

Review

From Waste to Value in Circular Economy: Valorizing Grape Pomace Waste through Vermicomposting

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Abstract: From the vineyard to the bottle, the winemaking process generates a variety of by-products, such as vinasses, spent filter cakes, grape pomace, grape lees, and vine shoots. To avoid damaging the environment and to reduce economic impacts, the by-products and wastes must be handled, disposed of, or recycled properly. This review focuses on an environmentally friendly approach to the management and added value of winemaking by-products, such as grape pomace or grape marc, by using vermicomposting. Vermicompost is a well-known organic fertilizer with potential uses in soil bioremediation and the conservation of soil health. To achieve environmental neutral agriculture practices, vermicomposting is a promising tool for resilient and sustainable viticulture and winemaking. Vermicomposting is a simple, highly beneficial, and waste-free method of converting organic waste into compost with high agronomic value and a sustainable strategy in line with the principles of the circular economy.

Keywords: grape pomace waste; wine industry; circular economy; vermicompost; soil; fertilizers



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1. Introduction

The circular economy (CE) is a concept that the European Union (EU) uses to define a new strategy for economic policy development. The EU developed in recent years an Action Plan for addressing the circular economy core ideas and drafted a fundamental document that includes actions to be carried out across member states in the coming years. The CE is defined as “an economy, where the value of products, materials and resources is maintained (...) for as long as possible, and the generation of waste minimized”. The key concept of the CE is to change the actual economic model, based on linear economy, into a sustainable strategy in line with the principles of circular economy models. The EU Action Plan includes a series of directives aimed at supporting member states’ actions towards a circular economy that stimulates areas such as eco-innovation, eco-labelling, nontoxic environment, chemicals, critical raw materials, and fertilizers [1]. Nowadays, scientists and policy makers consider this approach a new economic paradigm that should conserve natural resources and biodiversity, a clean environment, increased economic prosperity, and social welfare.

The wine industry plays a key role in the social–economic environment of many countries and has great importance in terms of raw material production and economic impact in the food processing industry. World wine production in 2022 was approximately 258 million hectoliters according to the data provided by the International Organization of Vine and Wine [2]. Most major wine producing areas in the European Union (EU) recorded increased productions with respect to 2021, namely, Italy (50.3 mhl, +1%), France (44.2 mhl, +17%), and Romania (4.6 mhl, +4%).

The winemaking process involves a complex series of operations, from growing the grapes, harvesting, fermenting, and aging in the winery to managing the waste generated in all the process stages. The main residue in winemaking is grape pomace, also called grape bagasse or grape marc. It consists of the stems, skins, pulp, and seeds that remain after the grapes have been pressed. The direct processing of grapes, including their stalks, results in a grape pomace composition of 30% grape stems, 30% seeds, and 40% skin and pulp grapes [3]. Common alternatives to using pomace in wineries are the processing of by-products into brandy spirits (orujo, grappa, zivania, țuică) or using them for ethanol production, the extraction of organic acids, or the production of grape seed oil and other food ingredients.

Grape skin is a valuable source of polyphenols; it contains around 70% of the phenolic compounds of the grape [4]. This waste could be used for the extraction of valuable compounds using safe and sustainable methods. Among the sectors that could directly use the extracted polyphenols from this type of waste are major industries such as cosmetics, food, and pharmaceuticals. In accordance with the European Parliament's Waste Framework Directive [5], "waste prevention should be the first priority of waste management and re-use and material recycling should be preferred to energy recovery from waste".

As the current management of wine residues is still in the early stages of development, the emphasis is on its application as an organic soil remediator. In small geographical areas frequently exposed to agricultural activities, the improper disposal of this waste has released excessive amounts of polyphenols into the soil, as phenolic compounds are responsible for the phytotoxic activity of grape pomace. This practice can cause problems that inhibit plant growth; therefore, farmers and local authorities should monitor this issue accordingly [6]. Another issue related to grape marc application to soils has been the initial net nitrogen (N) fixation or increased N leaching [7]. In general, the practical agricultural technologies often associated with the application of grape by-products directly into soil can be limited by strategies that stabilize grapes through organic de-composition processes such as composting and earthworm composting, also known as vermicomposting [8].

A new, cheap, and rapid technology, vermicomposting technology is an acceptable means of effectively recycling organic waste and converting the waste into nutritious soil for crop production. Vermicomposting is a natural process that relies on the use of earthworms (mainly *Eisenia foetida* or *Eisenia andrei* species) with endogenous microorganisms present in waste as a result of the decomposition of organic matter. The final product obtained is vermicompost or earthworm humus, with a stable, uniform, and finely divided appearance. Vermicompost is also a nutrient-rich, peat-like material characterized by a high porosity, high water-holding capacity, and low carbon-to-nitrogen ratio (C:N).

It is important to consider each stage of the winemaking process, from vineyard to bottle, to understand the entire by-product spectrum. In terms of the processes that go into the production of a bottle of wine, the first waste product is the vine shoot, which is the residual waste from the cutting of the vine branches during the pruning process. Worldwide, 1.95×10^7 tons are generated annually in vineyards, equivalent to about 1.4–2.0 tons per hectare, according to Cebrián-Tarancón et al. [9] and Sánchez-Gómez et al. [10]. After pruning, the second process in winemaking that generates by-products is destemming, where grape stalks are removed. It is estimated that stalks account for about 25% of the total by-products of winemaking, but this is highly related to the grape variety and cultivation/winemaking practices, like vine shoots. Another main by-product of winemaking is wine lees, which is described in EEC Regulation No. 337/79 [11] as "the muddy residue, whether or not dried, which accumulates in wine containers after fermentation or during the storage of wine". Wine lees consist mainly of yeast cells dispersed in a mixture of ethanol and organic acids that contain proteins, insoluble carbohydrates, phenolic compounds, and other compounds that can be transferred to the lees during fermentation [12]. Among all the by-products of winemaking, wine lees may represent up to a quarter of the total waste of a winery [13,14].

