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Critical Reviews

Vine-pruning wood: A strategic feedstock for integrated circular biorefineries

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ABSTRACT

Vine-pruning wood is one of the most abundant yet underutilized lignocellulosic residues generated by viticulture. Unlike previous reviews focused on individual valorization routes, this review provides a comprehensive and systems-level assessment of vine-pruning wood as a strategic feedstock within the framework of the circular bioeconomy and integrated biorefineries. Its lignocellulosic matrix and bioactive compounds enable multiple valorization pathways, including agronomic applications (composting, mulching, and biochar), recovery of high-value bioactive compounds for oenological, pharmaceutical, cosmetic, and food applications, and the production of renewable energy carriers, advanced biomaterials, and fibrous products. Particular emphasis is placed on green extraction technologies and cascade biorefinery approaches, highlighting their potential to maximize resource efficiency through the sequential recovery of multiple value streams from a single biomass source. The review also integrates techno-economic assessment, life cycle assessment, and regulatory considerations as key elements for evaluating environmental performance, economic viability, industrial scalability, and industrial implementation. Despite significant progress, major challenges remain regarding technological maturity, process integration, biomass variability, and the deployment of digital and biotechnological tools. Furthermore, the lack of coordinated industrial symbiosis frameworks continues to hinder the transition from isolated valorization routes to fully integrated "zero-waste" systems. This review is aligned with the Sustainable Development Goals, particularly number 12 (Responsible Consumption and Production), and with circular bioeconomy policy frameworks by promoting the sustainable and integrated valorization of vine-pruning wood.

1. Introduction

The wine industry is a sector of considerable global socio-economic importance that has undergone significant transformations in recent decades, driven by the expansion of international markets, the increasing number of producers, and evolving consumer preferences (Fuentes-Fernández et al., 2022; Montalvo-Falcón et al., 2023). Despite its economic relevance, the entire wine chain is associated with notable environmental pressures, particularly those linked to vineyard management practices and the generation of substantial amounts of residual biomass. Among these, vine-pruning wood stands out as one of the most abundant and underutilized lignocellulosic resources generated annually in viticultural systems (Provenzano et al., 2024; Tumminelli et al., 2025).

Vine pruning represents a fundamental agronomic operation, marking the transition between production cycles and ensuring the regulation of vine growth, yield balance, and grape quality (Genisheva et al., 2023). This practice typically generates between 2 and 4 t ha^{-1} of fresh biomass, corresponding to approximately 1.1 t ha^{-1} yr^{-1} of organic dry matter rich in macro- and micronutrients (Bignami et al., 2023). Despite its abundance and intrinsic biochemical value, vine-pruning wood is still predominantly managed through low-value

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pathways, such as open-field burning or soil incorporation. Open burning, widely adopted in several wine-growing regions to control phytosanitary risks, contributes significantly to greenhouse gas emissions, particulate matter release, and air quality deterioration (Aliaño-González et al., 2020; Calderón-Martín et al., 2022; Dušek et al., 2016; Lemieux et al., 2004).

From a compositional perspective, vine-pruning wood is a lignocellulosic biomass rich in structural polymers (cellulose, hemicellulose, and lignin) as well as bioactive compounds, including phenolics with recognized antioxidant potential (Tumminelli et al., 2025; Zwingelstein et al., 2020). This composition positions it as a promising feedstock for multiple valorization pathways, ranging from the extraction of high-value compounds to the production of biomaterials and renewable energy carriers. Consequently, the sustainable management and valorization of vine-pruning wood have emerged as strategic priorities to enhance resource efficiency, reduce environmental impacts, and support the transition towards a circular and sustainable wine sector. These efforts are closely aligned with the objectives of Sustainable Development Goal 12 (Responsible Consumption and Production), particularly regarding the efficient use of natural resources and the reduction of waste generation (UNDP, 2025).

Within this context, the implementation of circular economy strategies is essential not only to improve the sustainability of wine production systems but also to unlock the full potential of vine-pruning wood as a valuable biomass resource (Abbate et al., 2025; Genisheva et al., 2023).

