



Grape Marc and Beyond: A Critical Review of Decoding Vermicompost Applications in Viticulture - Impacts on Soil, Microbiota, Plant Nutrition, and Dark Aspects

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Received: 20 January 2026 / Accepted: 12 May 2026 / Published online: 23 May 2026
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Abstract

Vermicompost is increasingly promoted as a circular, low-impact amendment for vineyard soils. However, its agronomic performance and constraints remain contrasting in several studies. This review integrates evidence on vermicompost produced from winery by-products (e.g., grape marc) and from non-winery feedstocks, both applied in vineyard systems. This review is organized around two complementary themes that remain underexplored in the literature, designed to capture the full vineyard ecosystem. (1) Effects of winery waste-derived vermicompost on crops and vineyards. We synthesize evidence on vermicompost produced from winery residues (e.g., grape marc), examining three outcome domains: germination and early growth, soils and microbiota, and yield and quality, first in *Vitis vinifera* L. and then in other crops. This cross-crop lens is used to identify shared mechanisms, dose ranges, and boundary conditions relevant to vineyard practice. (2) Application of vermicompost from alternative substrates in vineyard systems. We evaluate vermicomposts sourced from non-winery feedstocks (e.g., livestock manures) applied to vineyards, using the same three outcome domains. This tests the generalizability of benefits and risks beyond winery residues, enabling feedstock-specific comparisons (chemistry, maturity, salinity, micronutrients/trace metals). A whole-system vineyard perspective was adopted: circular flow of biomass from pruning residues and grape marc through their conversion into vermicompost, to its reintegration as an amendment in vineyards and, where relevant, in non-vine crops, thereby closing the grapevine-by-product loop. Finally, the last section addresses challenges and limitations (e.g., product heterogeneity, short study horizons, cation imbalances, metal mobilization, and methodological limits of microbiome inference), followed by Environmental footprint and Life Cycle Assessment considerations.

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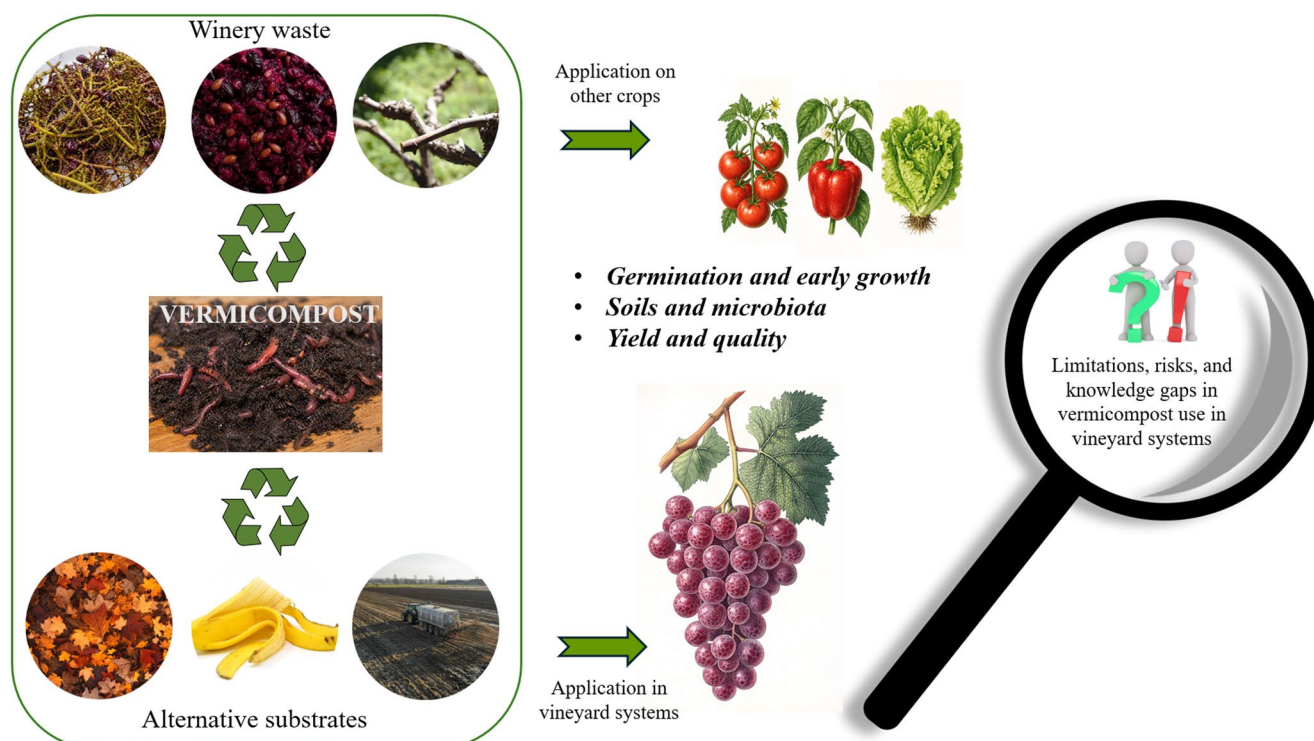
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Graphical abstract



Keywords Agricultural practices · winery industry · sustainability · grapevine · soil management

Abbreviations

C/N	Carbon to Nitrogen rate
OM	Organic Matter
EC	Electrical Conductivity
HMs	Heavy Metals
GI	Germination Index
GMV	Grape Marc-derived Vermicompost
LCA	Life Cycle Assessment
MPs	microplastics
AAPFCO	American Plant Food Control Officials

1 Background

1.1 Vermicomposting Process and Legislative Provisions

Vermicomposting represents a biological process that focuses on bio-oxidative transformations to convert organic waste into a stable, homogeneous, and humified product eligible for use as a soil amendment. This process is driven by the synergistic activity of earthworms and microorganisms (Lim et al. 2015). But what is the main difference with composting? Vermicomposting differs from traditional

composting primarily due to the active involvement of earthworms, which play a fundamental role in sustaining aerobic environments, mechanically breaking down organic material to expand the surface area accessible to microbial colonization, and progressively influencing the substrate's physical and chemical properties. Organic matter is homogenized during gut transit, and the resulting nutrient-rich casts enhance the agronomic value of vermicompost (Wang et al. 2007; Olle 2019; Vuković et al. 2021).

The vermicomposting process can be structured into four main steps, summarized in Table 1.

Each phase is characterized by distinct biological actors, environmental conditions, and biochemical transformations (Olle 2019; Mohite et al. 2024; Madhushani et al. 2024).

Vermicomposting predominantly employs epigei, or surface-dwelling earthworm species, as well as *Eisenia fetida*, *E. andrei*, *Eudrilus eugeniae*, and *Perionyx excavatus*. These species are preferred because of their ease of cultivation, rapid reproduction, adaptability to a variety of environmental conditions, and strong affinity for organic substrates (Chanu et al. 2019; Vuković et al. 2021).

Although the term “vermicompost” is commonly used in scientific literature to describe the product derived from the bioconversion of organic substrates by earthworms, its

Table 1 Overview of the main phases of the vermicomposting phases, including the typical ranges of key physicochemical parameters (i.e., temperature, moisture, pH, C/N ratio, and electrical conductivity), CO₂ respiration, humification index (HI), duration, oxygen conditions, and associated biotic activity. The table also summarizes the dominant biochemical processes and shifts in microbial and earthworm communities occurring from pre-composting to maturation and stabilization

Phase	Temp (°C)	Moisture (%)	pH	C/N	EC (dS/m)	CO ₂ Resp. (mg CO ₂ /g/d)	HI	Duration (days)	Oxygen conditions	Main process	Biotic activity
Pre-composting	45–65	50–60	6.96–7.85	20–60	2.0–4.5	High (around 1/3 of the CO ₂ emitted in the entire process)	10–20	9–15	Aerobic	Decomposition of volatile compounds, sanitization, and detoxification	Microbial only. Thermophilic microorganisms. <i>Bacillus</i> , <i>Pseudomonas</i> , <i>Pseudoxanthomonas</i> , lactic acid bacteria, biostimulant yeasts.
References	(Frederickson et al. 2007)	(Bernal et al. 2009)	(Frederickson et al. 2007)	(; Ravindran and Mneni 2016)	(Ravindran and Mneni 2016)	(Zhang et al. 2021)	(Jakubus and Michalak-Oparowska 2022)	(Nair et al. 2006; Olle 2019)	(Rostami 2011)	(Rostami 2011; Olle 2019; Madhushani et al. 2024)	(Bianco et al. 2022)
Adaptation and colonization	23–27.5	75–100	6–7	25–30	1.5–3.0	Increase	10–15	~10	Aerobic	Earthworm inoculation, early microbial structuring	Earthworms and mesophilic microorganisms. Low diversity; mostly Proteobacteria.
References	(Ravindran et al. 2019; Md Zaini and Syafi 2021)	(Ravindran et al. 2019)	(Ravindran et al. 2019; Cai et al. 2020; Md Zaini and Syafi 2021)	(Madhushani et al. 2024)	(Ravindran and Mneni 2016; Md Zaini and Syafi 2021)	(Santana et al. 2020)	(Ganguly and Chakraborty 2019)	(Kharbouch et al. 2018)	(Madhushani et al. 2024)	(Chen et al. 2018)	(Cai et al. 2018; Vuković et al. 2021; Karapantou et al. 2023)
Active vermidegradation	15–28	70–90	5.0–8.0	10–20	1–2.5	Peak and gradual reduction	10–15	~45	Aerobic	Maximum biological activity, humification, and N mineralization	Earthworms and mesophilic microorganisms. Increasing diversity. Firmicutes, Proteobacteria, Actinobacteria