The UN Sustainable Development Goals predict that the world demand for new resources is expected to increase dramatically in the coming decades [15]. The linear economic model is based on a “wasteful” mindset at the final stage of its life and is already recognized as an unsuitable model for dealing with questions of supply and demand. This mismatch can potentially lead to a series of risks in terms of society, economy and the entire ecosystem. To this end, this traditional economic model is replaced by a more sustainable-based model that evolves around the “circular economy” concept. The new economic model aims to promote the careful design and reuse of resources across the entire product chain using material reverse-flow logistics, emerging technologies, and the integration of by-products in different economic branches.

The fundamental idea underlying the circular economy model can be summarized in the “three R’s”, i.e., reduce, reuse, recycle, which are steps that are essential for waste treatment and a sustainable process approach. In this context, grape pomace, the most significant by-product of winemaking, has great potential to promote greater economic and environmental sustainability in wineries, as it can be reused in different process steps, such as in wine clarification stage and in green energy production. However, as consumer interest in health-promoting foods such as nutritionally modified products and functional foods is growing [16], the uses of grape pomace respond to the need for innovative food products with multiple potential functional properties. Moreover, regarding the societal aspects of these opportunities, the application of concepts based on the use of industrial waste is seen as favorable, which has led to a public acceptance of the great benefits in terms of clean and sustainable food production.

The present review reveals that the vermicomposting process has the capacity to support the circular (bio)economy approach according to the European Green Deal, which aims to reduce the use of agrochemicals, promote sustainable agriculture, and restore biodiversity. In addition, it is in accordance with zero-carbon waste strategies, which underlines its sustainability as an alternative for the cost-effective and environmentally friendly treatment of bio-waste.

The aim of this review is to provide an overview on the latest developments in the valorization of grape pomace as a value-added resource and to investigate its potential applications in the wine industry. Moreover, the potential of vermicompost for a circular economy and sustainable viticulture and its impact at a winemaking facility will be also analyzed. Through the development of an integrated recycling process, as depicted in Figure 1, the waste generated in the wine industry may be converted into high-quality vermicompost containing beneficial biofertilizers and plant repellent properties.

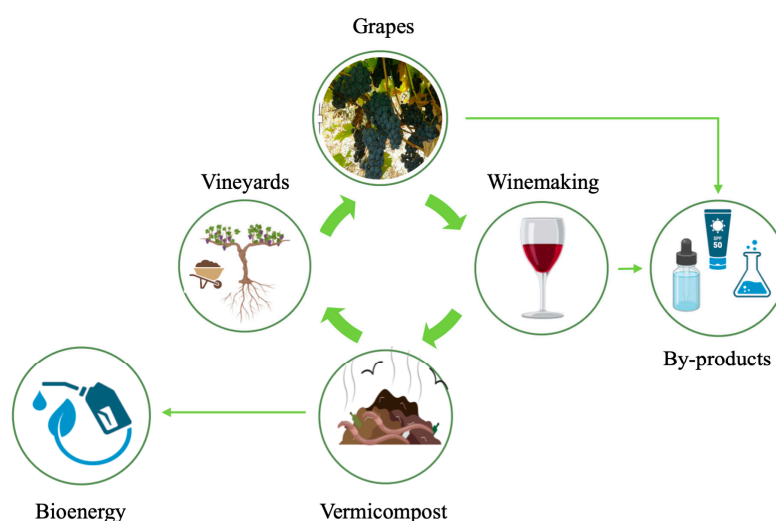


Figure 1. Schematic diagram for the winemaking process for zero waste and valuable by-products through vermicomposting. Green lines represent the flow of materials between different winemaking stages and resulting by-products or bioenergy sources.

This study is organized as follows: Section 2 presents the methodology used, Section 3 presents the valorization of by-products and wastes from winemaking process, Section 4 discusses an overview of the vermicompost production, while Sections 5 and 6 present the advantages of vermicompost and conclusions, respectively.

2. Methodology

The selection of the scientific literature for this review was made considering partially the following screening criteria:

- (a) **Relevant international databases and information sources.** Bibliometric sources such as Elsevier (Science Direct), MDPI, PubMed, Frontiers, Springer, and Wiley Online databases were used to retrieve articles, book chapters, and international proceedings articles. International databases of the European Commission were used for the selection of directives or reports related to the relevant keywords.
- (b) **Relevant keywords for the topics of interest were considered:** “grape pomace”, “grape marc”, “winemaking by-products”, “circular economy”, “vermicompost”, “valorisation of grape pomace”, “advantages of vermicompost”, “environmental”, “vineyards management”, “biofertilizers”.
- (c) **Period of publication:** articles between 2009 and 2024 were selected, published in the English language.
- (d) **Selection of the references cited in this review based on content analysis.** More than 139 articles were identified as interesting based on their abstracts, and 111 publications/reports were included, based on a thorough analysis of their content.

3. Valorization of By-Products and Wastes from Winemaking Process

Different techniques have been designed to reduce the environmental impact of wine technologies and promote their overall efficiency. These measures allow for the efficient recovery, management, and minimization of waste streams in line with the circular economy perspective, leading to a decrease in wine technologies’ environmental impacts while incorporating every component of the production chain and raising awareness [17]. In this regard, the wine industry is pushing for recycling solutions that would allow the waste to be used as raw materials for goods with additional value. The most significant (both in quantity and quality) by-products of the winemaking process are grape pomace and bagasse, which are significant sources of bioactive substances such as proteins, minerals, lipids, fibers in food, and polyphenols. They can be utilized for several different applications, as anthocyanin colorants, oils, or catechin polymers extracted from grape pomace and seeds. Additionally, the lees could be used for animal feed or, as a by-product in baked products. Table 1 presents a list with the most frequent compounds obtained from winemaking by-products.

Among the winemaking residues, the use of grape pomace is a great case study of the circular economy. Over 79 million tons of grapes are thought to be used each year, of which grape pomace makes up roughly 30%. Additional factors that should be considered are the environmental impacts and influence of climate change on the overall winemaking process. Ambient temperature and extreme weather fluctuations are among the factors that can negatively influence vine growth and, therefore, change the characteristics and quality of grape berries, must, wine, and pomace.

