Recovery of organic wastes in the Spanish wine industry. Technical, economic and environmental analysis of the composting process

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Abstract

The main organic wastes produced in modern wine industries include grape pomace (62%), lees (14%), stalk (12%) and dewatered sludge (12%). Some of these wastes are being used as by-products (grape pomace and lees) whereas the rest of organic wastes (stalk and wastewater sludge) has been traditionally incinerated or disposed in landfill. In this work, composting is proposed for the recovery of stalk and wastewater sludge to produce a sanitized organic amendment for application in the vineyard, closing the organic matter cycle. The environmental and economical analyses of the different alternatives to manage organic wastes from the wine industry are also presented. Composting costs are almost negligible when compared to other management options. From the environmental point of view, in-situ composting presents the best performance in 8 of the 10 impact categories analysed. Finally, the energy balance shows that the four composting systems involved less energy than systems based on mineral fertilizer consumption.

Keywords: Wine by-products, Composting, LCA, Organic wastes, Wine industry.

1. Introduction

The wine industry is an important sector in the economy of some countries, especially those from the Mediterranean area. Spain has one of the largest vineyards in the world, with a wine production of 44 millions hectolitres, of a total production in the European Union of 150 millions hectolitres [1,2]. Wine production has been traditionally seen as an environmentally friendly process. However, it requires a considerable amount of resources such as water, fertilizers and organic amendments, and on the other hand produces a large amount of wastewater and organic wastes. Innovative solutions must be proposed and tested to develop a real sustainable industry [3].

Therefore, the objectives of this work are: i) to revise briefly the most significant impacts derived from the large-scale wine production and its waste generation and to characterize the present strategies for the organic wastes management, ii) to carry out field composting experiments to determine crucial aspects for compost quality such as its stability and the fulfilment of the sanitation requirements in order to obtain a valuable product used as raw material for vineyard fertilization and iii) to study in detail composting from a technical, economic and environmental point of view as an innovative technology to recycle stalk and wastewater sludge (organic wastes that at present are being incinerated or disposed in landfill) into a final product that can be applied to the vineyard cultivation as a complement and partial substitute for chemical fertilizers and organic amendments.

2. The environmental impacts associated to the wine industry

Environmental analysis of the wine industry shows that the main effluents of the sector are wastewater and organic solid wastes. To fulfil the increasing legislation requirements, wastewater problems have been solved by the construction of wastewater treatment plants for one single industry or a group of cellars in developed countries. These facilities had a positive effect on minimizing the environmental impact on the aquatic ecosystems. However, the production of sludge from these treatment plants has been increasing over the last years.

In recent years, wine industry has invested not only in wastewater treatment but also in water saving and wine by-products and sludge valorisation. Problems associated with waste generation in the wine industry are of special relevance during the grape harvest, a very short period of time between September and October in the Mediterranean area.

It has been estimated that the Spanish wine industry generates within 2 and 3 million tons per year of wastes or by-products, mainly produced during the vintage period [1,2]. Most of the wastes generated in a cellar (80-85%) are organic wastes. In Figure 1, an approximate distribution of the wastes generated in the wine industry is presented. Grape pomace is produced during grape press and is constituted by peels and seeds. The rest of wastes are: lees, which are generated in the clarification of wine fermentation process; stalk, constituted by branches and leaves of the grapevine, and wastewater sludge from wastewater treatment.

Some of these wastes have been traditionally recovered by using them as raw materials in other industrial sectors [4,5]. Other materials, however, are not valorised due to their low economical value, such as stalk and wastewater sludge. The current management of these wastes is carried out via external companies. However, this is an expensive and difficult alternative for the wine industry, with high transport costs (low bulk density of stalk, transport required in short time, etc.), high disposal costs (incineration, landfill) and high environmental and social impacts. Additionally, international legislation on sludge application to soil is becoming more exigent and the direct application will be prohibited in the next future [6]. In these legislation drafts, treatment of sludge (by composting or anaerobic digestion) is required for sludge application to ensure a sanitized product.

3. Composting as a sustainable management of organic wine wastes

3.1. The role of composting in the organic matter recycling

Annually, the wine industry is using big amounts of chemical fertilizers and organic matter [4,5]. In this sense, the possibility of recovering organic wastes from the wine industry to vineyards may be presented as a sustainable strategy for the waste management. However, according to the new legislation initiatives the sanitation of sludge before its application to land will be mandatory [6]. This fact, jointly with the prevention of possible diseases in the vineyard crops, presents composting as the most suitable process to reuse the organic wastes of the wine industry in the vineyard crops.

Composting is a natural aerobic process of organic matter biodegradation from fresh materials to stable and mature organic matter, similar to humus. Composting can be technically and economically viable for most of the wine industry companies to convert organic matter residuals to an organic amendment for vineyard growth, avoiding the risk of pathogen infections because of the thermophilic temperature reached in a composting process. Additionally, compost has been reported as a suppressor agent for different crop diseases [7]. Some of the main potential advantages for the wine industry related to composting its own organic wastes and recycling the organic matter in the vineyard crops are summarized in Table 1.

Nowadays it is not a common practice for a wine industry in the Mediterranean area to compost its own organic wastes. Usually, this process is undertaken by companies dedicated exclusively to solid waste treatment or the wastes are directly disposed in landfill or incinerated. A part of the compost resulting from this external treatment is then bought by wine industries to be used as a fertilizer or organic amendment. Moreover, there is a lack of knowledge in wine industries on the composting process from a technical point of view. Most papers related to composting wine industry wastes are focused on co-composting these materials with wastes from other origins usually carried out at laboratory or pilot scale [8]. Recent works at industrial scale in this field can be very useful to the development of a new culture in the waste management strategies of the wine industry [9,10].