Table 1 (continued)

Phase	Temp (°C)	Moisture (%)	pH	C/N	EC (dS/m)	CO ₂ Resp. (mg CO ₂ /g/d)	HI	Duration (days)	Oxygen conditions	Main process	Biotic activity
References	(Ram-narain et al. 2019; Md Zaini and Syafi 2021; Mad-hushani et al. 2024)	(Ram-narain et al. 2019; Mad-hushani et al. 2024)	(Mad-hushani et al. 2024)	(Dume et al. 2023)	(Ravindran and Mnkani 2016; Md Zaini and Syafi 2021)	(Santana et al. 2020)	(Ganguly and Chakraborty 2019)	(Ferraz Ramos et al. 2022)	(Madhushani et al. 2024)	(Olle 2019; Madhushani et al. 2024)	(Cai et al. 2018; Vuković et al. 2021; Karapant-zou et al. 2023)
Maturation and stabilization	20–28	> 5	7.0–8.0	< 20	0.5–2.0	Low (< 2)	1.5–5	~ 75–120	Aerobic	Final stabilization, earthworm displacement, high microbial activity, polymerization of humic substances	Mainly microbial, minimal earthworms' activity. High diversity. Firmicutes (<i>Bacillus</i>), Proteobacteria (Azotobacter, <i>Pseudomonas</i> spp.), Actinobacteria (<i>Streptomyces</i> , <i>Cellulomonodaceae</i>)
References	(Ram-narain et al. 2019; Md Zaini and Syafi 2021)	(Mad-hushani et al. 2024)	(Ram-narain et al. 2019; Cai et al. 2020; Md Zaini and Syafi 2021)	Cai et al. 2020; Dume et al. 2023)	(Ravindran and Mnkani 2016; Md Zaini and Syafi 2021)	(Khatua et al. 2018)	(Ganguly and Chakraborty 2019; Das and Deka 2021)	(Ferraz Ramos et al. 2022)	(Madhushani et al. 2024)	(Madhushani et al. 2024)	(Cai et al. 2018; Vuković et al. 2021; Karapant-zou et al. 2023)

legal status varies across different regulatory systems. In the European Union (EU), the Fertilizing Products Regulation (Regulation (EU) 2019/1009 (2019)) harmonizes the directives for fertilizer production, including both inorganic and organic materials, such as organic soil amendments and compost. While vermicompost is not explicitly listed as a standalone category, it may be considered and marketed as a Component Material Category (CMC), such as compost, if it meets specified safety, traceability, and quality requirements, including limits for contaminants such as heavy metals, pathogens, and physical impurities (Falco et al. 2021; Reg (EU) 2019/1009 (2019)). Additional EU directives further support the use of vermicompost in agriculture. The Waste Framework Directive (Directive 2008/98/EC (2008)) promotes composting and vermicomposting as preferred methods for organic waste recovery within the waste management hierarchy (Directive 2008/98/EC (2008)). The Nitrates Directive (Directive 91/676/EEC (1991)) regulates the use of nitrogen-based fertilizers in vulnerable zones, encouraging practices, such as stabilized organic amendments utilization, like vermicompost, that reduce nutrient leaching and support sustainable fertilization (Directive 91/676/EEC (1991)).

Looking specifically at Italian legislation, it aligns with the EU framework but adds specific provisions through Legislative Decree 75/2010, which regulates the production and marketing of fertilizers and soil improvers. Italy does not define vermicompost as an autonomous category. Instead, vermicompost may be marketed under the classification of “mixed composted soil amendment” provided it meets the following requirements:

- The initial organic matrix must contain at least 20% mature livestock manure (on a dry weight basis);
- The composting process has to be managed under controlled aerobic conditions;
- The final product must comply with chemical (i.e., total organic carbon $\geq 20\%$, carbon-C/N ratio ≤ 25 , pH between 6.0 and 8.5) and microbiological (i.e., *Salmonella* spp. absence in 25.0 g, *Escherichia coli* under 1,000 CFU/g) standards.

From this, it follows that if vermicomposting is processed using only plant residues or pruning waste, without the inclusion of manure, the resulting material, although technically a vermicompost, cannot be legally labelled and marketed as “vermicompost” under Italian law. However, in such cases, this material can be used internally in agricultural operations as an on-farm amendment, but it cannot be placed on the market under the name “vermicompost,” nor registered as a fertilizer compliant with national regulations

(D.Lgs. 75/2010 (2010)); Falco et al. 2021; Vannucchi et al. 2024).

In the USA, the regulatory framework surrounding vermicompost involves a combination of federal, state, and local provisions. At the federal rank, the Environmental Protection Agency (EPA) regulates compost use but does not have specific regulations exclusively for vermicompost. Regulatory oversight is primarily focused on biosolids and solid waste management. In this context, vermicompost is only subject to stricter federal rules if the feedstock is derived from sewage sludge, in which case it may fall under the scope of the 40 CFR Part 503 Biosolids Rule (US EPA 2015). However, vermicompost use in organic farming is settled by the United States Department of Agriculture (USDA) under the National Organic Program (NOP). In accordance with the guidance document NOP 5021, a product can be classified as “vermicompost” and considered stable if certain conditions are met, such as a minimum processing duration of 30 days with active digestion promoted by earthworms (e.g., *E. fetida*), and if the final product is free from pathogens and viable weed seeds (NOP 5021 2011).

At the state level, regulations can vary significantly. Some states, such as California and Washington, have established rigorous ordinances for the production, registration, testing, and labelling of compost and vermicompost. Additionally, several states adopt or incorporate the guidelines of the US Composting Council’s Seal of Testing Assurance (STA), which sets quality and safety standards for parameters such as pH, salinity, heavy metals, and pathogen levels (US Composting Council ((US n.d.))). Finally, products sold as fertilizers or soil amendments must comply with specific labelling requirements. The Association of American Plant Food Control Officials (AAPFCO) fixes standard terminology for products like “Vermicompost,” “Worm Castings,” and “Soil Amendment.” In some states, additional requirements may apply regarding nutrient content, intended use, and product registration (AAPFCO 2017).

As regulatory frameworks surrounding vermicompost continue to evolve across regions, attention is increasingly shifting from purely legal definitions to its functional role in sustainable agriculture. This shift is especially relevant in perennial cropping systems such as vineyards, where soil functional integrity determines a pivotal role in long-term yield stability and adaptive capacity to climate change (Cataldo et al. 2022). In this regard, vermicompost offers a compelling opportunity, not only as a soil amendment but also as a means of transforming the substantial organic waste produced by the oenological industry into a high-value agronomic input. The wine chain, in particular, generates large volumes of organic residues, such as grape marc, stalks, and pruning waste, which often remain underutilized

or improperly managed (Zhang et al. 2017). Vermicomposting offers an effective means of transforming these materials into a valuable input that improves soil structure, nutrient cycling, and microbial vitality. As climate-related issues such as water stress and heat intensify, holding soil health becomes essential for ensuring crop resilience and productivity. By integrating waste valorisation with soil restoration, vermicompost offers a circular, climate-smart arrangement that adapts to the sustainable viticulture principles and contributes to long-term agroecosystem stability (Gabur et al. 2024).

1.2 Winery Industry by-Products as a Resource

The viticulture sector and the associated wine industry play a major role in the global economy and in social development, covering roughly 7,200,000 ha of vineyard and producing around 237 million hectoliters of wine annually (Molina-Alcaide et al. 2008; OIV 2024). As a consequence of this large-scale production, significant quantities of by-products are generated worldwide each year, mainly in the form of vine pruning residues (2–4 million tonnes per year), grape pomace or marc (10.5–13.1 million tonnes), and wine lees (1.26 million tonnes) (Molina-Alcaide et al. 2008; Nascimento-Gonçalves et al. 2024; Chetrariu et al. 2025).

Although winery residues can be directly incorporated into agricultural soils, their application is often constrained by unfavourable physicochemical properties, such as unsuitable pH (around 3.0–4.0), elevated carbon-to-nitrogen (C/N) ratios, and the presence of phytotoxic compounds like polyphenols, which may hinder seed germination and microbial activity.

Among these residues, pruning material is the most abundant in viticulture. It is chiefly composed of cellulose, hemicellulose, and lignin, and is typically disposed of by open-field burning, which contributes to CO₂ emissions and environmental pollution (Jesus et al. 2022).