For example, according to Rogiers et al. [18], climate change in Australia is having a variety of effects on viticulture, such as earlier harvests and wines with higher alcohol levels and less acidity. It seems that the possibilities are numerous and cover a wide range of applications due to the chemical composition of grape pomace and its rich favorable compounds.

Grape pomace has a high concentration of bioactive chemicals, primarily phenolics [19], which have anti-inflammatory and antioxidant properties, and can be used as pharmaceuticals, cosmetics, animal feed, fertilizers, food additives, ingredients for dietary supplements, antimicrobial substances, medical remedies, or biomass for biofuels [13]. Moreover, it has a high concentration of soluble sugars that are beneficial for the fermenta-

tion of ethanol, producing a drink called “grape spirit” [20]. The production of industrial ethanol for the pharmaceutical and cosmetic industries might boost the economic value of residual sugar fermentation. By being used to produce bioethanol, grape pomace also has the potential to be a significant fossil fuel substitute [21]. Grape pomace and lees must be sent to alcohol distilleries in accordance with European Council Regulation (EC) 479/2008 so that they can be converted into exhausted grape pomace and a liquid waste known as vinasse [22]. Small wineries typically disregard this legislation, producing waste such as grape pomace, wine lees, and grape stalks.

Table 1. Main characteristics of major winemaking by-products.

Waste	Composition (w/w)	Percentage (%)	References
Grape pomace/grape marc/grape bagasse	Cellulose	10–75	[23–26]
	Hemicellulose	6.1	
	Lignin	34–41	
	Moisture content	50–70	
	Proteins	<4	
	Condensed tannins (insoluble)	15	
	Pectin substances	20	
	Neutral polysaccharides	30	
Grape stalks/grape stems	Cellulose	20–30	[23]
	Hemicellulose	15–20	
	Lignin	17–26	
	Condensed tannins (insoluble)	6–16	
	Proteins	6	
	Ashes	6–9	
	Soluble polyphenols	1–3	
Seeds	Lipids (oils and fatty acids)	13–15	[27]
	Dietary fibers	48	
	Proteins	11.5	
	Polyphenolic compounds	5–8	
	Carbohydrates	60–70	
Lees	Dead yeast	N/A	[28]
	Grape pulp		
	Inorganic matter		
	Phenolics		
	Tartaric acid		
	Ethanol		
Vine shoots	Cellulose	34	[24,29]
	Hemicellulose	20–30	
	Lignin	20–27	
	Tannin	1.25	
	Proteins	5	
	Ashes	3–4	

The pre-processing of by-products using vermicomposting is thought to be the most well-known and environmentally friendly method, especially for recycling and increasing the added value of solid organic wastes under aerobic conditions [30]. This process converts wastes into vermicomposts, which are nutrient-rich, microbiologically active, stabilized peat-like materials. As earthworms can partially digest the polyphenols that negatively influence the grape marc, vermicomposting could be considered as a promising method to mitigate allelopathic effects.

Lees of wine are the residues left in stainless steel or barrels after different winemaking stages, such as fermentation, storage, or after wine filtration or centrifugation. The main use of these lees is in the production of alcohol and tartrates, which results in a further by-product known as lees cake [31].

Stems or stalks, due to their skeletal structure, are normally removed during the destemming and crushing processes. These steps generate large amounts of wastes per winemaking of around 2 to 3 million tons per season [32].

Frequent uses for vine stalks are soil amendments, animal feed additive, the absorption of pollutants, biomass for bioethanol production, and the extraction of beneficial antioxidants [33].

Given that grape pomace contains a sizable amount of organic matter and macronutrients, applying it as an organic soil amendment appears to be the best method for maximizing its value [34]. However, because it releases tannins and polyphenols into the soil, the direct application of it may have phytotoxic and anti-microbial effects that could hinder plant growth. Furthermore, groundwater pollution, gas emissions, and soil oxygen depletion are additional detrimental effects [35]. Therefore, before grape pomace is applied to soil, these environmental concerns could be decreased by treating it with the adequate technologies. By using aerobic biodegradation processes to biologically treat grape bagasse, winery industries may be able to handle and process their waste materials in a way that both solves environmental issues and generates revenue from the sale of the final goods.

In Table 2, the values of chemical composition linked to grape pomace are represented. The main compound in dried grape pomace is dietary fiber, with a percentage of about 43% to 75%. Dietary fiber mostly consists of lignin and cell wall polysaccharides. In general, seeds have more fiber than skin, and red wine pulp has more fiber than white wine. Nonetheless, the standards recommend consuming 25–30 g day^{−1} of dietary fiber. In 2014, Gazzola et al. [36] characterized the proteins found in concentrated grape seeds. Depending on the varietal and growing factors, grape pomace can have a protein concentration of 6% to 15% dry matter (DM). The most common potassium salt is tartrate, specifically potassium bitartrate. Tartrates make up a sizable portion of the wine pomace, with values ranging from 4% to 14% (DM). Grapes have a total of 10% extractable phenolics in the pulp, 60% in the seeds, and 30% in the skins. Anthocyanins, hydroxybenzoic and hydroxycinnamic acids (particularly rich in tartaric esters of the latter, mainly caftaric acid and coutaric acid), flavonols, flavan-3-ols, and stilbenes seem to be the most abundant of several phenolic compounds previously found in pomace [37]. Grape seed oil is utilized in many different applications, most notably in the manufacture of cosmetics. Seed oil content ranges from 8% to 15% (*w/w*), with significant concentrations of unsaturated oleic and linoleic acids. The primary fatty acids in grape seed oil are linoleic acid (C18:2), oleic acid (C18:1), and palmitic acid (C16:0), with percentages of roughly 70%, 15%, and 7%, respectively [38].

Table 2. Average chemical composition values linked to grape pomace; original data according to Bordiga et al. [38].