Several reviews published in recent years (2022–2025) have explored specific aspects of vine-pruning wood valorization, including bioactive compound extraction, biochar production, lignocellulosic materials, and individual biorefinery processes. However, these studies have generally addressed these topics independently, with limited integration of cascade biorefinery strategies, techno-economic and life cycle assessments, regulatory considerations, and emerging digital and biotechnological approaches. This highlights the need for a more comprehensive and systems-level synthesis capable of supporting the transition towards fully integrated circular biorefinery systems. Thus, this review provides a new comprehensive overview of the valorization opportunities associated with vine-pruning wood. It examines its chemical composition and high-value compounds, explores green extraction and processing technologies, and discusses current management practices alongside emerging valorization pathways. Furthermore, techno-economic, environmental, and regulatory aspects are addressed, and key research gaps and future perspectives are identified. The novelty of this review lies in its integrated assessment of vine-pruning wood as a strategic resource, advancing its role in sustainable valorization and high-value product development within the circular bioeconomy.

2. Composition, potential, and high-value compounds of vine-pruning wood

Once considered a low-value agricultural residue, vine-pruning wood has recently attracted increasing scientific and industrial interest. Its chemical composition makes it suitable for a range of valorization strategies, from material and energy applications to the recovery of high-value bioactive compounds (see Section 4) (Jesus et al., 2022; Lambert et al., 2013; Tumminelli et al., 2025; Zwingelstein et al., 2020).

2.1. Lignocellulosic structure and chemical composition

2.1.1. Structural polymers and chemical composition

Vine-pruning wood exhibits the characteristic lignocellulosic composition of agricultural woody residues. It is primarily constituted by cellulose, hemicellulose, and lignin, which form the structural backbone, together with minor inorganic components and extractable compounds (Čabalová et al., 2023; Jesus et al., 2022). Although structurally comparable to other agricultural woody biomasses, vine-pruning wood possesses specific physicochemical features that distinguish it from other feedstocks, which can influence the suitability and efficiency of different valorization and conversion pathways (Spinelli et al., 2012; Maj et al., 2022). As with most lignocellulosic materials, it contains a small fraction of non-structural constituents, including ashes, extractives, and other minor components, with its structural fraction being comprised mainly of cellulose, with varying percentages of hemicellulose, and lignin (Čabalová et al., 2023; Jesus et al., 2022). Cellulose constitutes the predominant carbohydrate fraction, conferring mechanical strength and structural integrity. Hemicelluloses form a heterogeneous polysaccharide matrix that is readily amenable to both biochemical and thermochemical conversion pathways (Donev et al., 2018). Lignin, while contributing to structural integrity, serves as a valuable reservoir of aromatic polymers. This makes it highly relevant for advanced material science applications, including the production of biopolymers, bio-composites, and stable lignin nanoparticles, as well as for fine chemical production (see Section 4.5) (D'Eusanio et al., 2023a; Jesus et al., 2022; Pereira et al., 2023).

2.1.2. Fiber morphology and material application

The fiber morphology of vine-pruning wood further reinforces its potential for material-based applications. A substantial proportion of its fibers fall within the 20–30μm width class, and the predominance of straight fibers, as indicated by high shape factor values, may enhance mechanical performance in composite formulations (Čabalová et al., 2023). In fact, although not intended to fully replace conventional timber feedstocks, vine-pruning wood can be incorporated as a supplementary component in wood-based composites, contributing to residue valorization, while supporting carbon footprint reduction within the materials sector (Wong et al., 2020).

In addition to serving as a reinforcement material, vine-pruning wood also represents a chemically rich matrix, containing extractable bioactive compounds that substantially broaden its valorization potential (see Section 2.3).

2.2. Fibers and nanocellulose

2.2.1. Lignocellulosic fibers

Within an integrated valorization perspective, vine-pruning wood represents a versatile lignocellulosic feedstock for fiber-oriented applications, complementing its role as a source of extractives (Section 2.3). Rather than being limited to classical fiber extraction, processing can yield a spectrum of fibrous fractions, from coarse lignocellulosic fibers to microfibrillated structures and, under more intensive treatments, nanocellulose. The performance of these fibers depends on the intrinsic heterogeneity of the wood and on the severity of the applied treatment, including chemical, thermal, or mechanical processes.