Its return to the vineyard soil may also pose phytosanitary risks, as it can promote the spread of pathogens including *Phaeoemoniella chlamydospora*, *Phaeoacremonium minimum*, and *Eutypa lata*, all associated with major grapevine trunk diseases (Gramaje et al. 2018; Nascimento-Gonçalves et al. 2024). Pruning residues constitute a lignocellulosic by-product characterized by elevated C: N ratios (typically 60–80), which inherently constrain their biodegradability and reduce microbial activity during vermicomposting. To mitigate this nutritional imbalance, external nitrogen inputs are frequently required; in some systems, the addition of mineral N sources (e.g., urea) has been adopted to stimulate microbial metabolism and accelerate organic matter decomposition (Wang and Schuchardt 2010). Nevertheless, within the framework of winery waste management,

a more ecologically sustainable strategy consists in the co-composting of pruning residues with nitrogen-enriched winery by-products, such as grape marc or vinasse sludge. This integrative approach not only optimizes the nutrient balance but also counteracts the acidic conditions often associated with wine-derived residues, thereby promoting more favorable conditions for earthworm activity, microbial succession, and the stabilization of organic matter during vermicomposting (Nogales et al. 2005).

Furthermore, from a life-cycle perspective, vineyard residue management significantly affects the environmental performance of wine systems, as grape production contributes on average 39% of the impact categories per 0.75 L of wine, mainly due to pruning waste management and diesel consumption by agricultural machinery (Harb et al. 2021). LCA (life cycle assessment) studies indicate that integrating by-products into closed-loop systems leads to more favourable environmental outcomes compared to conventional waste management, mainly through biomass valorisation and improved resource efficiency (Cinardi et al. 2024, 2026).

Grape marc depicts the principal solid by-product of the winemaking process. It consists of skins, pulp, and seeds (Rodriguez et al. 2025) and is rich in polyphenolic compounds, qualifying it as a promising raw material for the extraction of oils, antioxidants, antimicrobials, and, especially from red grapes, anthocyanins, which are widely used as natural food colorants (Streche et al. 2023). Grape marc is commonly sent to distilleries to recover residual ethanol for the production of alcoholic beverages, resulting in a secondary by-product: exhausted grape marc (Gómez-Brandón et al. 2023). It may also be used as animal feed, although its high polyphenol content can negatively affect rumen microbes and enzyme activity, reducing digestibility (Gómez-Brandón et al. 2019). Its employment as a soil amendment aligns well with circular economy principles, due to its high content of organic matter and nutrients, and the large volumes produced annually. Indeed, grape marc typically accounts for 11–35% of the crushed grape's total weight, depending on grape variety and processing method. However, direct application is limited by several factors: low pH, seasonal availability, and the presence of phytotoxic compounds, namely phenols, ethanol, and organic acids (Paradelo et al. 2011; Muhlack et al. 2017; Gómez-Brandón et al. 2019). Composting or vermicomposting can help address these limitations, improving stability and agronomic value (Paradelo et al. 2011; Gómez-Brandón et al. 2020). Indeed, despite the initial acidity and high polyphenol content of grape marc can represent a source of stress or even toxicity for earthworms, when the process is properly managed (e.g. grape marc is pre-composted or mixed with other organic residues), vermicomposting, through the

combined action of earthworms and microorganisms, boosts the degradation of polyphenols, stabilization of organic matter, improvement of the C: N ratio, and the humic substances formation. Additionally, it fosters beneficial microbial communities and gradually stabilizes the pH toward neutrality (Nogales et al. 2005).

Other winemaking residues, such as wine lees, can be valorized through co-vermicomposting with grape marc or pruning waste. Although lees are acidic (pH < 5) and rich in organic compounds that may be phytotoxic, their combination with other byproducts may help improve vermicomposting process performance and reduce toxicity (Nogales et al. 2005; Romero Taboada et al. 2006).

But what is the innovative aspect of this review? The creativity of this review lies in its distinctive dual perspective, which encompasses two different but interconnected objectives. First, it offers a critical overview of vermicompost obtained from winery by-products and its application to crops, with a particular focus on grapevines, by addressing the important issue of by-products of the wine industry. Second, it examines the use of vermicompost produced from alternative organic substrates when applied to vineyard systems, providing a detailed overview of its uses and consequences in the vineyard. By linking these two areas, the review offers a more holistic perspective on the potential of vermicompost in viticulture from the by-products of viticulture used in production to its effect on the vine, emphasizing research gaps, highlighting new research directions, and underlining criticisms and future perspectives.

2 Literature Search and Selection Criteria

This review was conducted using a structured narrative approach aimed at critically synthesizing the available literature on vermicompost applications in viticulture and related systems. A comprehensive bibliographic search was performed across major scientific databases, including Web of Science, Scopus, and Google Scholar. Particular attention was given to studies published over the last 15 years, with a preference for the most recent contributions to reflect current advancements and trends in the field. The search strategy combined keywords related to vermicomposting processes, feedstock origin, and agronomic applications, such as “vermicompost”, “grape marc”, “winery waste”, “vineyard”, “*Vitis vinifera*”, “soil amendment”, “soil microbiota”, and “yield”. Additional keywords referring to non-winery substrates (e.g., “manure vermicompost”, “agricultural residues”) were included to expand the scope of comparison. The selection of studies was based on their relevance to the review’s objectives, prioritizing peer-reviewed articles that reported experimental evidence on the

effects of vermicompost on plant performance, soil physicochemical properties, microbial activity, and crop yield and quality.

After screening, the selected literature was analysed and organized into three main thematic domains: (i) germination and early growth, (ii) soil properties and microbiota, and (iii) yield and quality. Within each domain, studies were first examined in the context of grapevine systems and subsequently extended to other crops when relevant. This classification was adopted to facilitate comparison among studies, identify consistent patterns, and highlight discrepancies associated with variations in feedstock composition, application rates, environmental conditions, and experimental design.

No formal meta-analysis was performed due to the high heterogeneity among studies in terms of vermicompost origin, experimental conditions, and reported variables. Instead, results were critically interpreted to provide an integrated overview of current knowledge, highlighting both convergent findings and existing research gaps.

Briefly, this review is structured into distinct domains, each addressing a key aspect of vermicompost application. The section “Effect of winery waste-derived vermicompost on crops and vineyards: Current evidence and critical insights” (3) is structured into three analytical subsections: germination and early growth, soils and microbiota, and yield and quality. Within each subsection, the agronomic, biochemical, and microbiological effects of winery waste-derived vermicompost will be addressed first with reference to *Vitis vinifera* L. applications, and subsequently extended to other cultivated species, allowing for a comparative interpretation of its cross-crop applicability. In addition, the next section, “Application of vermicompost from alternative substrates in vineyard systems: Current evidence and critical insights” (4), is also structured into three analytical subsections: germination and early growth, soils and microbiota, and yield and quality. Within each subsection, the agronomic, physicochemical, and microbiological effects of vermicompost derived from non-winery feedstocks (e.g., livestock manures, crop residues, and mixed organic wastes) are examined in vineyard systems.

3 Effects of Winery Waste-derived Vermicompost on Crops and Vineyards: Current Evidence and Critical Insights

Most of the existing research on vermicomposting of winery byproducts has focused primarily on grape marc, due to its status as the major solid byproduct of wineries. Its high annual availability and uniform composition make it particularly suitable for both laboratory and farm-scale

experiments (Domínguez et al. 2014; Karapantzou et al. 2023). Vermicompost obtained from exhausted grape marc using *E. fetida* and *E. andrei* typically exhibits a slightly acidic to neutral pH and a low C/N ratio, generally ~10 (Table 2). Over the course of the 120-day process, potassium concentrations tend to decrease, while enzymatic activity increases significantly, particularly in the early stages. Earthworm activity contributes to the transformation of the microbial community, enriching the vermicompost with nitrogen-fixing and decomposer microorganisms. This, in turn, enhances overall microbial biomass and activity, resulting in a product with demonstrated biostimulant properties for plant growth and no phytotoxic effects (Karapantzou et al. 2023).

Conversely, fewer academic studies have addressed the application of mixed winery residues, such as combinations of grape stalks, lees, and marc. These studies are typically conducted at a pilot scale, likely due to the increased heterogeneity of the input material, which complicates process standardization and operational control (Nogales et al. 2005; Fernández-Bayo et al. 2015). Nevertheless, when mixed winery residues such as vine shoots and vinasse sludge are used, the resulting vermicompost, produced with *E. fetida*, shows a more neutral pH and maintains high enzymatic activity throughout the process. The combination of a lignocellulosic material with recalcitrant properties and a nitrogen-rich residue leads to the formation of a humic-rich vermicompost with improved stability and potential agronomic value (Nogales et al. 2020).

3.1 Germination and Early Growth

The successful establishment of a vineyard depends heavily on the health and management of young grapevine rootstocks during the first season. Proper handling of nursery material, including hydration, disinfection, and planting depth, is essential to ensure uniform root development and early shoot growth. Initial care influences long-term vineyard performance by enhancing stress resilience, nutrient uptake efficiency, and structural balance. Moreover, rootstocks exposed to early biotic or abiotic stress may exhibit delayed development or fail entirely. Therefore, early agronomic practices play a critical role in unlocking the genetic and productive potential of the vine (Munoz et al. 2023). In copper-contaminated vineyard soils, young *Vitis vinifera* rootstocks often experience limited growth and photosynthetic efficiency due to metal toxicity (Betancur-Agudelo et al. 2020).