Component	Grape Pomace
Dry matter (g kg ^{−1} FM)	329–490
Ash (g kg ^{−1} FM)	18–24
Organic matter (g kg ^{−1} DM)	827–959
Total sugars (g kg ^{−1} FM)	150–330
Neutral detergent fiber (g kg ^{−1} DM)	569–626
Acid detergent fiber (g kg ^{−1} DM)	480–543
Acid detergent lignin (g kg ^{−1} DM)	320–388
Total dietary fiber (g kg ^{−1} FM)	190–380
Total nitrogen (g kg ^{−1} DM)	10–17
Lipids (g kg ^{−1} FM)	4–10
Condensed tannins (g kg ^{−1} DM)	

Table 2. Cont.

Component	Grape Pomace
Free	16–38
Fiber-bound	19–34
Protein-bound	56–131
Total	91–203

FM—fresh matter; DM—dry matter.

3.1. Antimicrobial Effects

In recent years, consumers are paying growing attention to the origin of fresh food products from ecological sources, such as vegetables and fruits, especially grapes. Microbiological activity is a key factor in the production of safe and nutrient-rich grapes; therefore, producers are trying to diminish the use of synthetic antimicrobial compounds due to increased environmental and health concerns. Antimicrobial activity in phenolics is caused by iron deprivation or hydrogen bonding with microbial enzymes or vital proteins [39]. Natural phenolic flavonoids contain anthocyanins, flavonoid alkaloids, and anthoxanthins. Flavonols are regarded as the main phenolic compounds in grapes with antimicrobial properties. They have exhibited synergistic actions with antibiotics and are able to suppress pathogenic agents. Sateriale et al. [40] report favorable results regarding the ability of Aglianico (*V. vinifera* L.) grape pomace extracts to increase the antibacterial activity and act in combination with antibiotics to prevent the development of biofilms. This indicates that grape pomace extracts can be considered as good alternatives for the design of natural antimicrobial agents for the control of food-borne pathogens (Figure 2).

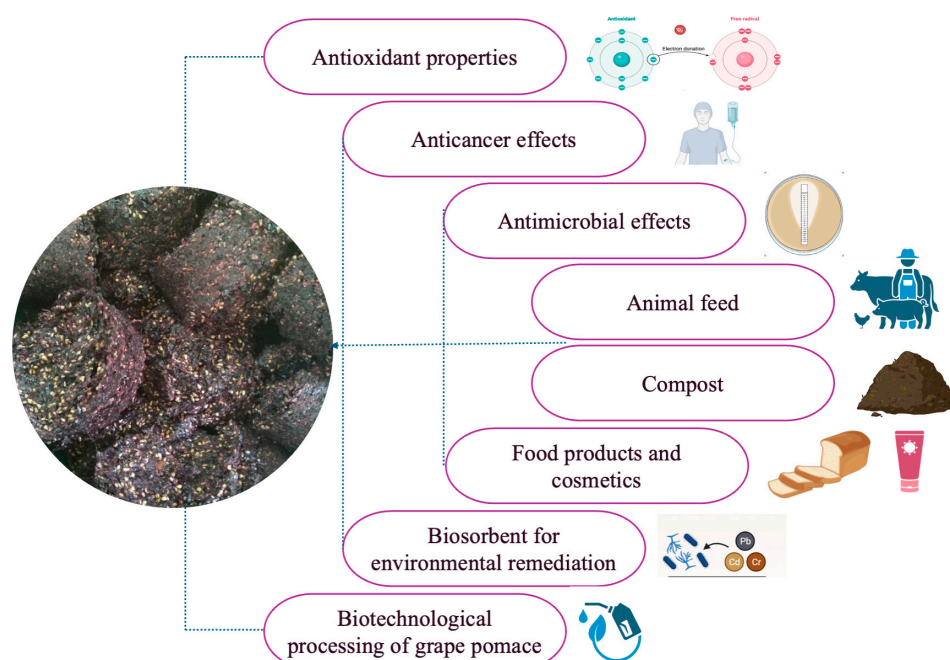


Figure 2. The usefulness and valorization of grape pomace.

3.2. Antioxidant Properties

Phenolic compounds with high antioxidant capacity can be extracted from grape marc, considering the circular economy principles. According to Kabir et al. [41], hydroxylated cinnamates have a greater number of increased beneficial effects than their benzoate counterparts. The antioxidant capacity of phenolic compounds could act as hydrogen donors, free radical binders, metal chelators, and singlet oxygen quenchers. The antimicrobial and antioxidant properties of food products aim to increase the physical–chemical

composition and their shelf life. Consumers are becoming more concerned about some of the adverse health effects of artificial additives frequently used by the food industry. This has encouraged the identification and wide use of antioxidants and antimicrobials naturally occurring in fresh food products. Dumitriu et al. [42] has reported that the use of an ethanolic extract from grape pomace in wine can increase the antioxidant properties of sweet wines. Moreover, the use of alternative fining agents during winemaking, at various doses, can influence the antioxidant activity and color parameters of “Cabernet Sauvignon” red wines [43]. Also, the aging period increases antioxidant activity levels and color in red wines by the higher accumulation of bioactive substances in finished wines [44].

3.3. Anticancer Effects

Grape marc is a wealthy source of phenolic compounds and is often utilized to enrich dietary supplements (Figure 2). Multiple pathways have been identified in cell line models, by which grape seed extract exhibits exceptional anti-tumor properties in prostate, breast, leukemia, bladder, colon, and other tumors [45]. Through the modification of the redox balance, grape seed may be able to contribute to the inhibition of cancer by acting as both a pro-oxidant and an antioxidant. A study by Del Pino-García et al. [46] investigated the effects of grape pomace used as a chemoprotective agent in colorectal therapies. In a second study, it was shown that phenolic acids extracted from seedless red wine marc had an increased bio-accessibility in the human colon than those from grape seeds, which tend to be easily digested in the small intestine [47].