3.2. Co-composting wastewater sludge and stalk

In a previous work at full scale [10], we demonstrated that composting of stalk and wastewater sludge was possible using the windrow composting system with a volumetric ratio of 2:1 (stalk:wastewater sludge). The compost produced presented high organic matter content and high level of stability (respiration index lower than 1 mg $O_2 \cdot g$ organic matter$^{-1} \cdot h^{-1}$). Sanitation was also achieved after a long thermophilic period. These properties make compost a suitable organic fertilizer for vineyard. However, the seasonal stalk production in vintage and the larger amounts generated in that period compared to sludge production were highlighted as important issues to address when implementing this option at full scale in the wine facility. For this reason, it is crucial to study if stalk can be composted alone at full-scale, despite some apparently unfavourable properties for composting such as a very high porosity and moisture content, an acidic pH (Table 2) and a high C/N ratio [9]. The possibility of composting stalk without the addition of other co-substrate would produce a large amount of compost to be reused in the vineyard, closing the organic matter cycle in the wine industry.

3.3. Composting of stalk

3.3.1. Methodology

A full-scale windrow composting system was used to study the possibility of composting stalk without any co-substrate. Stalk was collected from the grape harvest during the period from August to November in 2006. A large amount of recently collected stalk was ground to 5 cm (approximately 200 m^3) and used to build a pile of trapezoidal shape. Pile dimensions were as follows: height: 2 m, width: 3 m and length: 26 m. The characterization of stalk is shown in Table 2. Initial mixing and pile turnings were performed using a front-end loader. Pile turning was performed weekly during the composting experiment. The pile was not covered and it was situated on a concrete floor to collect the possible leachate generated in the process. This configuration was selected to simulate typical conditions expected for composting in the wine industry both at small and large cellars. Temperature and interstitial oxygen of the piles were routinely monitored. Temperature was measured with a portable Pt-100 sensor (Delta Ohm HD9214) and oxygen concentration in interstitial air was measured with a portable O_2 detector (Oxy-ToxiRAE, RAE) connected to a portable aspiration pump. Both parameters were measured at two different depths of pile, 40 and 90 cm, in at least seven different points. Temperature and oxygen values are presented as average values.

Analytical parameters were analyzed in the laboratory after extracting a representative solid sample from the pile. For this purpose, four equidistant points of the pile (two for each side of the pile at a medium height of the pile) were sampled after turning by extracting about 20 L of compost at each point. The total sample volume (about 80 L) was manually mixed and a final volume of 2 L (1 kg) was used to carry out the analytical procedures, except in the case of Air-filled porosity (AFP), in which a non-mixed sample of 20 L was used to preserve the sample structural properties.

Final stability of compost obtained from stalk was measured by the respiration index. It was determined using a static respirometer based on a model previously described [11] and following the modifications and recommendations given by the U.S. Department of Agriculture and U.S. Composting Council [12]. The experimental respirometer has been described in previous works [13]. Values of respiration index are expressed as mg of oxygen consumed$\cdot$g organic matter (OM)$^{-1}\cdot$h^{-1} and are presented as an average of three replicates.

Routine analytical methods such as moisture, dry matter and organic matter, pH, bulk density and maturity grade were determined according to the standard procedures [12]. Porosity (expressed as air-filled porosity) was measured in situ using a self-made constant volume air pycnometer constructed according to previous works [14]. Ethanol, glucose, fructose, glycerol, succinic acid, tartaric acid, malic acid and lactic acid were analysed both in solid stalk and in a leachate of stalk (obtained from 50 g of stalk/75 ml of distilled water extraction) using High-Performance Liquid Chromatography (HPLC). Specifically, a Water Alliance 2695 HPLC was used with a column ION-300 and equipped with a refraction index-based detector (sensibility 32) and variable wavelength ultraviolet detector (200-400 nm). Flow was 0.4 ml/min and eluent was distilled water with H_2SO_4 0.0085 M.

3.3.2. Compost sanitation

Figure 2 shows the climatic conditions during the composting period (September 2006 to January 2007). They are typical for a Mediterranean-type climate, characterized by mild temperatures (average temperature within 5-15ºC) and low precipitation regime, except during some short periods (days 5-10 and 60-70).

The main parameters of the composting process (temperature, oxygen and moisture content) are presented in Figure 3. Temperature is one of the most important parameters to monitor a composting process, because it is an indicator of the development of an active thermophilic microbial population, which is required for compost sanitation. In the composting of stalk, the process reached average temperatures over 50ºC in one week and over 60ºC during three weeks (Figure 3). Values of temperatures over 55ºC were measured for more than ten weeks (days 20-100). As pile turnings were carried out approximately once a week, it can be concluded that the totality of the material was exposed to temperatures in the thermophilic range. Besides, according to US Environmental Protection Agency Rule 503, total sanitation of biosolids is obtained at 55ºC for 15 days and turned 5 times, which was the case of stalk composting [15]. In relation to oxygen content, the values were always high (over 15%), which is in accordance with the stalk high porosity. In any case, it can be concluded that no oxygen limitations are expected to be found in stalk composting, and the prevalence of aerobic conditions is guaranteed. On the other hand, moisture presented high values with several increases that coincided with rainy periods. However, the overall trend is of moisture decrease because of water evaporation, as it is typical of composting processes [16]. In fact, moisture reduction in the whole composting period (71.1%) is responsible of a large part of total weight loss (66.6%), jointly with organic matter reduction (67.7%, Table 3).