Ferreira et al. (2018) tested various soil amendments to address this issue, identifying grape pomace-derived vermicompost (30 g C kg⁻¹) as the most effective. Treated plants

exhibited an 89% increase in shoot biomass, a chlorophyll concentration of 3.66 mg g⁻¹ fresh weight, and a 123% improvement in photosynthetic rate. These gains were supported by a rise in stomatal conductance to 0.14 mol m⁻² s⁻¹ and an A/Ci ratio of 0.067, compared to 0.08 and 0.030 in control plants, respectively. Enzymatic assays revealed a 58% reduction in POD and a 60% reduction in SOD activity, indicating lower oxidative stress. Although root biomass remained unchanged, the proportion of fine roots (less than 0.2 mm) and thick roots (greater than 0.8 mm) increased, enhancing nutrient acquisition potential. Nutrient analysis showed increased phosphorus uptake and a decrease in leaf copper content from 19.2 to 4.7 mg kg⁻¹, along with improved iron availability, likely due to organic complexation mechanisms.

Despite these promising results, this is currently the only available evidence regarding the use of vermicompost in grapevine propagation material. No studies have yet assessed its influence on rooted cuttings under non-contaminated soils, or in commercial nursery conditions, where improving root architecture, nutrient uptake efficiency, and early stress tolerance would be particularly valuable. This represents a critical research gap, since the nursery phase strongly affects vineyard establishment and long-term vine performance.

To assess the consequence of vermicompost on seed germination and early plant development, one of the most widely used parameters is the germination index (GI), developed by Zucconi et al. 1981; that is commonly used for evaluating the phytotoxicity and maturity of compost and vermicompost. This index combines seed germination rate and root elongation to provide a comprehensive assessment of potential phytotoxic effects (Yang et al. 2021). In general, a GI above 80% indicates that a compost can be considered mature and non-phytotoxic (Selim et al. 2012). Although this threshold was originally defined for compost, it can be extended to vermicompost due to its compositional and functional similarities (Karapantzou et al. 2023). This parameter is particularly relevant when vermicompost is derived from potentially phytotoxic substrates, which may still retain harmful substances such as polyphenols, short-chain fatty acids, high electrical conductivity (EC), and heavy metals (HMs). Although the vermicomposting process significantly reduces these substances, incomplete degradation or non-optimal conditions may result in residual phytotoxicity (Nogales et al. 2020; Gómez-Brandón et al. 2020).

In the available studies on winery industries-derived wastes, two main species have been used to assess phytotoxicity using GI: cress seeds (*Lepidium sativum* L.), as in the original method from Zucconi et al. (Nogales et al. 2005,

Table 2 Physicochemical characteristics and agronomic quality of final vermicomposts derived from viticultural and winery residues, including pH, electrical conductivity, C/N ratio, nutrient content, organic Matter, and phytotoxicity

Feedstock	Earthworm species	Day	pH	EC (dS/m)	C/N	Total C (%)	Total N (%)	P (g/kg)	K (g/kg)	Phytotoxicity	OM (%)	Reference
Spent grape marc	<i>Eisenia andrei</i>	112	7.24	1.66	29	41.8	1.4	4.97 (P reported as P ₂ O ₅)	18.2 (K reported as K ₂ O)	No (GI=93)	nd	(Nogales et al. 2005)
Lees cake and vine shoots (2:1, wet basis)		112	7.68	0.79	13	36.5	2.8	8.82 (P reported as P ₂ O ₅)	5.2 (K reported as K ₂ O)	Yes (GI=68)	nd	(Nogales et al. 2005)
Vinasse biosolids and vine shoots (2:1, wet basis)		112	7.44	1.02	13	34.5	2.68	13.4 (P reported as P ₂ O ₅)	8.8 (K reported as K ₂ O)	No (GI=81)	nd	(Nogales et al. 2005)
Grape pomace	<i>Eisenia fetida</i>	150	8.5	nd	16	nd	2.1	nd	nd	nd	nd	(Freixas and Landa 2012)
Grape pomace	<i>Eudrilus eugeniae</i>	90	8.98	nd	15.83	13.3	0.84	2.13 (P reported as P ₂ O ₅)	0.94 (K reported as K ₂ O)	nd	20	(Seenappa 2012)
Grape marc	<i>Eisenia andrei</i>	112	7.1	0.27	12.68	37.60	2.96	8.36	11.4	nd	74.98	(Dominguez et al. 2014)
Grape marc	<i>Eisenia andrei</i>	112	7.5	0.18	11.64	47.10	4.09	2.45	6.22	nd	76.97	(Gómez-Brandón et al. 2020)
Grape marc	<i>Eisenia fetida</i>	120	6.9	0.8	22	nd	1.6	2.5	2.9	No	nd	(Nogales et al. 2020)
Lees cake and grape marc (2:1)		120	7.3	1.6	14	nd	1.98	3.3	4.6	No	nd	(Nogales et al. 2020)
Vinasse sludge and vine shoots (2:1)		120	7.3	1.3	11	nd	2.6	5.3	5.8	No	nd	(Nogales et al. 2020)
Albariño grape marc	<i>Eisenia andrei</i>	63	nd	nd	24	50	2.1	1.86	13.49	nd	93	(Gómez-Brandón et al. 2022)
Mencia grape marc		63	nd	nd	22	50	2.3	1.82	11.96	nd	94	(Gómez-Brandón et al. 2022)
Distilled grape marc (Mencia)		63	nd	nd	21	49	2.3	1.86	13.16	nd	92	(Gómez-Brandón et al. 2022)
Distilled grape marc	<i>Eisenia andrei</i>	56	7.53	0.11	35	50	1.4	1.24	15.7	nd	89.91	(Gómez-Brandón et al. 2023)
Grape marc	<i>Eisenia andrei</i> and <i>Eisenia fetida</i>	120	6.5	1.24	10.90	21.36	1.95	0.24 (reported in ppm)	0.35 (reported in ppm)	No (GI=119.85 (>80=no phytotoxicity))	nd	(Karapantzou et al. 2023)
Vine shoots, lees, and grape pomace (1:1:2)	<i>Eisenia fetida</i>	90	8.13	1.1	16.88	nd	2.26	4.1	31	No (GI=111)	65.63	(Sánchez-Suárez et al. 2025)
Vine shoots, lees, and grape pomace + sewage sludge (1:1:2:2)		90	7.39	2.66	11.21	nd	2.75	7.1	15.38	No (GI=82.6)	53.00	(Sánchez-Suárez et al. 2025)

2020), and barley seeds (*Hordeum vulgare* L.) (Karapantzou et al. 2023). The initial GI values of different raw winery residues are typically very low, ranging from 0 to 63%. For example, Nogales et al. 2020; reported an initial GI of 0% for exhausted grape marc, which increased to 24% when mixed with lees cake, while Nogales et al. 2005 reported a GI of 63% for a mixture of grape marc and vine shoots.

After vermicomposting, however, GI values increased consistently across all studies, often surpassing the 80% threshold and reaching up to 119.85%. Interestingly, vermicompost derived from spent grape marc alone showed the highest GI values, ranging from 93% to 119.85%, whereas mixtures of different winery residues tended to yield slightly lower GI values (Nogales et al. 2005, 2020; Karapantzou et al. 2023). The only exception was found in the study by Nogales et al. (2005), where the vermicompost obtained from a combination of lees cake and vine shoots reached a final GI of only 68%. This result, however, still marked a substantial improvement compared to the raw mixture's initial GI of just 2%, which was associated with an extremely high polyphenol content (32 g/kg). Even after vermicomposting, polyphenols remained relatively high (around 7 g/kg), likely explaining the incomplete detoxification. In contrast, spent grape marc with an initial polyphenol concentration of 2.9 g/kg showed a much higher initial GI (61%) and surpassed the 80% threshold after vermicomposting. Further evidence supports the suitability of GMV as a component of plant growth media. Mixtures containing 25% and 50% GMV with either peat or commercial substrates resulted in barley germination rates above 90% in both cases (Paradelo et al. 2012).

These findings underline the effectiveness of vermicomposting in detoxifying winery residues by reducing key phytotoxic compounds such as polyphenols and electrical conductivity. For example, Nogales et al. (2020) observed that in a mixture of vine shoots and vinasse sludge, polyphenol levels dropped from 17.8 to 1.2 g/kg and EC from 6.7 to 1.3 dS/m, with the GI increasing from 0% to 90%. Another apt example comes from Domínguez et al. (2014) study. Here, grape marc presented acidic conditions (pH 4.5–4.8), high salinity (> 5 dS m^{-1}), and a wide C: N ratio (35–40:1), all indicative of immaturity and phytotoxicity. After vermicomposting, the substrate stabilized, with pH adjusted to neutrality (7.0–7.2), EC reduced to 2–3 dS m^{-1} , and C: N narrowed to 12–15:1. Bioassays confirmed the loss of phytotoxicity, as the germination index increased from $< 20\%$ to values above 80%, often reaching 100–120% in tests with *Lactuca sativa* L. and *Lepidium sativum* L. Overall, vermicomposting consistently improved phytotoxicity parameters, converting highly inhibitory raw materials into safe and plant-compatible soil amendments.