3.4. Animal Feed

Numerous studies have explored the utilization of grape pomace as a possible ruminant feed ingredient over the past centuries. In the last few years, multiple scientists have shown that up to 3% of the total grape marc can be used in animal feed [48–51]. In the EU, dry grape extract is authorized as a potential feed additive for the majority of animal species, with the exception of dogs [51].

In a recent study by Marin et al. [52], the inclusion of grape seeds in the diet did not alter the behavior of pigs. However, it inhibited the protein export of molecules involved in regulation by decreasing the levels of certain cytokines of inflammation (IL-8, IL-1 β , IFN- γ , and TNF- α) in the pig liver. In pig feed, the incorporation of fermented grape marc improves meat color stability and total polyunsaturated fatty acids (PUFAs) in adipose (subcutaneous) fat whilst reducing lipid peroxidation. Moreover, according to the following assumptions of Kafantaris et al. [53], a specific quantity of grape pomace, when included in the feed, influences the productivity and redox capacity of porcine piglets by enhancing different antioxidant systems in the piglet’s body tissues and blood. The results were found to be comparable to the results of the *in vitro* investigation by Alipour and Rouzbehan [54], with grape pomace feed value and nutrient digestibility being better after ensiling but decreasing the levels of total phenolic content, especially for condensed tannins.

Ebrahimzadeh et al. [55] suggested that the addition of grape pomace to the diet of broiler chickens improved immunity and antioxidants and decreased the cost of the diet per kg of liveweight.

However, ensiling offers a possibility of storing grape marc (which is produced seasonally) for year-round use as a low-cost forage supplement, thereby enhancing its value potential. The available energy value of grape marc is limited in comparison to other dietary sources, such as wheat and oat straw [54].

3.5. Compost

Grape marc is a mixed product of pulp, stems, seeds, and skins, and, because of its inherent risk of contamination, it is not normally allowed to be used directly as a soil improver. To contribute to the improvement of soil quality and grape production, grape marc is an ecological waste that should be composted and reused as a soil conditioner and

organic fertilizer. The degree of stability and the level of maturity of the compost show the possibilities of the application of the organic waste treatment [56].

3.6. Food Products and Cosmetics

A nutrient-rich (macro- and micronutrients) and antioxidant-rich material, grape pomace is of high relevance for the development of new functional products, given the many benefits to health that can be derived from its consumption.

There are a plethora of studies on food products based on grape pomace products, such as the use of grape pomace and its derivatives to supplement meat and fish products [57,58]; the incorporation of grape pomace in dairy products [59,60]; and bakery products with added grape pomace—bread, biscuits, cookies, and muffins [61,62]. Grape pomace has also been studied as an added ingredient in other types of food not included in the aforementioned examples, such as cereals, pancakes, pasta, and salad dressings [63–65].

Grape pomace has been explored as a cosmetic component because it is a valuable source of oil. Wittenauer et al. [66] showed that raw grape by-product extract has an anticoagulant activity against proteolytic enzymes, such as collagenase and elastase, that degrade and disorganize extracellular proteins (such as collagen and elastin), proving its importance in such products. Glampedaki and Dutschk [67] have obtained aqueous solutions of wine and grape pomace oil, with potential use for the cosmetic industry. However, many studies on the use of grape pomace in the cosmetic industry describe the processes to obtain bioactive substances for subsequent incorporation into new products as a means of replacing synthetic compounds [68].

3.7. Biosorbents for Environmental Remediation

Some agricultural waste materials, such as grape marc, have been proposed as possible biomaterials for the elimination and/or recuperation of heavy metal contaminants from wastewater [69], which otherwise would cause high toxicity or other problems like bioaccumulation in the trophic chains (Figure 2).

The binding of metal ions is due to the presence of carboxyl or amino- or hydroxy-functional groups in the proteins and also in the phenolic compounds. The performance of different residue materials, including grape marc, for pesticide adsorption was studied by Rodríguez-Cruz et al. [70], who observed that the incorporation of the organic residual material in the soil improved the adsorption of the assessed synthetic hydrophobic pesticides. A similar trend was also found in the case of soils that had been exposed to these residues for twelve months before the application of pesticides, despite the decrease in adsorption ability due to variations in the level of carbon in the organic matter with the time of incubation.

An innovation from Perez-Ameneiro et al. [71] proposed the removal of phosphorus, ammonium, nitrate, potassium, magnesium, and sulphate micronutrients from winery wastewater by adsorption using grape marc immobilized in calcium alginate spheres. Grape marc was subjected to three months of anaerobic digestion treatment prior to adsorption with both sodium alginate and calcium chloride. Moreover, the addition of these nutrients could increase the adsorbent properties for later use as fertilizers [71]. This would substantially improve the potential for the utilization of sorbents, although it depends on the accessibility of the same trace elements for desorption after soil incorporation, which needs to be further investigated. However, the chemical analysis of pesticide residues in various wines seems not to have any direct consumer risk in the short- to long-term timeframe [72].

3.8. Biotechnological Processing of Grape Pomace to Produce Value-Added Products

Wineries worldwide produce approximately 13 million tons of grape marc waste each year. Most of this waste contains carbohydrates that can be directly converted into ethanol and other biofuels. Converting plant biomass into liquid biofuels can be a difficult process due to the structurally complex nature of plant material, which requires pre-treatment or

enzymes for efficient decomposition. The remaining residue can be used as animal feed or fertilizer [73]. In general, winery waste is of sufficient raw quality to form a series of valuable substrates in combustion technologies and to generate sufficient levels of heat and electricity.

Grape marc has the potential to produce biochar or combined gas mixtures at high temperatures. Grape marc contains many water-soluble carbohydrates, such as glucose and fructose, that can be converted to ethanol by fermentation, yielding up to 270 L/ton. During the fermentation process, the sugary part is broken down by the addition of *Saccharomyces cerevisiae* for conversion to ethanol. Ethanol is derived from biomass, which has sustainable potential as a transportation fuel and a substitute for gasoline [74]. Moreover, the energy balance among ethanol resulted from biomass, and the energy required to produce it is positive, which is a key factor in the production of renewable and globally available clean energy.