In general, it can be concluded that the parameters studied showed that stalk composting is possible at full-scale, and the sanitation requirements defined for windrow composting are fulfilled.

3.3.3. Final compost characteristics

Apart from the sanitation issue, the most important factor to decide the application of compost from stalk in the vineyard is related to its agronomical properties. Table 2 shows a summary of the main properties found for composted stalk. From the chemical point of view, it is worthwhile to mention the high level of organic matter and a slightly alkaline pH. On the other hand, products and by-products from the wine fermentation, such as ethanol, reducing sugars and organic acids, which were present in a considerable amount in fresh stalk and leachate from stalk, were completely biodegraded after composting (data not shown). The physical properties also appeared suitable for soil application, with a high level of porosity. Other works have reported some beneficial structural properties of stalk such as global porosity, pore space and water holding capacity [10].

In relation to stability parameters, respiration activity showed a progressive decrease during the composting process (Figure 4), which is more evident during the first 20 days, when it is probable that the degradation of easily biodegradable organic compounds occurred. During the rest of the composting period, a slower stabilization of organic matter is observed (Figure 4), leading to a final respiration activity index of 0.72 mg $O_2 \cdot g\ OM^{-1} \cdot h^{-1}$, which is considered as very stable according to international compost regulations [17]. The other test measured, based on the maturity of the final compost, also produced the highest maturity grade (V, Table 2), which confirmed that compost from stalk was suitable for organic soil amendment.

4. Economical estimation

The management internalization of the wastes produced in the wine industry has several economical benefits: the external management costs are eliminated as well as the cost of buying compost or other organic amendments to external providers. At the same time this practice provides intangible benefits such as the improvement of the social perception about the company and the independency from external manufacturers (Table 1). On the other hand, an initial investment cost is required before starting the in-situ composting of organic wastes. Table 4 shows the total costs derived from the external management and the investment cost required for implementing the composting system in a wine production facility, according to Spanish local prices and providers. These values can be considered representative of the European Mediterranean area, where most of the world wine production is located. The main investment costs consist on: the preparation of the land to be used for composting (construction of concrete floor and leachate collection system, which is compulsory), the stalk shredder and the additional equipment required for pile turning. Due to the seasonal stalk production, the pavement area is only dedicated to the composting process and storage of stalk and final compost during seven months per year. The rest of the year, the same area is used for other purposes such as maintenance of wine production equipment. In consequence, only the 58.3% of the pavement investment cost has been considered in the economical evaluation. The equipment for pile turning consists in a tractor and a shovel, both being used for other operations in wine cellars. According to local wine producers, only a 5% of the tractor and a 30% of the shovel purchase costs have been considered as attributable to compost production. Since these percentages are again typical for other wine industries, this cost estimation can be representative of this sector in the European area. Finally, research costs are estimated by considering the time cost of technical personnel involved in the project development, according to local salaries.

As can be observed in Table 4, total cost of external management is 33.63 € per ton of organic waste produced (sludge and stalk). Composting costs account for 14.07 € per ton of organic waste produced in terms of labour and depreciation (amortization) costs. Thus, the annual saving reached is 19.56 €/t. In relation to initial investment, the total cost is 95.58 € per ton produced in one year, which also includes the research cost (experimental design and specific analytical measures). Total investment has been divided into different concepts. The investment costs in Table 4 have been estimated considering the total amortization period of each concept, according to Equation 1.

$$\text{Investment cost} = \frac{{}^{\text{total investment}}\!\big/\!{}_{\text{amortization time}}}{\text{tons of waste generated in 1 year}} \qquad \text{(Equation 1)}$$

Considering the economical benefits of process internalization as previously described, the total investment return period can be calculated according to Equation 2, and it has been estimated as inferior to five years.

$$\text{Total investment return period} = \frac{\text{total investment (euros)}}{\text{annual profits (euros per year)}} \qquad \text{(Equation 2)}$$

Thus, implementing in-situ composting of organic wastes produced in a wine facility can be considered highly viable from an economical point of view.

5. Environmental impacts of composting using Life Cycle Assessment (LCA)

The methodology selected to perform the environmental analysis was LCA. It assesses all the global environmental impacts associated to a product, process or activity by accounting and evaluating the resources' consumption and emissions [18]. This analytical tool follows the ISO14040 guidelines [18], according to which LCA is divided into four steps: (1) goal and scope definition, (2) inventory analysis, (3) impact assessment and (4) interpretation. The environmental analysis was developed using the software program SimaPro 7.0 by PRé Consultants and using the CML 2 baseline 2000 V2.02 method [19].

5.1. Goal and scope definition

The main aim of this LCA is to evaluate the environmental and the energy performance of different management options for the organic wastes generated during the wine production. This part of the study has three significant additional specific goals; first, to compare the management system based on landfill disposal with the organic wastes composting in in-situ (i) and ex-situ (e) conditions. The second objective is to determine the environmental suitability of composting stalk alone (Si and Se) or mixed with wastewater sludge (SSi and SSe). Finally these composts are compared with two external reference systems: Mineral fertilizer (MF) and Industrial Compost from source-selected organic fraction of municipal solid wastes (C) to determine the viability of using organic wastes from the wine industry as fertilizers.

5.2. Functional unit

As the function of the all fertilizers, both organic and chemical, is to add nutrients to soil, the functional unit selected for this study is: to provide 1 kg of Nitrogen to vineyard lands.