3.2 Soils and Microbiota

Soil functions as a biologically active matrix whose dynamic microbiome engages in plant–soil feedbacks and cross-kingdom signaling, thereby modulating grapevine physiology, transcriptomic profiles, secondary metabolism, and inducible defense pathways. Enhancing soil microbial activity can therefore play a key role in defining a wine's aromatic profile and unique characteristics (Gilbert et al. 2014; van Leeuwen 2022). In a 10-week incubation (Paradelo et al. 2011), vineyard soil amended with grape marc-derived vermicompost (GMV) at 2–4% dw showed dose-dependent increases in cumulative CO_2 -C (endpoint ≈ 25 mg C- CO_2 g^{-1} in the control vs. ≈ 30 and ≈ 37 mg C- CO_2 g^{-1} at 2% and 4% GMV, respectively), together with no net N mineralization; weekly N balances were consistently negative at 2% (clear immobilization) and fluctuated around zero at 4%. Kinetic fits to a two-pool first-order model indicated that the mineralization potential ($C_0 \cdot k$) rose from 24 to 54 and 42% $C \cdot yr^{-1}$ at 2% and 4% GMV, while the slow pool ($C_0 \cdot k'$) increased from 4.4 to 5.9–6.0% $C \cdot yr^{-1}$; inorganic N remained nitrate-dominated, with immobilization at 2% consistent with stimulated microbial demand. The GMV displayed near-neutral pH (7.0), low EC (0.71 dS m^{-1}), very high OM (948 g kg^{-1}) and K (8,495 mg kg^{-1}), supporting its agronomic suitability. Model projections estimated ~ 1.7 – 2.1 t $ha^{-1} yr^{-1}$ (bulk GMV) to maintain SOC and ~ 8.1 – 8.7 t $ha^{-1} yr^{-1}$ to reach 3.5% SOC, with requirements $\approx 10\%$ higher under $+2$ °C, underscoring GMV's potential in microbially mediated C accrual under warming scenarios. Collectively, these responses (respiration and modeled mineralizable pools augments, and N immobilization) indicate strong microbial activation following GMV addition, even though no taxonomic profiling of the soil microbiome was performed in this study. Field studies further support these observations. In vineyards cultivated with Albariño (Rosado et al. 2022b) and Mencía (Rosado et al. 2022a) cultivars in Spain, the application of GMV was shown to induce notable alterations in soil and rhizosphere microbial communities, with potential downstream effects on fruit and wine quality. These microbial shifts included increased abundance of beneficial taxa such as *Lachancea*, *Pseudomonas*, *Debaryomyces*, and *Oenococcus* spp.—microorganisms previously linked to improved wine aroma, fermentation performance, and sensory complexity (Wei et al. 2020). In particular, the presence of *Debaryomyces* is commonly associated with enhanced citronellol, nerol, and geraniol compounds, while *Oenococcus* plays a key role in malolactic fermentation (Garcia et al. 2002). Notably, neither Rosado et al. (2022a) nor Rosado et al. (2022b) report the field application rate (e.g., kg vine $^{-1}$ or t ha^{-1}) of GMV. The absence of dosage information limits cross-study comparability,

thereby precluding standardized confrontations and hindering guideline development for field deployment. Moreover, recent studies indicate that vermicompost amendments may contribute to plant health not only by improving soil fertility but also by influencing the microbial community and plant metabolism. In particular, increases in beneficial microorganisms with potential biocontrol activity, together with the stimulation of metabolic pathways related to secondary metabolites, have been observed as possible mechanisms that reduce disease incidence. Rosado et al. (2022b) reported that the application of grape marc-derived vermicompost increased the relative abundance of *Paenibacillus* spp. in the rhizosphere. Among these, *P. alvei* strain K165 has been analyzed for its biocontrol potential against grapevine trunk disease (GTDs) pathogens, particularly *Phaeomonella chlamydospora* (Gkikas et al. 2021). The antagonistic activity of *Paenibacillus* spp. is predominantly attributed to the production of lipopeptide antibiotics (e.g., polymyxins, fusaricidins), cell wall-degrading enzymes (e.g., chitinases, β -1,3-glucanases), and siderophores that sequester iron, limiting pathogen development (Ali et al. 2021; Dobrzyński and Nازیębło 2024). These findings suggest that vermicompost application may favor the establishment of beneficial microbial consortia in the rhizosphere, potentially improving plant health and contributing to the suppression of trunk disease pathogens through both direct antagonism and plant-mediated defense activation. Similarly, through predictive functional profiling using PICRUSt2, other authors inferred an enrichment of microbial pathways related to terpenoid and amino acid biosynthesis, alongside a reduction in sugar-related pathways (Rosado et al. 2022a). Terpenoids are well-known plant defense compounds that function in response to biotic stress (e.g., insect attack, pathogen invasion). Their increased synthesis may represent a priming effect induced by vermicompost, potentially reinforcing the plant's intrinsic defense capacity (Toffolatti et al. 2021). It is noteworthy that these results are based on metagenomic predictions rather than direct transcriptomic measurements in *Vitis vinifera*. Consequently, the suggested upregulation of terpenoid pathways reflects a potential functional shift in the microbial community, which may indirectly influence grape secondary metabolism and wine aromatic traits, but remains to be validated experimentally.

Regarding the physicochemical properties of vineyard soils, available studies provide contrasting results. In a laboratory experiment, Fernández-Bayo et al. (2015) observed no significant changes in soil pH following the incorporation of vermicomposts derived from winery residues, even at very high application rates (up to the equivalent of 260 t/ha). However, the same study reported marked improvements in soil cation exchange capacity (CEC): in sandy soils, CEC nearly doubled at 260 t/ha and increased by

40–50% at 130 t/ha, while in clay soils the effect was even more pronounced, with values more than doubling already at the lower dose. Concerning soil organic carbon (SOC) and total nitrogen, long-term field applications of grape marc vermicompost at more moderate rates (7 t/ha per year for three years in two Isabela vineyards) did not result in measurable increases, and in some cases even led to reductions in surface layers, likely due to enhanced mineralization (Kokkonen et al. 2025). In contrast, the higher-dose laboratory study of Fernández-Bayo et al. (2015) found substantial increases in SOC, particularly in sandy soils, where organic carbon rose more than sevenfold at 260 t/ha, while in clay soils it increased approximately fourfold compared to the control. For other macro- and micronutrients, Kokkonen et al. (2025) reported no significant differences relative to untreated soils.

The use of GMV has also been investigated in non-viticultural contexts, where it consistently improved both physico-chemical and biological properties of substrates. When incorporated into artificial substrates such as slate-derived wastes, GMV increased total C and N contents by 35–50% compared to the control and boosted the availability of inorganic N in nitrate form (NO_3^-), with concentrations three to ten times higher depending on the dose (4–16%). At similar application rates, a marked enrichment in macro and micronutrients such as P, K, Mg, and Ca was observed, while cation exchange capacity (CEC) approximately doubled at 8–16% GMV doses. Moreover, pH was buffered towards neutrality (6.8–7.2), mitigating the initial alkalinity of the substrate. Collectively, these changes transformed the slate-derived waste into a more fertile and chemically balanced medium, able to support the growth of herbaceous species such as Italian ryegrass (*Lolium multiflorum*), whose germination improved from 78% to 88% upon GMV addition (Paradelo et al. 2007, 2009).

In terms of microbial functions, GMV also stimulated biological activity in slate-derived substrates, which typically exhibit negligible microbial activity. Paradelo et al. (2007, 2009) reported that at 8–16% GMV doses, microbial biomass carbon increased 15- to 40-fold relative to the control, while dehydrogenase activity, an indicator of microbial activity, rose 20- to 50-fold. These findings highlight the role of GMV not only in improving substrate fertility but also in enhancing microbial functionality in non-vineyard soils.

Despite the growing body of literature on the properties of vermicompost derived from winery residues (Dominguez et al. 2014), field-based studies on vineyard systems remain scarce. Although the results of Rosado et al. (2022a, b) are promising, further investigations are urgently needed to assess the effectiveness of grape-derived vermicompost under a wider range of environmental backgrounds, soil

types, and grape cultivars. Parallel to this, investigations conducted in non-viticultural contexts highlight the broader agronomic potential of grape marc vermicompost beyond viticulture, suggesting possible applications in a range of cropping systems. Nevertheless, field-scale research is needed to confirm these benefits under real agronomic conditions, both in vineyards and in other crops, and to explore the on-field use of winery by-products other than grape marc as vermicomposting substrates.