Consequently, the scientific community has been interested in researching alternative fining agents to encourage sustainable winemaking practices. Due to its great tolerance, grape marc is an excellent solution for this process, and, as a result, there are many published research studies on grape marc fining in relation to commercial fining agents. Gil-Muñoz et al. [75] pointed out that fining with grape marc may have the potential to reduce the content of volatile compounds in wines but in a manner like that of commercial agents. Solfrizzo et al.'s [76] used grape pomace for removal of a contamination of red wines with Ochratoxin A (OTA). The results show that fining with an alternative fining, grape pomace, removes up to 80% of OTA.

Moreover, grape marc has been applied in studies regarding the decontamination of wastewater from both food and non-food industries. The available literature presents reports on the adsorption capacity of grape marc, both treated or untreated, for the elimination of undesirable compounds from aqueous media like pesticides and metals. The thermal process of grape pomace and other grapevine plant materials generates biochars, which show improved adsorption properties and contribute to the concepts of cleaner production and circular economy [77].

4. Overview of the Vermicompost Production

The aim of vermicomposting waste is two-fold: to preserve the environment and to obtain a clean and neutral fertilizer. The process of the bioconversion of biomass waste by vermicomposting, in line with the concepts of the circular economy, not only contributes to breaking the classical “produce, consume and discard” model of agriculture but also produces value-added products that have the potential to improve farmer revenues, crop yields, and soil health.

This would be of particular concern to the future winemaking process, which is expanding and yields a wide spectrum of liquid and solid waste products that require management, treatment, and re-use in a sustainable way.

Morphologically, vermicomposts have a consistent dark color and a muddy odor. They offer a greater total available surface area, which provides more microsites for microbial degradation and a greater adsorption and fixation of organic nutrients. Vermicompost is a valuable source of alternative organic amendments to soil, primarily because of its enhanced biotic properties.

Vermicompost is a major source of macro- and micro-nutrients, and it can provide significant key nutrients to crops to promote increased yields. The overall chemical characteristics of vermicompost are presented in Table 3. The physico-chemistry composition of vermicompost has a wide variability and is strongly dependent on the type of residues used [78–80].

Table 3. Physical–chemical properties of the vermicomposts, according to Kinigopoulou et al. [78], for vermicompost 1; Mazur-Pączka et al. [79] for vermicompost 2; and Romero et al. [80] for vermicompost 3.

Parameter	Units	Vermicompost 1 [78]	Vermicompost 2 [79]	Vermicompost 3 [80]
Organic carbon		-	98,153	-
Total nitrogen		37,000	4911	-
P		623	274	3700
K		1300	3563	1500
Na		8400	-	114
Mg		4430	288	4800
Ca	mg kg ⁻¹	15,670	1989	38,000
Fe		304	-	1100
Cu		42.4	-	87
Mn		304	-	95
Zn		492	-	99
Cd		-	0.8	-
Pb		-	0.7	-
C/N ratio	-	7.5	19.98	11
pH	-	5.6	6.33	7.6

These properties have been associated with the circulation of plant growth factors, such as fulvic and humic acids, in the soil or plant growth medium, as well as their ability to provide plants with plant growth hormones, like auxins, gibberellins, etc. [20,21].

Vermicomposting has been demonstrated by a large number of studies to be a suitable process for the management of raw grape marc from both white and red oenological processes (Table 4), resulting in a nutrient-rich, biologically active, and polyphenol-free end product. This category of winemaking by-product has the capacity to be a useful amendment to soils if handled correctly and in a sustainable manner. However, management strategies should consider that some phenolic compounds have the potential to be harmful to plants, and their occurrence in soils can interfere with seed viability and affect the growth of root systems.

Table 4. An outline of vermicomposting research relating to the raw and distilled grape pomace.

Materials	Grape Variety	Set-Up Conditions	Days	References
Grape pomace	White grape pomace (<i>Vitis vinifera</i> cv. Albariño)	Laboratory scale	720	[81]
Grape pomace	White grape pomace (<i>Vitis vinifera</i> cv. Albariño)	Pilot scale	112	[82]
Grape pomace	White grape pomace (<i>Vitis vinifera</i> cv. Albariño)	Pilot scale	720	[81]
Grape pomace	White grape pomace (<i>Vitis vinifera</i> cv. Albariño)	Pilot scale	91	[83]
Grape pomace	Red grape pomace (<i>Vitis vinifera</i> cv. Mencía)	Pilot scale	91	[84]
Grape pomace	Red grape pomace (<i>Vitis vinifera</i> cv. Mencía)	Pilot scale	112	[85]
Grape pomace	White and red grape pomace (<i>Vitis vinifera</i> cv. Albariño and Mencía)	Pilot scale	63	[86]
Grape pomace	White and red grape pomace (<i>Vitis vinifera</i> cv. Albariño and Mencía)	Laboratory scale	294	[8]
Distilled pomace	White grape pomace (<i>Vitis vinifera</i> cv. Albariño)	Pilot scale	42	[87]
Distilled pomace	Not specified	Pilot scale	180	[88]

A series of stages are involved to realize the efficient bioconversion of organic wastes to vermicompost. The first stage refers to microbial decomposition, where the microbes present in the waste start the decomposition process. Simultaneously, this stage is characterized by the active ingestion of waste by worms and burrowing through the waste. The second stage consists of earthworm burrowing and biomass ingestion. Earthworms, waste-associated microorganisms, and earthworm-associated microbes work together to promote the vermicomposition of biomass material into highly nutrient-dense (N, P, and K) materials suitable for agricultural soil fertilization. It is noteworthy to note at this stage that earthworms reside in the higher layers of the decaying waste, around 4–6 inches (10–15 cm) deep [89]. This final phase may be called maturation or aging. High nutrient content, a declining microbial population, and increased enzyme activity are characteristics of aging vermicompost. An excellent sign of a mature vermicompost is its carbon-to-nitrogen ratio (C:N), which should be between 12 and 25. Multiple studies indicate that the optimal level should be below 15. Also, other measured maturity parameters of vermicompost are humus contents, germination index, and dissolved organic carbon. The vermicompost obtained through this process is suitable for direct use on farms and promotes plant vegetative growth, seed germination, fertility, soil conditioning, yield, and disease pressure suppression [89].