5.2.1 Nitrogen references values for the functional unit

According to the experimental data, the nitrogen content for systems Si and Se is 4.0 g N/kg compost, for systems SSi and SSe is 5.3 g N/kg compost, for system C is 18.6 g N/kg compost and for MF is 367.6 g N/kg fertilizer.

5.3. Systems description

The analysed systems (Si, Se, SSi and SSe) include the recovery of the organic wastes and their composting. Figure 5 shows a schematic representation of the stages considered for the in-situ compost systems analysed (Si and SSi), including the mass balances estimated according to experimental values. The composting process for ex-situ systems (Se and SSe) includes the transport of the waste to a composting plant located at 14 km and its return to land.

On the other hand, two external systems have been considered: the Mineral Fertilizer (MF), which is based on the production of ammonium nitrate with a nitrogen content of 35% [20] and its transport from 500 km of distance [21], and the production of industrial compost (C), obtained from a standard composting plant that treats source-selected organic fraction of municipal solid wastes using in-vessel composting process with emissions treatment based on biofiltration, and 14 km of transport distance.

5.4. Inventory analysis

The data related to experimental compost production used in this analysis have been obtained from the experimental study explained in Sections 3.2 and 3.3. Data related to energy requirements for the composting process were supplied by Miguel Torres S.A. Table 5 shows the summary of the energy flows related to the in-situ compost production in the enterprise analysed and the ex-situ compost production that assumes a transport distance of 14 km. The data of industrial compost production (C) has been obtained in previous research studies carried out in real composting plants located in Spain treating source-selected organic fraction of municipal solid waste [22,23]. For mineral fertilizer production (MF), data from Ecoinvent system process v. 1.2 (2005) have been used [20].

5.5. Avoided impacts

The several options of composting, as well as offering a fertilizing product, provide a way of organic wastes management, while the production of mineral fertilizer only provides a fertilizing product. As proposed by Finnveden [24] and Ekvall and Weidema [25], to make these systems comparable and to avoid ignoring the extra function of composting, the boundaries of the system should be expanded to consider an alternative type of managing organic wastes that is not composting. The method selected has been landfill disposal, whose environmental burdens were subtracted from those systems that include composting. For the landfill of organic wastes, it was considered that organic materials decompose in anaerobic conditions and that the 53% of the landfill gas generated is collected and burned [26].

5.6. General environmental results

Table 6 shows the results obtained from the environmental analysis. They demonstrate that in-situ composting of the mixture stalk-sludge is the waste management option that presents the lowest environmental impact for all the categories studied. Specifically, in-situ composting of the mixture stalk-sludge (SSi) is the option with the best environmental performance of the six waste management options included in Table 6. The management of organic wastes in the SSi system compared to composting of stalk alone (Si) supposes an impact reduction from 13% to 53% depending on the environmental category considered.

The management system Si allows to reduce within 10% and 83% the environmental impacts when is compared to the Se management system. When SSi and SSe are compared the results show that the reduction obtained is within 15 and 84%. Therefore, in-situ composting options (Si and SSi), by avoiding transport stages, are more favourable than ex-situ options or landfill disposal.

5.6.1 Environmental performance considering avoided impacts

To complement the environmental analysis, Table 7 shows the environmental results obtained for each system defined in Section 5.3, considering the avoided impacts from the non-landfilled organic wastes. The comparison of the environmental performance of the six systems under study is presented as a percentage of the environmental impact reduction in relation to the highest impact (highlighted in black) found for each category.

The composting system Si presents the best behaviour in eight of the ten impact categories analysed. The other three composting systems are classified according to their impact reduction as Se, SSi and SSe for the majority of categories. When avoided impacts are considered, the amount of recovered organic wastes that are not disposed in landfill have a crucial influence on the environmental performance of the systems. In consequence, stalk composting systems (Si and Se), which need a larger quantity of organic waste to obtain 1 kg of N in compost, present the lowest impacts.

All the experimental composting systems (Si, Se, SSi and SSe) reduce in higher percentage the environmental impact in all categories analysed when compared to the worst option (MF or C depending on the category considered); with the exception of Potential of Ozone Layer Depletion and Potential of Acidification categories. The causes for the highest impact in system Se in the category of Potential of Ozone Layer Depletion is the large amount of waste treated and the fact that transport of material is unfavourable because of the low bulk density of stalk (Table 2). On the other hand, the main reason for the highest contributions to Potential of Acidification in systems SSe and SSi is the ammonia emission produced during the wastewater sludge composting process. However, it should be pointed that a relatively simple system based on biofiltration and using compost as filter media could be considered for the reduction of such emissions [27,28]. In fact, a biofiltration system with efficiency of 56% [22] has been assumed for the industrial compost system (C). On the other hand, no ammonia emissions were detected in the stalk composting systems (Si and Se). Finally, it must be noted that ammonia emissions in systems SSi and SSe supposes more impact in Potential Eutrophication category compared with systems Si, Se and C.

5.7. Energy balance

Figure 6 shows the energy investment and energy balance for each analyzed system. The invested energy for the system C is higher (521 MJ-eq per kg N) than the other considered systems. The next systems in the scale of energy invested requirements are both experimental systems that consider ex-situ compost production. Mineral fertilizer production (MF) presents the lowest energy consumption for all the systems under study (76 MJ-eq per kg N).

The energy balance (white bars of Figure 6), when saved energy of wastes not disposed in landfill is considered, shows that the four composting systems involved less energy than systems MF and C. The Si system presented the most favourable energy balance, whereas the system C had the lowest benefit in terms of energy.