3.3 Yield and Quality

Currently, scientific literature evaluating the effects of vermicompost derived specifically from winery industry residues on crop yield and quality is limited and primarily focused on viticulture. It was reported that an average increase in grape yield of approximately 14% following the application of GMV in two different vineyards (Rosado et al. 2022a, 2022b). In another field trial conducted in an irrigated Spanish vineyard (cv. Cayetana Blanca), (Sánchez-Suárez et al. 2025) applied 18 tonnes per hectare of vermicompost derived from mixed winery residues (vine shoots, lees, grape marc) and observed a significant development in vegetative growth: canopy surface area increased from 3.9 to 4.5 m² per vine and yield, which increased from 2.8 kg to 3.7 kg per vine in control and treated plants, respectively. Improvements were also noted in must quality parameters, including higher ethanol potential (12.3% and 13% v/v in control and treated plants, respectively), increased yeast assimilable nitrogen (235 mg/L and 278 mg/L), and greater total amino acid content (4.7 mM and 6.7 mM). These enhancements were associated with improved macronutrient uptake, particularly nitrogen, phosphorus, and potassium, as evidenced by higher concentrations of these nutrients in leaves at veraison, which likely contributed to the observed increases in yield and quality. On the contrary, in Brazil, with reduced application rates (7 t/ha), no worthy of attention differences in yield or fruit quality were found on the Isabella and Chardonnay cv. (Kokkonen et al. 2025). Notably, this study also reported no increase in leaf nitrogen content, potentially explaining the lack of growth and productivity response compared to the Spanish trial. This outcome reflects the already adequate supply of N (leaf N around 15–30 g/kg) and other key elements (exchangeable K: 87.84–101.59 mg/dm³ and available P: 20.52–10.66 mg/dm³) in Brazilian soils, resulting in no detectable changes in leaf nutrient status of treated plants and, consequently, no improvements in grape yield or quality. These contrasting results highlight the importance of application rate, as well as initial soil fertility and plant nutrient status, in determining the agronomic effectiveness of vermicompost. In particular, higher doses (e.g., 18 t/ha in the Spanish vineyard)

appear more effective in enhancing nutrient uptake and crop productivity than lower rates.

While GMV has been extensively characterized as a stable, polyphenol-depleted amendment, robust yield/quality trials on non-vine crops are still missing. To date, the only direct yield trial is the study by Paradelo et al. (2012), who tested GMV as a partial substitute for peat and commercial substrates in barley, reporting productivity increases of approximately 120% and 170%, respectively, compared with the controls. Evidence from grape marc compost indicates that winery residues can sustain commercial yields in greenhouse tomato and increase field yields in melon, whereas a broad body of studies with non-GMV vermicomposts consistently show higher yields and improved product quality in vegetables (e.g., tomato, pepper, lettuce) (Reis et al. 2001; Requejo et al. 2014; Pinter et al. 2019). These findings support the plausibility of GMV benefits beyond vineyards, but targeted field trials quantifying yield and quality endpoints remain a critical research need.

4 Application of Vermicompost from Alternative Substrates (e.g., manure) in Vineyard Systems: Current Evidence and Critical Insights

Winery residues used as vermicomposting feedstocks align with circular bioeconomy objectives by recirculating nutrients within the vitivinicultural system (Nascimento-Gonçalves et al. 2024). Nevertheless, they constitute only a narrow subset of the vermicompostable feedstock space. Given the growing demand for low-impact soil restoration strategies in vineyards (Lucchetta et al. 2023), the evidence base should be broadened to include vermicomposts derived from non-winery substrates (e.g., livestock manures, mixed crop residues, and other farm by-products), enabling feedstock-specific comparisons of agronomic efficacy, nutrient delivery, and potential risk profiles. These materials are widely available and often rich in nitrogen and organic matter (Adhikary 2012; Joseph 2019), and may provide agronomical benefit to vineyards when used as soil amendment. Including different types of vermicompost in the discussion allows for a more comprehensive evaluation of the role of vermicompost in viticulture.

4.1 Germination and Early Growth

Vermicompost has also been investigated for its potential role during grapevine propagation, particularly in the nursery phase, where root system establishment and early shoot development are critical for successful vineyard establishment. In a greenhouse propagation of Pinot noir cuttings

(Flores 2014), commercial vermi-products (feedstock not reported by authors) were tested as peat-perlite amendments (vermicompost 5–40% v/v) or as weekly drenches (vermi-extract 2.5–20 mL) against a steer-compost control. Vermicompost increased root length by ~15% and root area by ~40%, whereas 10% vermicompost gave the best rooting among vermicompost doses (the 5% dose was suboptimal); no significant differences emerged between vermicompost and vermi-extract overall. These outcomes suggest early-stage benefits dominated by biostimulant/microbial effects rather than bulk nutrient supply, but interpretation is limited by the unspecified vermicompost feedstock. Similarly, (Açıkbaş and Bellitürk 2017), using vermicompost derived from cow manure and *E. fetida*, conducted a pot experiment with vine cuttings with different incorporation rates (10 to 40% v/v). The most pronounced effects were observed at 20 and 30% doses, where shoot length and fresh weight increased more than threefold compared to the control. Shoot length rose from 32.3 cm (control) to 72.8, 114.3, 110.3, 97.3 cm at 10–40%, with an optimum at 20%; fresh/dry shoot mass increased from 6.31/1.92 g (control) to 23.8/6.80, 41.3/11.85, 46.1/12.97, 34.9/10.12 g at 10–40%, peaking at 30% for biomass. Together, these findings indicate that vermicompost can significantly stimulate both below and aboveground development of young grapevines, although further research is required to optimize application rates and to confirm these effects under field nursery conditions.

4.2 Soils and Microbiota

Evidence from vineyards suggests that vermicompost from residues other than winery wastes can enhance certain soil properties, although effects on microbiome appear less consistent. The application of dairy cow manure vermicompost (15 t/ha) in Californian vineyard (var. Primitivo) led to a significant increase in CEC (from 13.8 to 15.9 mmol_c kg⁻¹ in the first year) and, during the second year, higher SOM content on the row (1.4% in the control and 1.8% in the treatment) and a doubled nitrate concentration (Luck 2022). In Spain, the application of ~2.3 t/ha (dw) vermicompost from wheat straw increased vineyard SOM content from 1.86 to 2.7% and significantly increased nutrient content, with NO₃⁻, P₂O₅, and K₂O concentrations reaching 0.17, 0.3 and 0.181% compared to 0.027, 0.09, and 0.005% in the control, respectively (Palenzuela et al. 2023). Similar results were reported in an Italian Sauvignon blanc vineyard from (Mondini et al. 2018), where manure vermicompost applied annually at 10 t/ha enhanced the extractable P from 0.2 mg/g in the control to 14.5 and 16.1 mg/g in the first and second year, respectively, and increased SOM from 1.8 to 2.4% in the second year. In Argentina, chicken manure

vermicompost applied at 8 t/ha on a Sauvignon blanc vineyard significantly increased soil P content (from 4.29 to 7.14 mg/kg), without altering pH or other macroelements (Martínez et al. 2018). Across these studies, however, no significant effects were observed in soil microbial biomass, activity, or composition (Martínez et al. 2018; Mondini et al. 2018; Luck 2022), suggesting that the main benefits of non-winery vermicompost in vineyards are their ability to enhance SOM and nutrient content, while their influence on microbiota remains limited. Importantly, most of the trials tested moderate application rates (around 2–10 t/ha), which may be sufficient to affect chemical properties but not strong enough to drive measurable shifts in microbial communities. Future research should explore the impact of higher doses, as well as the long-term application, to better understand if vermicompost application can modulate soil microbiota.

4.3 Yield and Quality

In a field experiment in Pakistan using table grapes (*Vitis vinifera* var. King's Ruby), Javed et al. 2017 observed that the dispensation of vermicompost derived from cow dung and sugarcane filter cake (4:1), even in the absence of NPK fertilizers, led to increased yield and bunch weight compared to the control, with values comparable to those obtained using conventional fertilization. Similarly, Yeole (2021), in India, reported that putting on 2 tons per hectare of vermicompost from organic manure combined with vermiwash significantly increased berry size in two table grape varieties (Thompson, a white variety, and Sharad, a black variety), with an average diameter increase of 3–4 mm.

Beyond yield, vermicompost also appears to positively affect grape and wine quality. In the study by Javed et al. (2017), grapes from treated plants showed increased total sugar (TS) content, particularly at doses of 2 and 3 tonnes per hectare, while total acidity (TA) remained unchanged. Similarly, a significant rise in °Brix was observed: from 10.6 to 14.4 in Sharad, and from 12.4 to 18.2 in Thompson. While TA remained stable in Sharad, it decreased in Thompson from 4.18 to 3.64, potentially enhancing fruit palatability (Yeole 2021).

In addition to improving yield and sugar content, vermicompost may also exert influence on the aromatic bouquet of wine. In Spain, Palenzuela et al. 2023; applied ~2.3 t ha⁻¹ (dw) of vermicompost produced from spent mushroom substrate (wheat-straw residue from *Pleurotus ostreatus* cultivation). Relative to untreated controls, wines from treated vines showed greater sensory complexity, with higher intensities in fatty, herbal, floral, waxy, fruity, green-fruit, and citrus notes, and a higher total polyphenol index, a quality-relevant metric in red winemaking. In particular, they

exhibited higher TPI (60 vs. 49) and a color shift (increases: A_{520} and A_{620} ; reduction: A_{420}), alongside a richer volatilome: significant increases were observed in key odorants (e.g., β -damascenone $385 \mu\text{g L}^{-1}$; ethyl octanoate $348 \mu\text{g L}^{-1}$; iso-amyl acetate $102 \mu\text{g L}^{-1}$; β -phenylethyl acetate $503 \mu\text{g L}^{-1}$).