Vermicomposting is a suitable, environmentally friendly method to biostabilize raw pomace from white and red wine production processes, according to research by Gómez-Brandón et al. [85]. Further studies are required to ascertain the ideal rate of change in order to guarantee the high nutrient release and synchronization of plant absorption, enhanced yield, and improved plant nutritional quality when vermicompost made from grape pomace is applied in the field. Furthermore, Gómez-Brandón et al. [86] discovered that the vermicompost made from the Mencia and Albarino grape types had the ideal levels of electrical conductivity (EC), pH, and moisture for application to soil. The micro- and macronutrient content increased as the mass fell as a result of earthworm activity. Additionally, it was noted that the amount of microbial biomass and its activity declined after 42 weeks, both with and without earthworm treatment, suggesting that the material had stabilized. During 16-week laboratory trials, Nogales et al. [88] also noted that the combined action of earthworms and microorganisms boosted the biodegradation of different winery wastes. This was corroborated by the disappearance of hydrolytic enzyme activities, such as β -glucosidase, particularly in the last phases of the vermicomposting process, which was most likely caused by the gradual depletion of easily accessible organic substrates.

In addition, vermicompost is known to reduce pesticide content due to its high organic matter content. In a recent study, vermicomposts were shown to decrease the presence of diuron in soils of sandy loam with poor organic carbon content, thus limiting the risk of the leaching of systemic herbicide in a winery–distillery setup. The presence of large amounts of organic carbon and lignin in this type of vermicompost helps to explain its high pesticide sorption capabilities [90].

Nevertheless, a more in-depth analysis of the contribution of exogenous degradation enzymes is required to understand the specific mechanisms involved in vermicompost-based bioremediation.

5. Advantages and Disadvantages of Vermicompost

Vermicompost is a win–win technique because it not only deals with the pollution caused by organic waste but also recovers the nutrients necessary for plants and enables resource utilization (Figure 3). Earthworms decompose organic matter and increase the availability of nutrients such as phosphorus, nitrogen, and potassium that can stimulate plant growth [91]. Moreover, earthworms ventilate the soil, ameliorate its texture, and let water and air move more easily from surface to plant roots.

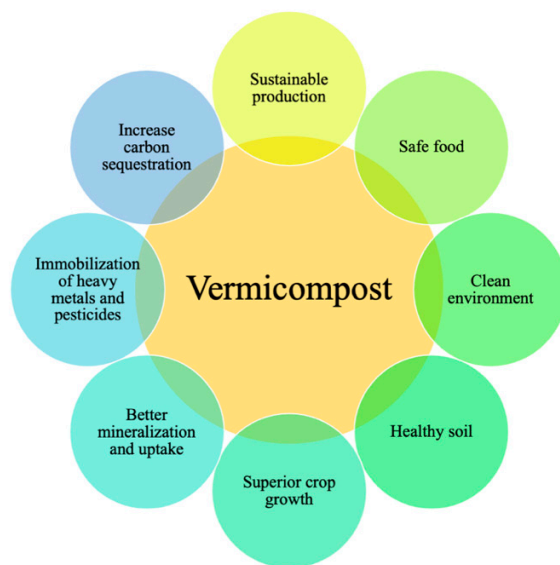


Figure 3. Advantages of use of vermicompost in neutral agriculture practices.

“Worms are the intestines of the earth”, as affirmed by Aristotle, emphasizes the interconnectedness of all living things and the importance of positive ecological balance [92]. Moreover, earthworms are known to be efficient metal accumulators because they can function as ecosystem engineers [93]. Microorganisms play a significant role in vermicomposting by decomposing and mineralizing organic residues from wastes [94]. Extracellular digestive enzymes secreted by these bacteria facilitate the breakdown of complex substances, including cellulose and phenolic compounds [95]. The earthworms in this mesophilic technique, which uses microbes and worms active at 10–30 °C, break down waste materials into vermicompost, or “black gold”, much more quickly than in a standard composting procedure.

The American Earthworm Technology Company produced 500 metric tonnes of vermicompost, which is worldwide-recognized for developing this environmentally beneficial waste management method in the late 1970s [96]. Since then, vermicomposting has gained popularity in a number of nations, including the United States, the Philippines, Japan, the United Kingdom, Cuba, France, Italy, and India [97].

In comparison to non-composted organic wastes and mineral fertilizers, vermicompost has several benefits that enhance crop growth, biomass, and yield. Humic and fulvic acids help vermicompost release nutrients gradually, which improves the plant availability of soil nutrients and encourages root development for improved nutrient and water uptake. Vermicompost also transforms inaccessible nutrients into forms that are readily available to plants, giving them access to micro and macronutrients. Additionally, it has been discovered to have more sulfur than fertilizers made of minerals. Even though vermicompost has a lower organic carbon content than other organic manures, the constant application of vermicompost helps the soil accumulate carbon. It guarantees a sufficient supply of nitrogen, enhancing soil characteristics and carbon sequestration [98].

Vermicompost provides vital nutrients, active compounds that promote growth (such as auxins, gibberellins, and cytokinins), and is non-toxic to plants. It is also environmentally benign. In addition to providing beneficial properties such as permeability, aeration, drainage, and microbiological activity, these substances promote plant growth. Moreover, it is an environmentally friendly method of waste management that yields several advantages, such as less trash ending up in landfills, the production of high-grade fertilizer, and enhanced soil health [99,100]. It is an excellent method for waste management in both rural and urban locations since it is easy to use, inexpensive, and adaptable [97]. It has been demonstrated that vermicompost increases soil fertility and lowers levels of harmful metals, including Cd, Pb, and As [101]. Urmi et al. [98] examined several treatments in

relation to carbon sequestration in grain crops to determine how they affected the organic carbon stock, total carbon stock, and organic carbon sequestration. These methods hold great promise for reducing carbon emissions and advancing sustainable farming practices.