6. Conclusions

Several conclusions can be obtained from this work:

1) Wine industry presents a high potential for recovering its organics wastes in the vineyard production, closing, by this way, the organic matter cycle. The high amount of organic wastes generated in the wine production makes interesting to evaluate new management procedures.

2) Composting is technically and economically feasible for the production of compost from organic wastes derived from wine production. Both inversion and operation costs are low, which represents a short return period.

3) The compost obtained presents a high agronomical value, being stable and sanitized according to the international requirements.

4) The environmental impacts of in-situ composting organic wastes from the wine production are lower than those of other management systems. All the experimental composting systems reduce in higher percentage the environmental impact in all categories analysed when compared with the

worst option (mineral fertilizer or industrial compost), with the exception of Potential of Ozone Layer Depletion and Potential of Acidification categories.

5) The energy balance for composting systems is favourable in terms of energy savings. The four composting systems analysed involved less energy than systems based on mineral fertilizer or industrial compost consumption.

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Tables

Table 1: Potential advantages of in-situ composting for the wine industry.

Type	Advantages
Environmental advantages	- Avoid the environmental impacts associated to waste transport. - Self management of organic wastes. - Minimization of wastes. - Close the organic matter cycle. - Minimization of fertilizer requirements.
Agronomic advantages	- Self production and control of the organic fertilizers used in vineyard crops. - Easy transport and application to soil. - Effect of suppression of plant diseases. - General improvement of the soil.
Economical advantages	- No cost of transport and final disposal of stalk and wastewater sludge. - Total or partial reduction in the cost of organic fertilizers. - Possibility of obtaining public financial help. - General improvement of the company image and perception from society.

Table 2: General initial and final properties of stalk during composting.

Parameter	Initial stalk	Final (composted) stalk
Moisture content (%)	75.0 ± 0.2	64.9 ± 0.2
Dry matter (%)	25.0 ± 0.2	35.1 ± 0.2
Organic matter (%, dry basis)	91.5 ± 0.3	63.1 ± 0.3
pH	5.0 ± 0.1	9.4 ± 0.1
Air-filled porosity (%)	71 ± 2	65 ± 1
Bulk density (kg/l)	0.5 ± 0.1	0.3 ± 0.1
Respiration index (mg O_2· g OM^{-1}· h^{-1})	8 ± 1	0.72 ± 0.05
Maturity grade	I	V

Table 3: Reduction of some bulk parameters during the stalk composting process.

Parameter	Reduction (%)
Total weight	66.6
Total Volume	44.4
Moisture	71.1
Dry matter	53.1
Organic matter	67.7

Table 4: Costs of external and internal waste management and investment cost required for in-situ composting. External management costs include transport, taxes and final disposal for sludge and stalk management and transport, taxes and compost cost for compost purchase (considering the quantity of compost obtained from 1 ton of waste generated).

External management costs (€/ton)			
Sludge management			14.95
Stalk management			7.47
Compost acquisition			11.21
Total external management costs			*33.63*
Investment (€)			
Item	*Total cost (€)*	*Dedication (%)*	*Composting cost (€)*
Research cost	26,213	100	26,213
Stalk shredder	24,000	100	24,000
Tractor	30,000	5	1,500
Shovel	6,000	30	1,800
Pavement	127,500	58.3	74,375
Total investment cost			*127,888*
Internal management costs (€/ton)			
Labour cost			0.78
Investment depreciation			
Research cost (4 years amortization time)			4.90
Land preparation (15 years amortization time)			6.35
Stalk shredder (10 years amortization time)			1.79
Tractor (10 years amortization time)			0.11
Shovel (10 years amortization time)			0.13
Total internal management costs			*14.07*
Total savings (€/ton)			**19.56**
Return period (year)			**4.9**

Table 5: Inventory analysis for the compost production from stalk and stalk mixed with wastewater sludge.

Stage	Machinery	Units[1]	Energy consumption	
			System S[2]	System SS[2]
Transport to grind area	Tractor with payloader	l diesel	0.134	0.059
Grinding	Grind machine	Kwh	4.918	2.146
Stalk transport to piles	Tractor with payloader	l diesel	0.134	0.155
Sludge transport to piles	Tractor with payloader	l diesel	-	0.028
Sludge and stalk mix	Tractor with payloader	l diesel	-	0.155
Turning over piles	Tractor with payloader	l diesel	0.358	0.702
Industrial plant transports[3]	Lorry	t·Km[4]	15.12	12.68

[1] All values are related to the functional unit selected for this study (1 kg of Nitrogen)

[2] S: Stalk composting; SS: Stalk and Sludge composting.

[3] This stage is only added in ex-situ systems (Se and SSe). It includes organic waste transport to the industrial composting plant and transport of compost produced to fields.

[4] Unit of measure of goods transport which represents the transport of one ton by road over one kilometre, as defined by Eurostat [29]

Table 6: General environmental analysis of the waste management options, without considering avoided landfill impacts. Results are referred to functional unit.