From a cascade biorefinery perspective, the production of fibers, nanocellulose, and composite materials represents one of several high-value valorization routes that can be integrated within the hierarchical utilization of vine-pruning wood. Depending on the selected processing strategy, these material applications may be combined with the recovery of bioactive compounds and subsequently followed by thermochemical or biological conversion of the remaining lignocellulosic fractions into biochar and bioenergy, thereby maximizing resource efficiency and economic value.Vine-pruning wood has been utilized to develop novel fibers. Investigations of wet and dry pre-treatment methods demonstrated that wet treatments required lower chemical concentrations and shorter extraction times, producing fibers with superior length, fineness, strength, and elongation relative to those obtained via dry pre-treatment (Rana and Sethi, 2025). When compared to conventional fibers such as jute, flax, kenaf, hemp, ramie, sisal, and coir, these fibers demonstrated remarkable elongation, tenacity, and length while maintaining moderate and comparable fineness. These properties underline the potential of such fibers as sustainable alternatives for high-performance applications.

2.2.2. Nanocellulose production

The extraction of nanocellulose from vineyard residues has also been investigated extensively. Sequential alkaline and bleaching treatments followed by acid hydrolysis produced cellulose nanocrystals with high crystallinity (~82%) and enhanced thermal stability, positioning vineyard residues as an underutilized feedstock for nanocellulose production (El Achaby et al., 2018). In these procedures, vine shoots were cut into 50–100 mm segments and milled to approximately 2 mm particles prior to chemical processing. The resulting cellulose nanocrystals (CNCs) retained a cellulose I structure, exhibited higher thermal stability than CNCs obtained from other sources using the same extraction route, and demonstrated strong reinforcing potential for nanocomposite materials, highlighting the high-value potential of vineyard residues for nanocellulose production.

In a similar approach, cellulose and cellulose nanofibers were obtained from vine pruning residues through autohydrolysis and bleaching followed by TEMPO-mediated oxidation and ultrasonication (Araújo et al., 2023). Different micronized stem fractions were tested to optimize cellulose extraction and nanofibrillation. The resulting fibers were characterized in terms of structure, crystallinity, morphology, and thermal properties. Additionally, this study demonstrated the feasibility of producing cellulose-based films from vineyard waste, which could be applied to environmentally friendly coatings for cultural heritage conservation.

2.2.3. Composite materials and fiber modification

In addition to nanocellulose, grapevine fibers have been processed for polymer-based composites. In this context, physical processing steps such as drying, grinding, and sieving are commonly applied to obtain fibrous fractions with controlled particle size and morphology, as illustrated in Fig. 1. Fibers obtained from pruning residues through these processes were incorporated into polylactic acid (PLA) matrices to assess their reinforcing potential (Chang et al., 2024). The study also evaluated the influence of polybutylene succinate, compatibilizers, and lubrication agents on fiber dispersion and interfacial adhesion. The incorporation of grapevine fibers affected both mechanical and thermal properties of the composites, highlighting their potential as a lignocellulosic resource derived from vineyard residues.

Majka et al. examined the effect of chemical modifications on *Vitis vinifera* fibers, including mercerization in sodium hydroxide (NaOH) solution and polymer encapsulation, to evaluate their thermal behavior and compatibility with PLA (Majka et al., 2024). Mercerized fibers exhibited enhanced surface exposure of cellulose, improved adhesion to the polymer matrix, and increased thermal stability. The results emphasized that targeted chemical treatments can tune the interaction of grapevine fibers with polymer matrices without focusing on final application specifics.

2.2.4. Green processing and emerging applications

From a green-processing perspective, mild chemi-thermomechanical pulping has been applied to winery residues, including grape stalks and vine shoots, to produce high-quality fibers suitable for papermaking or further nanocellulose processing (Elissetche et al., 2022). The first stage employed mild chemical treatment with low concentrations of sodium sulfite (Na_2SO_3) and/or NaOH at controlled temperatures, followed by mechanical refining of fiber bundles. This approach yielded fibers with good pulp quality, low fines content, and suitable morphology, demonstrating that environmentally friendly pulping methods can valorize vineyard waste for applications such as paper, packaging, or further processing into nanocellulose.

