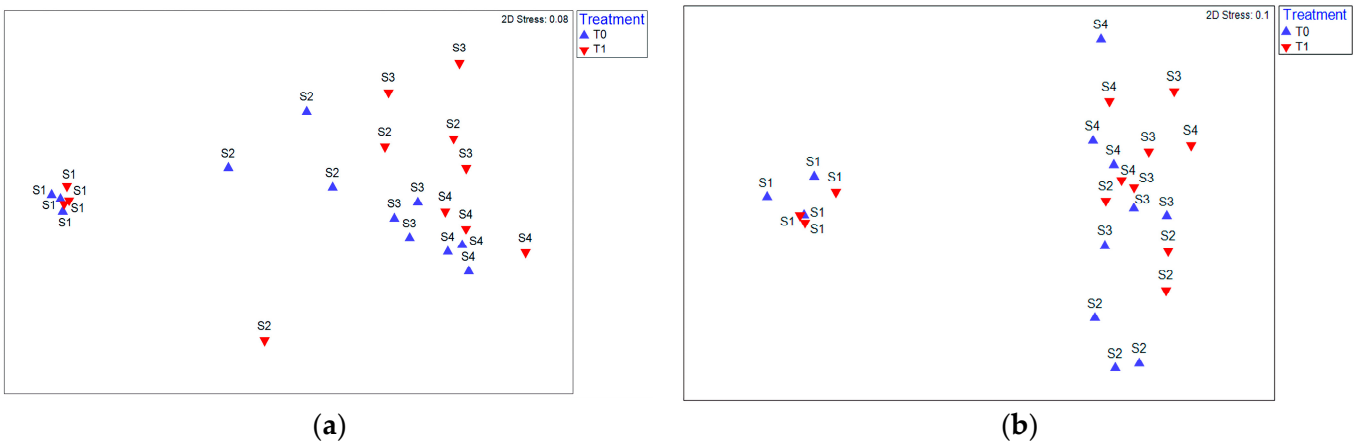


Figure 5. Non-metric Multidimensional Scaling nNMDS, for (**a**) bacteria and (**b**) fungi. T0—Traditional composting; T1—forced aeration system, through the four stages of composting: mesophilic (S1), thermophilic (S2), stabilization (S3), and maturation (S4).

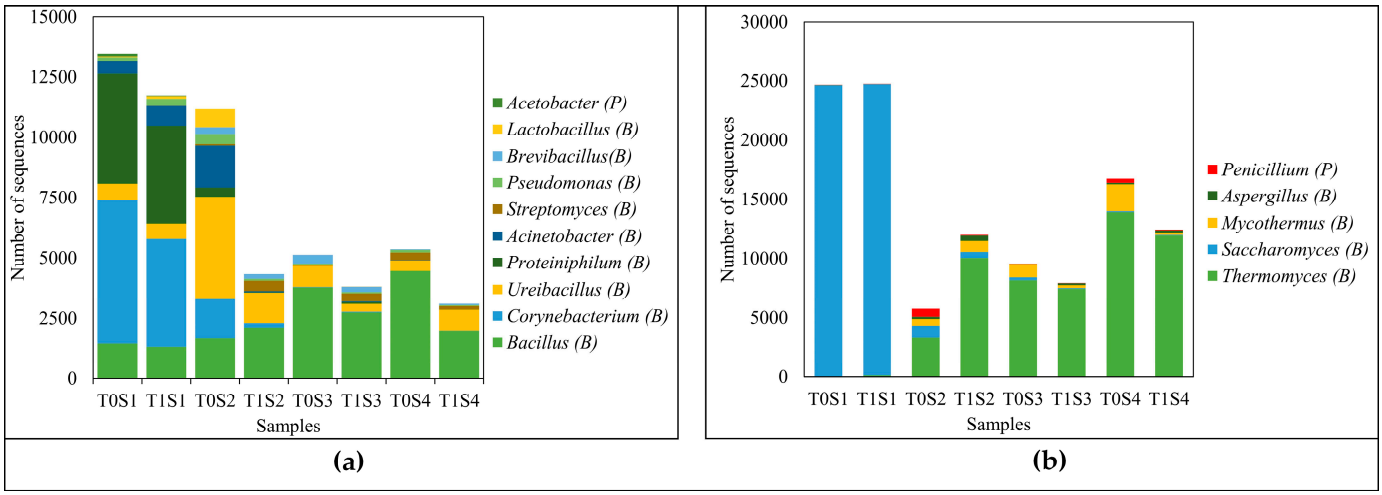


Figure 6. Pathogenic (Pat) and beneficial (Ben) microorganisms along the composting processes for (**a**) bacteria and (**b**) fungi. T0—Traditional composting; T1—forced aeration system, through the four stages of composting: mesophilic (S1), thermophilic (S2), stabilization (S3), and maturation (S4).

4. Discussion

Temperature is a critical factor in the composting process as it directly influences microbial activity and is also regulated by the aeration rate and humidity of the windrows [25]. Previous studies have shown that the use of a semipermeable cover (TOPTEX cover) can help obtain a more stable compost as this kind of cover permits a flow of air through the windrow [39]. The results showed that forced aeration (T1) effectively raised and

maintained higher temperatures within the compost pile during the time the experiments were performed (Figure 3), which aligns with previous findings that controlled aeration can enhance temperature and reduce moisture content, which is an indicator of organic matter degradation [27].