Impact Categories	Unit	Stalk (S)			Stalk and Sludge (SS)		
		Composting in-situ	Composting ex-situ	Landfill Disposal	Composting in-situ	Composting ex-situ	Landfill Disposal
Abiotic Depletion (AD)	kg Sb eq	0.04	0.08	0.12	0.03	0.07	0.10
Global Warming (GWP100)	kg CO_2 eq	3.31	8.88	239.51	1.79	6.46	203.93
Ozone Layer Depletion (ODP)	kg CFC^{-11} eq	0.000002	0.000003	0.000002	0.000001	0.000002	0.000002
Human Toxicity (HT)	kg 1.4-DB eq	2.49	5.56	75.30	1.43	4.00	64.12
Fresh Water Aquatic Ecotoxicity (FWAE)	kg 1.4-DB eq	0.35	0.68	679.88	0.18	0.46	578.87
Marine Aquatic Ecotoxicity (MAE)	kg 1.4-DB eq	7306	8073	329644	3411	4054	280668
Terrestrial Ecotoxicity (TE)	kg 1.4-DB eq	0.02	0.03	0.54	0.01	0.02	0.46
Photochemical Oxidation (PO)	kg C_2H_4	0.002	0.004	0.05	0.001	0.002	0.04
Acidification (A)	kg SO_2 eq	0.05	0.08	0.13	0.03	0.05	0.11
Eutrophication (E)	kg PO_4 eq	0.001	0.008	0.91	0.001	0.01	0.77

Table 7: Comparison of the environmental performance of the six systems studied considering the subtraction of the avoided landfill impacts. The percentage of environmental impact reduction in relation to the highest impact is presented for each category. The absolute value of highest impact of each category is marked in black.

Impact Categories	Unit	Mineral fertilizer	Composting stalk in-situ	Composting stalk-sludge in-situ	Composting stalk ex-situ	Composting stalk-sludge ex-situ	Industrial compost
Acronym		MF	Si	SSi	Se	SSe	C
Abiotic Depletion (AD)	kg Sb eq	-69%	-195%	-180%	-103%	-103%	■
Global Warming (GWP100)	kg CO_2 eq	■	-2908%	-2503%	-2776%	-2392%	-2570%
Ozone Layer Depletion (ODP)	kg CFC^{-11} eq	-50%	-187%	-227%	■	-70%	-49%
Human Toxicity (HT)	kg 1.4-DB eq	■	-2976%	-2570%	-2733%	-2366%	-2648%
Fresh Water Aquatic Ecotoxicity (FWAE)	kg 1.4-DB eq	■	-221745%	-188854%	-221530%	-188673%	-222819%
Marine Aquatic Ecotoxicity (MAE)	kg 1.4-DB eq	■	-30089%	-25895%	-29946%	-25775%	-29814%
Terrestrial Ecotoxicity (TE)	kg 1.4-DB eq	■	-1903%	-1659%	-1831%	-1599%	-1407%
Photochemical Oxidation (PO)	kg C_2H_4	■	-10743%	-9291%	-10051%	-8711%	-9114%
Acidification (A)	kg SO_2 eq	-99%	-103%	-2%	-100%	■	-71%
Eutrophication (E)	kg PO_4 eq	■	-19170%	-4064%	-18895%	-3833%	-15784%

Figure Legends

Figure 1: Approximate distribution of the organic wastes produced in the wine industry.

Figure 2: Climatic conditions during the stalk composting process.

Figure 3: Temperature. oxygen and moisture content during the stalk composting process.

Figure 4: Stability (measured as respiration activity) of the stalk during the composting process.

Figure 5: Scheme of the in-situ systems analysed: stalk composting (Si) and stalk and wastewater sludge composting (SSi). Dotted boxes correspond to mass balance used for Life Cycle Assessment. Continuous boxes correspond to operations performed in systems Si and SSi.

Figure 6: Energy consumption of each system and its energy balance. Codification: Si: in-situ stalk composting, Se: ex-situ stalk composting, SSi: in-situ stalk and sludge composting, SSe: ex-situ stalk and sludge composting, MF: mineral fertilizer and C: industrial compost from municipal solid waste.

Figure 1: Ruggieri et al.

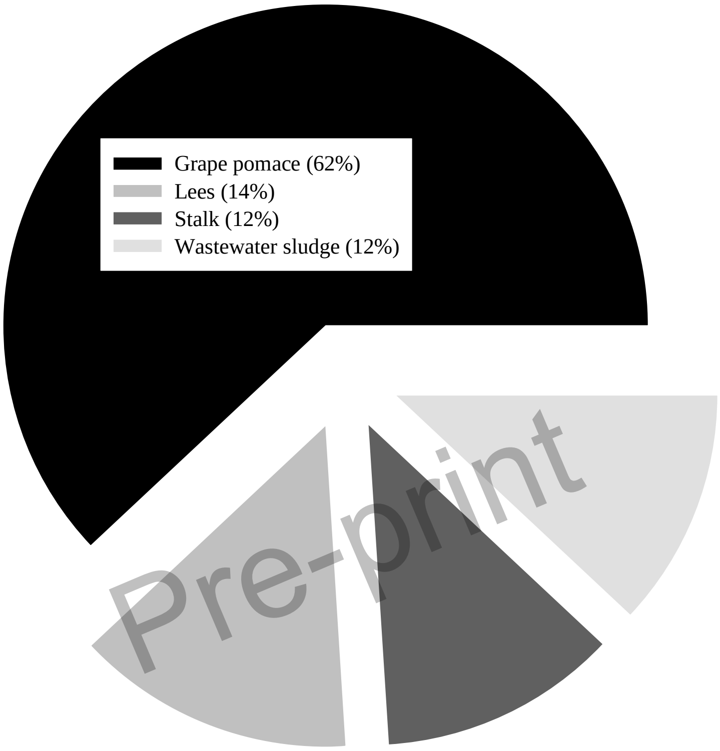

Figure 2: Ruggieri et al.