Similarly, the chemical, physical, and mechanical properties of vine prunin fibers have been characterized after treatment with varying concentrations of NaOH (1–7 wt%). Fibers were categorized into outer bark and inner bark types, exhibiting distinct anatomical structures, cell types, and tensile properties, while their chemical composition and crystallinity remained relatively similar. Lower alkali concentrations (1–3 wt%) produced fibers with superior morphology, cellulose content, crystallinity, and single fiber tensile strength, indicating optimal treatment conditions. These fibers present potential for use in composite materials (Bakar and Kamke, 2020).

Beyond materials science, grapevine fibers have also been explored in the wine industry. Cell wall fibers obtained from grape pomace were used as fining agents to modulate color and tannin content in red wines. The effectiveness of fining depends on the initial composition of the wine and the applied fiber dose, and while promising in unripe or overripe wines, the impact tends to decrease over time and does not generalize to industrial-scale applications (Gil et al., 2018). This illustrates that grapevine fibers can possess functional properties beyond lignocellulosic applications, though such uses involve a different set of characteristics than those relevant for fiber valorization.

Overall, these studies collectively illustrate the versatility of vineyard residues as a lignocellulosic resource. By applying mechanical, chemical, and green-processing methods, fibers and nanofibers with tailored properties can be obtained. Such valorization not only generates high-value materials but also provides opportunities for secondary applications, including use in enology or polymer composites, while maintaining a focus on fiber properties and processing parameters. The main processing routes, products obtained and representative applications discussed throughout this section are summarized in Table 1.

2.3. Phenolic and antioxidant fractions

2.3.1. Stilbenes: the characteristic phenolic compounds of vine-pruning wood

Beyond its structural polymers, vine-pruning wood contains a diverse range of bioactive and low-molecular-weight constituents, including polyphenols, stilbenes, proteins, soluble carbohydrates, and mineral elements associated with its lignocellulosic tissues (Guerrero et al., 2016; Aliaño-González et al., 2020). Among these, phenolic compounds represent one of the most valuable chemical fractions

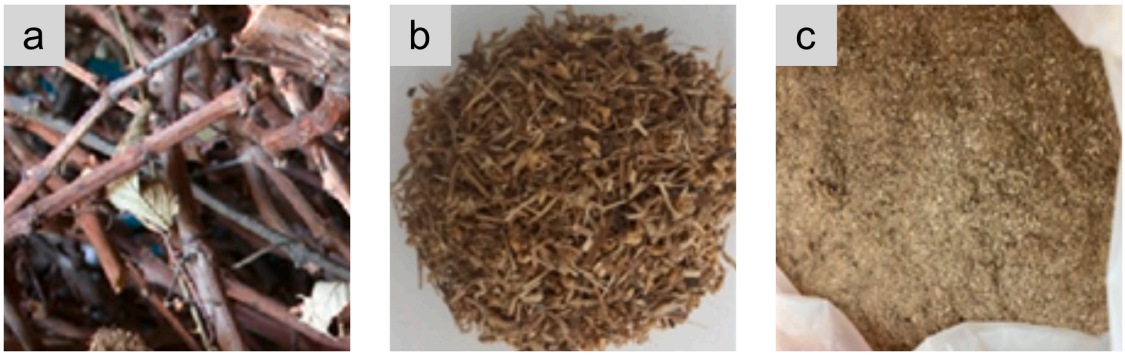


Fig. 1. Representative images of grapevine shoots (a), ground grapevine fibers (b), and grapevine powder (c).

Table 1
Main processing routes for the production of lignocellulosic fibers and nanocellulose from vine-pruning wood.