In contrast, other experiments in wine grape vineyards have yielded less consistent results, even at higher doses. In an Italian Sauvignon blanc vineyard, Mondini et al. (2018) applied $10 \text{ t ha}^{-1} \text{ year}^{-1}$ of manure vermicompost over three consecutive years but found no significant effects on grape yield or must quality parameters. Likewise, Martínez et al. (2018) published that the application of 8 t ha^{-1} of chicken manure vermicompost in an Argentine Sauvignon blanc vineyard did not significantly affect yield, trunk diameter, or pruning weight.

In summary, these findings highlight the potential of vermicompost not only as a substitute or supplement for mineral fertilization but also to enhance grape quality and wine characteristics. Nevertheless, the contrasting outcomes across studies suggest that the effects of vermicompost may be context-dependent. Further probing is needed to be conscious of its effects across different grapevine varieties, assess how vermicompost derived from diverse feedstocks influences grape production, and determine optimal application rates. Long-term studies are also necessary to evaluate the effects of vermicompost on plants, yield, and soil, in order to support its integration into routine vineyard management practices.

5 Challenges and Limitations

The use of vermicompost in viticulture offers several agro-nomic and environmental advantages, yet some limitations and risks must be carefully considered before its widespread adoption (Fig. 1).

5.1 Potential Phytotoxicity and Heavy-metal (HM) Accumulation

Despite reports that grape-residue vermicompost can lower Cu^{2+} availability (Ferreira et al. 2018), concerns persist about HM and microelement build-up at toxic levels. The most striking case was reported by Trentin et al. (2019); the authors transplanted young grapevines into Cu-contaminated soil amended with grape-residue vermicompost at 86.7 g kg^{-1} ; after winter pruning, all treated vines died while controls survived. The mortality was attributed to a sharp rise in soluble Mn (5.556 vs. 0.555 mg L^{-1} in controls), consistent with severe Mn phytotoxicity, indicating that this vermicompost was unsuitable under those conditions. Other studies have also reported increases in soil

metal concentrations following vermicompost addition. For example, Luck (2022) observed higher Cu concentrations in vineyard rows after two years of dairy cow manure vermicompost application (15 t/ha cumulative), with values rising from 0.56 to 0.75 mg/kg . Similarly, Palenzuela et al. (2023) found that the application of $\approx 2.3 \text{ t/ha}$ (dw) of wheat straw vermicompost in a Syrah vineyard increased Cr, Cu, Ni, and Pb concentrations, even if all the concentration remain widely under the threshold, while Paradelo et al. (2007) reported increases in Mn, Cu, and Zn in GMV-amended substrates, especially at higher doses (8 – 16%).

With the notable exception of the Mn case (Trentin et al. 2019), measured increases generally fell well under regulatory limits, suggesting low short-term risk, albeit warranting site-specific monitoring (Luck 2022; Palenzuela et al. 2023). Moreover, several studies indicate that vermicompost can also immobilize or reduce the availability of certain metals (Ferreira et al. 2018; Sánchez-Suárez et al. 2025), further highlighting the complexity of these interactions.

In light of these findings, the HMs content of both vermicompost and soils should be carefully monitored, and application rates adjusted accordingly, to minimize potential risks while maximizing agronomic benefits.

5.2 Variability in Vermicompost Quality

A second, and equally critical, limitation concerns the high variability in vermicompost quality, which is subject to several factors, including the feedstock used, the earthworm species and their density, the associated microbial communities, and the degree of compost maturity (Cruz et al. 2024).

For instance, Nogales et al. (2005) analyzed vermicomposts from different winery residues: GMV, lees cake mixed with vine shoots, and vinasse biosolid mixed with vine shoots, as well as from manure. They reported marked differences in nutrient concentrations: vermicomposts containing vine shoots showed the highest total N (28 and 26.8 g/kg) compared to GMV and manure (14 and 20.6 g/kg); P_2O_5 was highest in vinasse + vine shoots vermicompost (13.4 g/kg) and lowest in GMV (4.97 g/kg), while K_2O peaked in GMV (18.2 g/kg vs. 5 – 8 g/kg in the others). However, in a later study, Nogales et al. (2020) remarked that while the relative pattern for N and P persisted (higher N in vine shoot mixes and lower P in GMV), absolute concentrations varied substantially, and GMV now showed the lowest K_2O content (2.9 g/kg), far below the earlier value.

Earthworm species also influence the final product. Rajendran and Rajendram (2014), using supermarket vegetable waste, found that vermicompost produced by *Eudrilus eugeniae* contained more N, P, and K (2.04% , 1.64% , and 1.32%) than that from *Perionyx excavatus* or *E.*

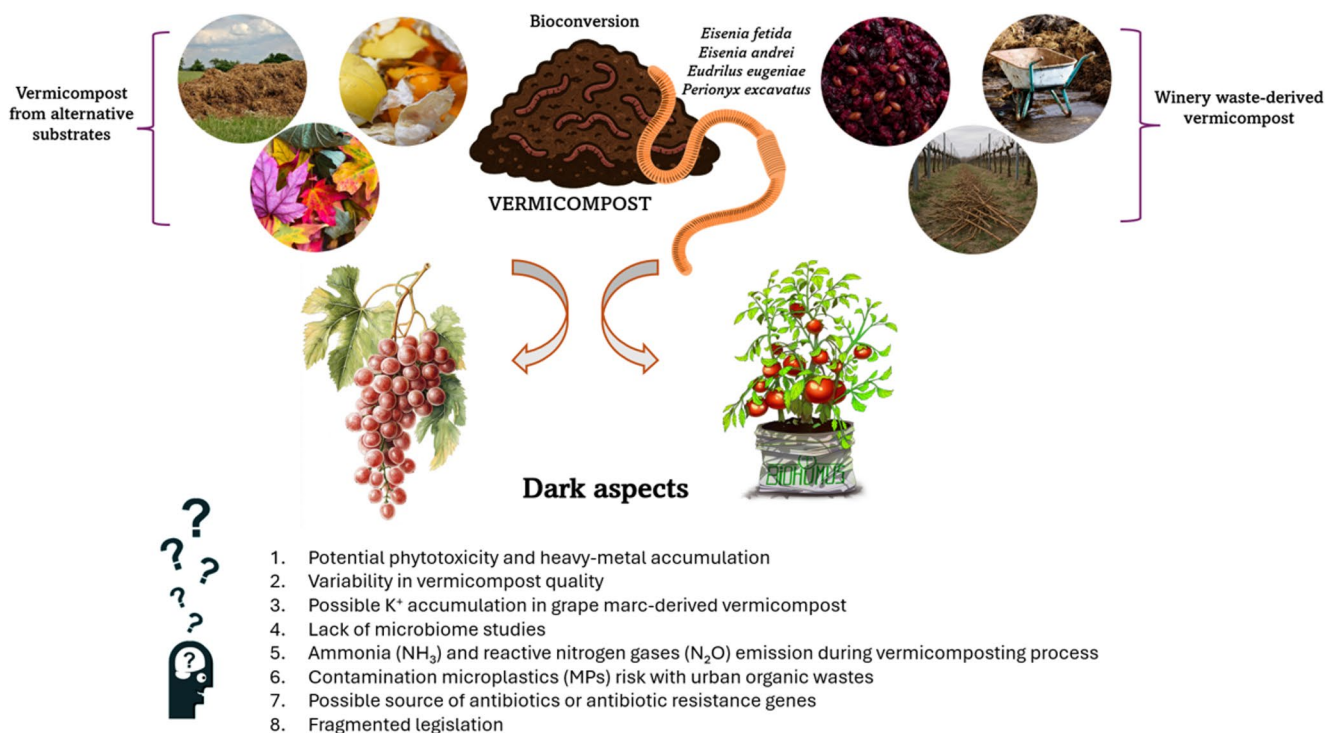


Fig. 1 A summary of the dark aspects of the vermicomposting process and application

fetida. Similar conclusions were delineated by other authors (Elsayed et al. 2022), who obtained the highest nutrient concentrations using *E. eugeniae* and *P. excavatus*. These differences are likely linked to the distinct microbial communities associated with each worm species. Supporting this, Gebrehana et al. (2023) showed that *E. eugeniae* was associated with higher abundance of Gram⁺ and Gram⁻ bacteria, AMF, actinomycetes, and total PLFA in PCA analyses, indicating a more active and diverse microbiota. The same study also highlighted that feedstock type strongly shapes microbial communities: for example, mixtures of soybean and banana residues aligned with more protozoa, fungi 18:1 and higher bacterial: fungal ratios, whereas maize and banana residues favored fungal biomarkers.

In summary, these findings underline that vermicompost is not a uniform product: its chemical and biological properties can vary widely according to both the starting materials and the biological agents involved. This variability complicates the prediction of agronomic outcomes and underscores the need for reporting detailed characterization data when testing vermicompost in vineyards.

5.3 Potassium Accumulation and Cation Imbalance

Vermicompost application often enriches soils with macro and micronutrients, including potassium (K), which can

lead to substantial increases in soil K concentration. For example, it was reported an increase from 142 to 1912 mg/kg following vermicompost addition (Przemieniecki et al. 2021). This aspect is particularly relevant for GMV, which is typically rich in K (Nogales et al. 2005). Elevated K availability can be beneficial, as this element plays key roles in photosynthesis, osmotic regulation, and fruit quality (Destia 2025). However, excessive K can disrupt the balance among cations, especially the K/Ca/Mg ratio. It is well established that K competes antagonistically with Ca²⁺ and Mg²⁺ for plant uptake: an oversupply of K can reduce Ca and Mg absorption, potentially inducing Mg deficiency, which manifests as characteristic interveinal leaf chlorosis (Shikhamany et al. 2018; Xie et al. 2021) or berry shrivel (Griesser et al. 2017).