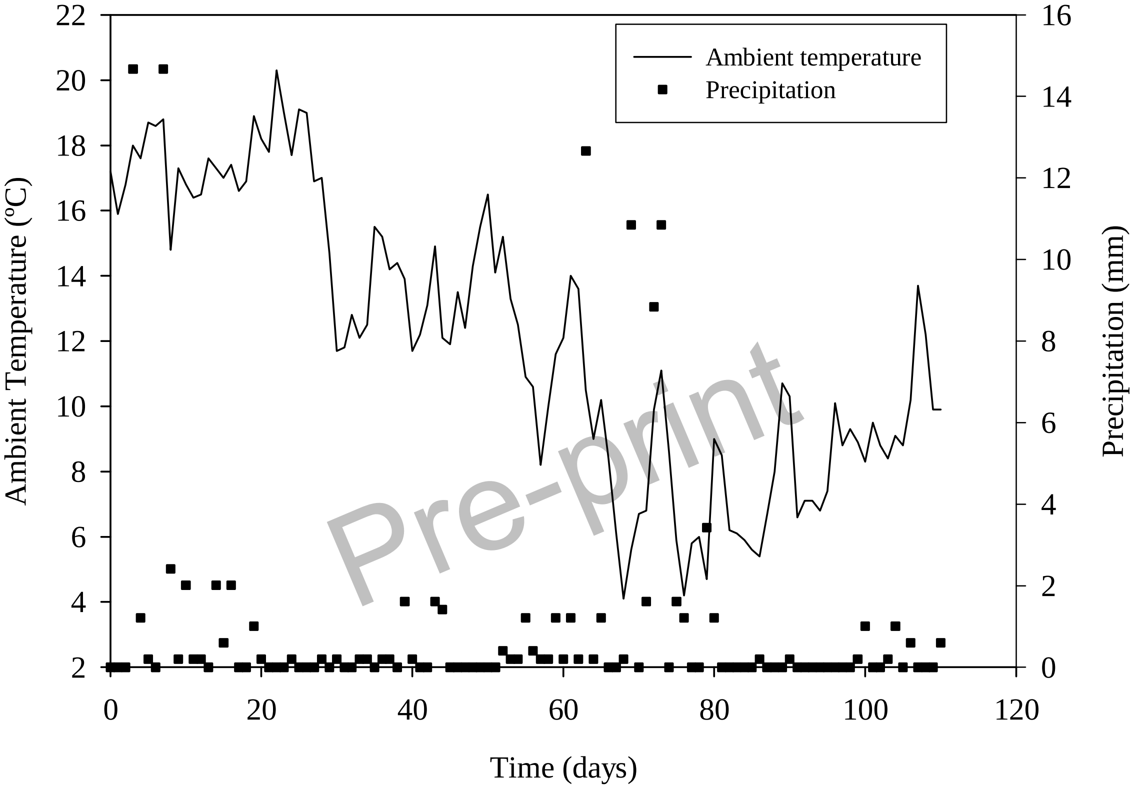

Figure 3: Ruggieri et al.

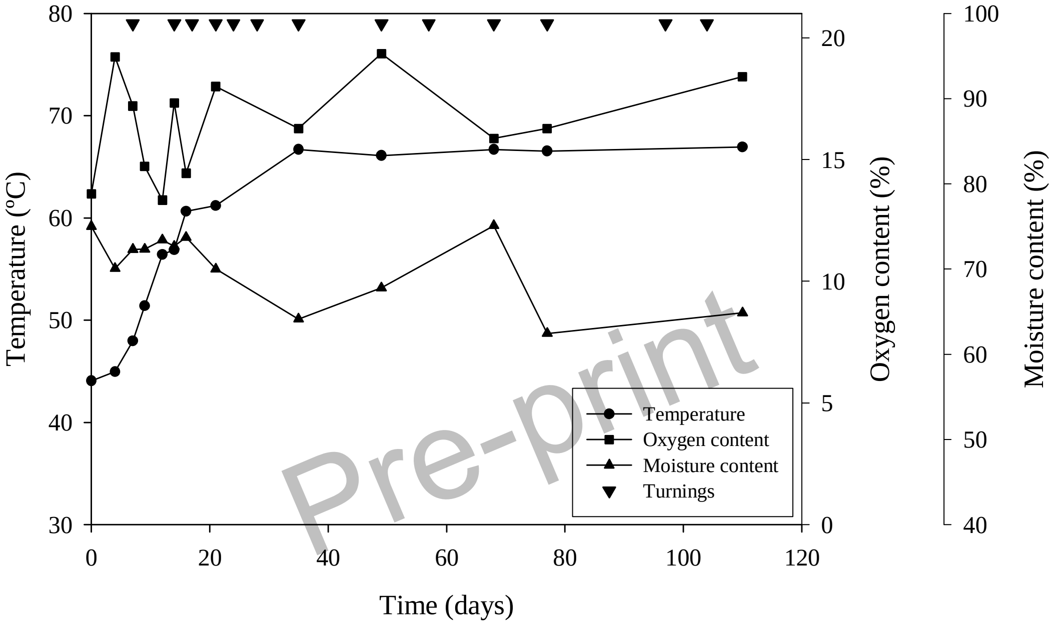

Figure 4: Ruggieri et al.