Processing route	Main processing steps	Main product obtained	Representative application	References
Wet and dry fiber extraction	Wet or dry pretreatment followed by fiber extraction	Lignocellulosic fibers	Sustainable textile fibers and reinforcement materials	(Rana and Sethi, 2025)
Alkaline treatment + bleaching + acid hydrolysis	Alkaline delignification → bleaching → acid hydrolysis	Cellulose nanocrystals (CNCs)	Nanocomposites and advanced cellulose materials	(El Achaby et al., 2018)
Autohydrolysis + bleaching + TEMPO oxidation + ultrasonication	Fractionation followed by TEMPO-mediated oxidation and ultrasonication	Cellulose nanofibers (CNFs) and cellulose films	Sustainable coatings and cellulose-based films	(Araújo et al., 2023)
Mechanical processing + PLA compounding	Drying, grinding, sieving and incorporation into PLA	Fiber-reinforced biocomposites	Biodegradable polymer composites	(Chang et al., 2024)
Mercerization (NaOH) and polymer encapsulation	Alkaline surface modification and polymer treatment	Surface-modified lignocellulosic fibers	Improved fiber–matrix adhesion in composites	(Majka et al., 2024)
Chemi-thermomechanical pulping	Mild Na_2SO_3/NaOH treatment followed by mechanical refining	Cellulosic pulp and fibers	Papermaking, packaging and nanocellulose production	(Elissetche et al., 2022)
NaOH treatment (1–7 wt%)	Alkali treatment of outer and inner bark fibers	Modified lignocellulosic fibers	Composite materials	(Bakar and Kamke, 2020)

(Rayne et al., 2008; Lambert et al., 2013; D'Eusanio et al., 2023b). Given their broad applicability across food, nutraceutical, cosmetic, pharmaceutical, and agricultural sectors, the recovery of these secondary metabolites constitutes one of the most promising valorization pathways for this viticultural residue (see Section 5). Vine-pruning wood is particularly rich in polyphenolic compounds, including both flavonoids and non-flavonoids, with stilbenes being its most distinctive and abundant classes (Lambert et al., 2013). Indeed, more than forty stilbene derivatives have been consistently identified in vine-pruning wood, including resveratrol, ε-viniferins, piceatannol, and various oligomeric forms, alongside associated phenolic acids such as protocatechuic, vanillic, syringic, caffeic, ferulic, coumaric, and sinapic acids (Gabaston et al., 2017; Ewald et al., 2017). Most studies report that stilbenes are present at comparatively high concentrations in vine-pruning wood, often exceeding those of other polyphenolic classes on a dry weight basis, with trans-resveratrol and trans-ε-viniferin consistently emerging as the predominant constituents (Pawlus et al., 2013; Lambert et al., 2013; Gorena et al., 2014; Houillé et al., 2015; Gabaston et al., 2017; Goufo et al., 2020). Nonetheless, other stilbenes, such as isohopeaphenol and vitisin B, have also been detected in substantial amounts, but their identification and relative abundance varies across varieties, sampling periods, and annual growing conditions, reinforcing the distinctive stilbenoid fingerprint of vine-pruning wood (Richard et al., 2016; Guerrero et al., 2016; Aliaño-González et al., 2020). This reinforces the concept of a variety- and environment-dependent phenolic composition. In fact, particularly with stilbene composition, it is not only genotype-dependent but also sensitive to post-pruning handling. Drying conditions and storage time have been shown to influence both the qualitative profile and quantitative levels of stilbenes, adding a dynamic dimension to the valorization potential of this biomass (Gorena et al., 2014; Ewald et al., 2017; D'Eusanio et al., 2023b). These factors must therefore be considered when designing extraction strategies or standardization protocols (Gorena et al., 2014).

2.3.2. Other phenolic compounds and oxidant potential

In addition to stilbenes, vine-pruning wood contains other polyphenolic families that, although generally present in lower relative abundance, contribute significantly to its phytochemical complexity and functional properties (Zhang et al., 2011; Kodeš et al., 2021; Filimon et al., 2023). Frequently detected compounds include flavanols such as catechin, epicatechin, and procyanidins, as well as phenolic acids including sinapic, ferulic, gallic, and protocatechuic acids (Çetin et al., 2011; Zhang et al., 2011; Ferreyra et al., 2021). These may occur both as freely extractable constituents and as matrix-bound phenolics associated with the lignin or hemicellulosic structures. Although the majority of studies on vine-pruning wood phenolics have focused predominantly on stilbenes, the entire phenolic fraction can contribute to the antioxidant, antimicrobial, and broader bioactive properties attributed to vine-pruning wood extracts (Oluwole et al., 2022; D'Eusanio et al., 2023b; Navarro-Orcajada et al., 2023). Thus, vine-pruning wood represents an abundant, annually renewable, and largely underutilized source of stilbenes and related phenolics, aligning well with circular bioeconomy and biorefinery concepts in which bioactive compound recovery can precede or complement energy and material valorization pathways.