Notwithstanding the manifold advantages of vermicompost and organic manures, there are certain constraints associated with their extensive use in grain crops. Difficulties include high transportation costs, high application rates, and environmental concerns related to their use; these are especially problematic in developing nations with scarce animal supplies and a fuel dependence on agricultural waste. To assure the overall production and exploitation of vermicomposts, it is necessary to investigate possible solutions for these difficulties (Figure 3).

In the literature, there are few reports of potential disadvantages to vermicomposting, such as adequate management required and the monitoring of some parameters (pH, temperature, humidity, and C:N ratio); this process requires a lot of labor, time, space, and costs [102,103]. Moreover, worms seem to have a negative impact on pathogen activity in soils. Also, worms show a high sensibility to soils with variable pH and moisture content, making the application of this agriculture practice labor consuming due to the necessity of supplementary physico-chemical soil parameter control [103].

Vermicompost has gained significant attention in horticultural practices. Its application in the production of vegetables and fruits has shown promising results in improving growth, yields, and nutritive qualities. Recent studies in the literature demonstrate the effectiveness of vermicomposting in cucumber [104], strawberry [105], tomato, cabbage plant [94], and spinach production [106]. The major advantage of vermicompost is that it resembles peat and has much better stability and water-holding capacity. For improved winemaking practices, earthworms (*Eisenia andrei*) have been utilized in a number of studies to cure raw white grape marc at the lab and on pilot scales [8,82] for up to 16 weeks. According to the findings of these studies, the grape marc stabilized after around two weeks, as shown by decreased levels of cellulose content and microbial activity. Extended investigations surpassing 16 weeks revealed a noteworthy reduction in carbon-to-nitrogen (C:N) ratios, phenolic content, and phytotoxicity in contrast to an increase in pH and nutritional content. Particularly, in the Domínguez et al. [82] study, organic matter fell from 91% to 75% and pH raised from 4.36 to 7.10 throughout the course of 112 days of vermi-reactor operation. From an initial value of 58 mg gallic acid equivalent/g dry weight (GAE/g dw), the polyphenol content of the grape marc decreased by around 80% to 12.5 mg GAE/g dw. This suggests that vermicomposting is a promising tool that can reduce the polyphenol content of grape marc and generate compost with high agronomic values that can be used as a soil fertilizer.

Paradelo et al. [107] reported that grape-marc vermicompost had an influence on vineyard soil. In soil treated with 2.4 and 4% dry-weight grape-marc vermicompost, nitrogen and carbon mineralization were observed. The addition of grape-marc vermicompost increased both the soil's potential for carbon mineralization and its available nitrogen concentration compared to the unmodified control. Modeling indicates that mass additions of 1.7–2.1 t/ha of vermicompost would be required to maintain levels of organic matter in vineyard soil.

Reintroducing vermicomposted grape marc to the vineyard soil provides benefits beyond maintaining organic carbon levels, as noted by Paradelo et al. [107]. By restoring lost nutrients like phosphate and nitrogen to the soil, it also aids in its recovery. Gómez-Brandón et al. [108] evaluated the efficacy of vermicomposting for the valuation of distilled grape marc, one of the main solid by-products of the winery industry, over the course of a 56-day pilot research. The number of total polyphenol and microbial activity both sharply decreased after 14 days of vermicomposting, which is indicative of stable materials.

The findings of Palenzuela et al. [109] indicate that the spent substrate of mushroom cultivation compost and vermicompost added to vineyard soil increases its organic matter and macronutrient content while having no negative effects on its physico-chemical properties. Among the oenological criteria that are typically examined, the largest concentration of chemicals that give wines their crimson and violet colors comes from grapes that have

been treated with vermicompost. The vermicompost wine had the largest concentration of fragrances, particularly fruity, flowery, herbal, green fruit, fatty, and waxy scents, according to the composition of aromas. Last but not least, compost wine had the lowest overall scores for the scent series; yet, its fatty, citrus, and green series outperformed the others.

Additionally, in terms of plant health and safe agricultural usage, the end product's macro- and micronutrient content matched those considered necessary for a high-quality vermicompost. Overall, it demonstrates the potential of vermicomposting as an environmentally friendly technique for the biological stabilization of distilled grape marc that meets the demands of both environmental preservation and fertilizer production. Rosado et al. [110] demonstrated in their study the feasibility of establishing an integrated cycle that would allow the bagasse produced in the wine industry to be transformed into premium vermicompost with attributes of both biostimulator and vine protection. Sustainability is based on methods that allow valuable by-products to be recovered with the least amount of waste stream discharge. Multiple studies have showed that using vermicompost in the winemaking industry has the potential to increase yields, improve quality, and reduce costs for farmers. Vermicompost introduction in vineyards will eventually produce more environmentally friendly, sustainable, and neutral wines with distinctive qualities and typicity.

6. Conclusions

The wine industry can benefit substantially from the reuse of residual grape waste by generating a range of high value-added products. Wine production is an industry that generates significant amounts of waste, which should be managed accordingly.

Recently, the academic and professional winemaking communities focused on more profitable and environmentally responsible practices for managing the wine production process, while trying to add value for winemaking wastes. Vermicomposting is an economical and eco-friendly technique for waste management and biofertilizer production. Research can improve the knowledge of practicing vermicomposting in the wine industry and contribute to the development of farming practices that are both economical viable and more environmentally sustainable. For an industry-scale implementation of vermicompost from grape marc, there is still a need for further technological and agronomical investigations to establish the optimal rate to ensure high nutrient availability and synchronization for plant absorption and an improved yield and nutritional content of the crop.

An additional benefit of vermicomposting is that it improves soil organic carbon and sequesters aggregate carbon, leading to a wine industry with a neutral carbon footprint. In this context, wineries should consider the sustainable valorization of pomace as a useful strategy to minimize their environmental impact and as a tool to reduce their carbon footprint throughout the production process.

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