Moreover, elevated K concentrations in grape tissues, and consequently in berries, may negatively affect wine-making. High K levels can increase must and wine pH by reducing free acids, particularly tartaric acid, which tends to precipitate as potassium bitartrate. This process ultimately lowers total acidity and can compromise wine stability and sensory quality (Kodur 2011). For these reasons, especially in viticultural and oenological contexts, it is crucial to assess both soil and vermicompost K content prior to application, to ensure adequate nutrient balance and avoid unintended impacts on grape composition and wine quality.

5.4 Microbiome Functional Uncertainty

Most of the studies on vermicompost effects on vineyard microbiomes (Rosado et al. 2022a, b) are mainly based on 16 S rRNA or ITS sequencing, which detect microbial taxa and their relative abundance. Predictive tools such as PICRUSt2 are then used to estimate which metabolites might be produced by these microorganisms, and the predicted functions are subsequently correlated with possible effects on wine quality. Studies that measure actual metabolic activities, such as direct transcriptomic analyses, would provide a better understanding of these phenomena. As a result, functional interpretations remain largely inferential, and it is often unclear whether predicted microbial activities are truly expressed or relevant (Matchado et al. 2024). Moreover, correlations between microbial community composition and wine quality traits are still correlative in nature and highly sensitive to external factors such as climate, vintage, and vineyard management practices (Liu et al. 2020).

5.5 Environmental Impacts and Emissions

Life Cycle Assessment (LCA) studies indicate that the use of vermicompost, as well as other organic amendments, can provide significant environmental benefits when substituting mineral fertilizers, which are among the major contributors to the high environmental impacts of many agricultural processes (Phrommarat and Paopuree 2024). However, existing LCA assessments also emphasize important hot spots in vermicompost production, particularly the emission of ammonia (NH_3) and reactive nitrogen gases (N_2O) during the vermicomposting process, which can result in a high eutrophication potential (Cortés et al. 2020; Phrommarat and Paopuree 2024). For instance, emission factors of $12.8 \text{ g NH}_3 \text{ Mg}^{-1}$ have been reported during the vermicomposting process, contributing to eutrophication potential, whereas N_2O emissions (62.3 g Mg^{-1}) are mainly associated with global warming impacts (Komakech et al. 2016). LCA studies also highlight that the environmental performance of systems, including vermicomposting, is highly dependent on process conditions and emission dynamics, particularly methane emissions (Lahtinen et al. 2022). Overall, while vermicompost shows promise as a more sustainable alternative to mineral fertilizers, field-specific studies in viticulture remain scarce, leaving the translation of these potential benefits to vineyard systems still largely unexplored.

5.6 Microplastics and Emerging Contaminants

The use of biosolids or urban organic wastes as feedstock for vermicomposting exposes the final product to the risk of contamination by microplastics (MPs) and pharmaceutical

residues, due to the high content of such pollutants in the input materials. Even after vermicomposting, MPs can persist in the end product and subsequently contaminate the soil (Ragoobur et al. 2022; Poornima et al. 2024). Although the vermicomposting process can significantly reduce certain microplastic fractions, as illustrated by Ragoobur et al. (2022), who reported reductions up to 78% in sewage sludge vermicompost, a residual presence remains, raising concerns about their accumulation in agricultural soils. Similarly, it was reported (Hrčka et al. 2024) that while vermicomposting can decrease the concentration of several pharmaceutical compounds in sewage sludge and moulded pulp, some substances (such as caffeine, triclosan, and telmisartan) tend to accumulate in earthworm tissues. Considering that earthworms are a key component of terrestrial food webs, this bioaccumulation may pose risks to higher organisms along the food chain. Therefore, when using urban-derived feedstock, it is crucial to monitor and control the potential transfer of persistent contaminants, ensuring that vermicompost quality aligns with environmental safety and food-chain protection standards.

5.7 Antibiotic Resistance Risks

The long-term use of antibiotics in animal husbandry has led to antibiotic resistance becoming a significant global concern, posing a substantial risk to human health and food safety (Tang et al. 2024). Livestock manure can represent a huge source of antibiotics, antibiotic-resistant bacteria, or antibiotic resistance genes (AnReGs) in the ecosystem (Su et al. 2024). Could vermicomposting mitigate AnReGs?

Nowadays, a point that cannot be hidden is that the conventional composting technique and anaerobic digestion cannot efficaciously manage the AnReGs in livestock manure (Zhang et al. 2023). Results on the conversion of cow manure characterized by four different tetracycline concentrations (absence, 10, 100 mg/kg), employing *Eisenia foetida*, highlighted that the total AnReGs abundance in vermicomposting (0.05 copies/16S rRNA copies) was notably lower with respect to the traditional compost process (0.06 copies/16S rRNA copies) (Li et al. 2025). It's true that in this study, the vermicomposting amortized the total AnReGs quantity in cow manure around 53%; however, tetracycline contracted earthworm's capacity to remove AnReGs up to 38%. Experimental evidence (Kumar and Yadav 2025) shows their power to also moderate the ciprofloxacin and chlortetracycline amount, thereby limiting antibiotic resistance genes.

Vermicomposting could eliminate AnReGs, but the effect of residual antibiotics on its reduction efficacy remains unclear.

5.8 Regulatory and Standardization Issues

The last concern relates to the regulatory framework already mentioned. One of the main challenges hindering the large-scale adoption of vermicompost in agriculture is the lack of specific quality standards and clear product labelling. In the EU, Regulation (EU) 2019/1009 establishes rules for the commercialization of fertilising products, requiring transparent labelling of the feedstock used, contaminant analyses, and compliance with defined quality criteria (Reg (EU) 2019/1009 2019). Similarly, in the USA, the Association of American Plant Food Control Officials (AAPFCO) requires manufacturers to list the starting materials and to provide guaranteed nutrient contents on product labels (AAPFCO 2017). However, despite these frameworks, the frequent lack of conformity and transparency in commercial vermicompost products makes it difficult for farmers to compare and evaluate different products. Therefore, clear and standardised labelling is urgently needed to support both users and producers in understanding vermicompost properties and quality (Rastegari et al. 2023).

Overall, while vermicompost holds considerable potential as a sustainable soil amendment in viticulture, its use is not without challenges. The risks of phytotoxicity, nutrient imbalances, contaminant accumulation, and inconsistent product quality highlight the need for careful evaluation before field application. These issues are further compounded by the lack of standardized regulations and reliable labelling, which can hinder both the reproducibility of experimental results and the comparability of commercial products. Addressing these limitations will be essential to ensure that vermicompost can be safely and effectively integrated into vineyard management practices.

6 Conclusions

This review highlights the dual role of vermicompost in viticulture, considering both its application in vineyard soils and its production from vineyard-derived residues. When applied to soil, vermicompost consistently improves soil physicochemical properties, including aggregation, porosity, and organic matter content, while enhancing nutrient availability and cation exchange capacity. These changes are closely linked to shifts in the soil microbiome, with increases in microbial biomass, enzymatic activities, and beneficial functional groups involved in nutrient cycling. In *Vitis vinifera* L., such improvements translate into enhanced physiological performance, greater stress tolerance, and, in several cases, improved yield and grape quality, although responses remain dependent on application rate, soil type, and environmental conditions.

At the same time, the use of vineyard residues as feedstock for vermicomposting represents a valuable strategy for waste valorisation, enabling the transformation of pruning biomass and other by-products into stable, biologically active amendments. However, variability among substrates and processing conditions leads to heterogeneity in the final product, limiting cross-study comparability. From an environmental perspective, Life Cycle Assessment (LCA) studies suggest that vermicompost can reduce impacts when replacing mineral fertilizers, but also identify important hotspots, particularly related to nitrogen emissions (e.g., NH_3 , N_2O) and process-related variability. This indicates that the sustainability of vermicomposting depends not only on its agronomic benefits but also on the feedstock type and process management.

Overall, despite promising results, field-scale evidence in vineyards remains limited, especially regarding long-term effects on soil health, microbiome stability, and environmental tradeoffs. Future research should focus on field trials in vineyards to quantify long-term effects on soil properties, microbial communities, yield, and grape quality, while testing how different vineyard residues and vermicomposting conditions influence the final product.

Author Contribution All authors contributed to the writing process. Eleonora Cataldo conceived the review and supervised the work; Eleonora Cataldo, Pamela Lippi, Giovan Battista Mattii, and Eleonora Nistor drafted the text.

Funding Open access funding provided by Università degli Studi di Firenze within the CRUI-CARE Agreement. No specific grant from any funding agency, commercial or not-for-profit sectors.

Data Availability All data generated or analysed during this study are included in this published article.

Materials Availability Not applicable.

Code Availability Not applicable.

Declarations

Ethics Approval and Consent to Participate Not applicable.

Consent for Publication Not applicable.

Competing interests No conflicts of interest.

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