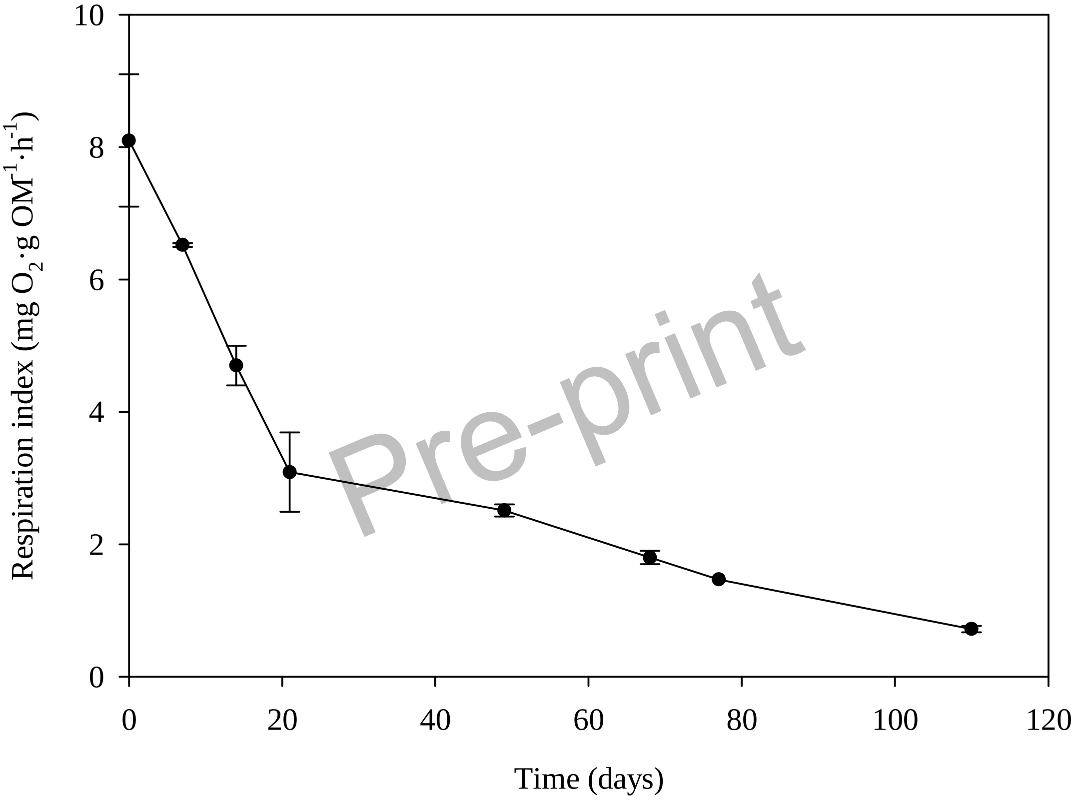

Figure 5: Ruggieri et al.

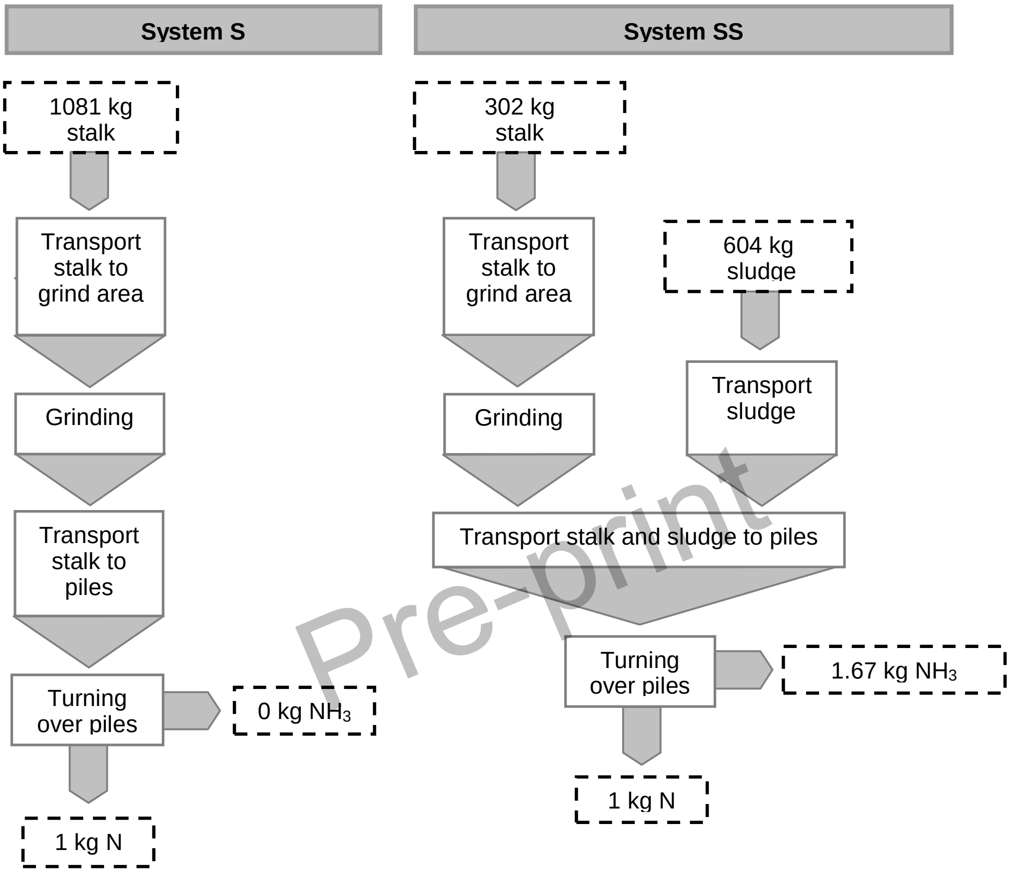

Figure 6: Ruggieri et al.