The decline in humidity to around 30% in both windrows by the end of the experiment (Figure 4a) indicates suboptimal conditions for microbial activity [25], potentially limiting further composting efficiency. This decline in the moisture of the piles is related to the biological process of composting, which tends to dry the material under composting due to the evaporation of water, as a result of the microorganism's activity, which generates a heating of the organic matter in decomposition, so watering must be performed frequently [40]. The increase in pH to more than 7.5, observed after 60 days in both windrows, indicates successful aeration and enhanced microbial activity (Figure 4b), as supported by previous studies where the positive relation between aeration and the pH level of the windrows was observed; if the aeration was not adequate, anaerobic conditions occurred, dropping the pH level to about 4.5 and delaying the composting process [27]. These changes in the pH during the different stages of the composting process were caused by the microorganisms itself, since, during the mesophilic stage, organic acids are release during the decomposition of the organic matter to later volatilize [41]. The observed increase in pH can be explained by the degradation of organic matter and the ammonification process facilitated by decomposing microorganisms [42]. The stabilization of pH later in the composting process reflects the transition to the stabilization phase, where the compost becomes more stable, ammonia volatilization increases, and C/N and microbial activity decreases [18,19].

A noticeable fluctuation in the pH levels during the composting process was detected in both treatments (Figure 4b), a decrease in the first stage of composting has been reported in previous studies, due to the organic acids releasing during the decomposition of simple organic substrates, and volatilization of the initial ammonia, but after the disappearance of these easily degradable organic matter, the mineralization of the leftovers and nitrification leads to an increase in pH [42].

The slow reduction in the C/N highlights the challenge of degrading the recalcitrant components of the initial substrates, such as the pomace seed, known for its high lignin content and which comprises almost 70% of the initial substrate in both piles. Lignocellulose is the major fraction of most vegetable waste, which mostly consists of cellulose, hemicellulose, and lignin, the last one being the most stable and refractory fraction of organic matter in the composting process, so its degradation is one of the major factors that could limit the composting efficiency [22]. This suggests that additional nitrogen sources might be necessary to accelerate the composting process in such substrates, such as sludge or manure, which have shown a greater reduction in the C/N in previous trials with similar substrates [11,39,41].

The increased apparent density observed during the composting process is consistent with previous research on composting this kind of raw materials [11], which is related to organic matter loss, moisture content changes, and subsidence [24,40,43,44]. The compliance of the compost with most of the Chilean Composting Standard 2880 parameters demonstrates the overall success of both composting methods, though the elevated NH_4/NO_3 in both systems and NH_4 concentration in T1 indicates potential issues with nitrogen management. Nevertheless, the slight increase in the NH_4 value may be due to a sampling issue that is reflected in the large standard error of the replicates analyzed. Additionally, previous research has shown an increase above the standard in the NH_4/NO_3 of compost samples from substrates similar to those used in this research [13].

The comparison between the forced aeration system (T1) and the traditional turning method (T0) highlights similar physical and chemical outcomes, despite differences in

temperature patterns. The forced aeration system appeared to enhance the composting process by maintaining higher temperatures earlier on, suggesting a potentially faster degradation rate compared to the traditional method. However, in large-scale composting, prolonged periods of high temperatures and low pH must be managed to avoid the risk of killing the decomposing microorganisms essential to the process. The results indicate that forced aeration (T1) influenced the bacterial community, particularly during the thermophilic stage, leading to greater differentiation compared to traditional composting (T0). The similar Shannon index values for bacterial diversity across stages suggest that both composting methods support comparable levels of bacterial diversity. However, the fungal communities exhibited more variability, likely due to the differences in temperature and aeration conditions between the windrows, which are known to affect fungal growth and activity.

The PERMANOVA analysis (Figure 5) further confirmed that temperature and humidity played significant roles in shaping the microbial communities, with the forced aeration method leading to faster temperature increases and, consequently, more differentiated bacterial populations during the thermophilic stage. This is in line with previous studies suggesting that microbial composition in compost is heavily influenced by aeration and temperature conditions [20].

The observed homogenization of both bacterial and fungal communities in the final stage indicates that, despite differences in earlier stages, both composting methods eventually lead to a similar microbial composition in the mature compost [14].

Regarding pathogen control, the high temperatures achieved during the thermophilic stage were effective in reducing pathogenic microorganisms in both composting systems. This aligns with established composting principles where high temperatures play a key role in pathogen reduction [21].

Beneficial microorganisms such as *Nitrosomonas* and *Saccharomyces* were more prevalent in the forced aeration system (T1), which could be due to the more favorable conditions for microbial activity created by the rapid temperature rise and consistent oxygen supply. The presence of these beneficial microbes enhances compost quality by promoting nutrient cycling and improving overall compost maturity [45].

In summary, while both composting methods produced compost that largely met the Chilean regulatory standards [29] and achieved high-quality compost, the forced aeration system (T1) demonstrated advantages in temperature control, microbial diversity, and pathogen suppression, suggesting its potential for more efficient composting in similar agricultural contexts.

5. Conclusions

In this study, various physical and chemical variables were evaluated in two composting systems at four key stages. Despite detailed evaluations, no significant differences were found in the final compost quality between the systems. Although the higher temperatures in the forced aeration system (T1) initially reduced the number of microorganisms, beneficial microorganisms were observed by the end of the process. Notably, traditional turning (T0) resulted in a higher abundance of beneficial microorganisms in the final compost. Microbiological analyses confirmed that both composts met the Chilean regulatory standards for quality.

One of the major problems detected during the composting process using forced aeration was the slow reduction in the C/N ratio, but this could be solved by adding nitrogen-rich substrates to the initial mix of the composting windrows to enhance the microorganism activity and regulate the initial pH level, expecting to implement these findings in future forced aeration composting process of wine residues.

Based on these findings, the static composting system with forced aeration (T1) emerges as a promising option for managing wine industry waste. It provides a compost of comparable quality to the traditional turning system (T0) while offering advantages in temperature control and pathogen suppression.

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