2.3.3. Aromatic compounds and minerals

Beyond phenolics, vine-pruning wood contains additional chemical fractions that can be strategically leveraged in integrated valorization routes, namely aromatic compounds, organic acids and mineral elements. In fact, vine-pruning wood potential in the infusion of wines and vinegar has been previously studied (more details in Section 5.3) (D'Eusanio et al., 2023b; D'Eusanio et al., 2023c).

2.3.4. Aromatic compounds

Aromatic compounds constitute an underappreciated fraction of vine-pruning wood. Processing methodologies, such as controlled toasting, can promote the formation and release of volatile and semi-volatile compounds associated with woody sensory notes, which has driven research in the use of vine-pruning wood as an alternative material for the ageing processes of beverages and related products (D'Eusanio et al., 2023a). In fact, there is even the interest of using vine-pruning wood of specific varieties to contribute to unique profiles and attributes (D'Eusanio et al., 2023c).

Few studies have explored the volatile composition, specifically the aromatic compounds of vine-pruning wood, as most of these originate from complex chemical transformations within the lignocellulosic matrix. Furanic derivatives, including furfural and methylated derivatives, are described as being some of the most common aromatic compounds found in vine-pruning wood, being typically associated with sweet and toasted notes (Delgado De La Torre et al., 2014; Sánchez-Gómez et al., 2014). D'Eusanio and collaborators (D'Eusanio et al., 2023b) also observed that aldehydes accounted for up to a third of the composition of vine-pruning wood chips, being known for their fruity notes, with hexanal being the most prevalent. However, the same authors denoted that, as with any woody material, moderate thermal treatment enhances these desirable aromatic compounds, but excessive temperatures promote the formation of potentially harmful volatiles such as benzene and other aromatic hydrocarbons (D'Eusanio et al., 2023b).

2.3.5. Mineral composition

In terms of mineral composition, very few studies have specifically explored this fraction in vine-pruning wood. Nonetheless, minerals are especially relevant, as macro- and microelements taken up from the soil remain partially retained in woody tissues and can be transferred to extracts and other products (Manyà et al., 2018). It has been documented that vine-pruning wood is rich in minerals such as nitrogen, sulfur, aluminum, potassium, calcium, iron, magnesium, phosphorus

and zinc; however, this mineral profile is highly variable, with element accumulation being strongly influenced by grapevine genotype, soil characteristics, and other growth conditions (Çetin et al., 2011; Sánchez-Gómez et al., 2014; D'Eusanio et al., 2023b). From a broader valorization perspective, this mineral pool supports the use of this woody material as soil amendment strategies, mineral-enriched biochar production, and other agricultural inputs, where nutrient return is key for lower chemical inputs (more details in Section 5.2) (Nascimento-Gonçalves et al., 2024; Azevedo et al., 2025; Maia et al., 2026). Furthermore, as most of these minerals have important biological roles in human health, it also has potential as an addictive for food products, improving the quality of vinegars, wines and other beverages (see Sections 5.3 and 5.8) (Aliaño-González et al., 2022; D'Eusanio et al., 2023b).

Collectively, the structural robustness and phytochemical diversity of vine-pruning wood position it as a strategic feedstock for integrated valorization pathways. However, effective implementation requires careful consideration of compositional variability and optimization of processing conditions to ensure appropriated and sustainable applications (more details in Section 7).

3. Green extraction and processing technologies for vine-pruning wood

3.1. Principles of green chemistry and sustainable extraction

The application of green chemistry principles to the valorization of vitivinicultural residues is based on the reduction of hazardous solvents, lower energy demand, improved selectivity, and enhanced process performance (Contreras et al., 2022). Conventional solid–liquid extraction methods typically require large volumes of organic solvents and prolonged heating, increasing environmental burdens and operational costs while potentially degrading thermolabile phenolic compounds (Xu et al., 2025). In contrast, sustainable extraction strategies seek to minimize solvent consumption, prioritize safer alternatives, and integrate processes within circular biorefinery frameworks. Nevertheless, the true sustainability of these approaches must be assessed beyond laboratory efficiency, considering scalability, energy balance, and overall environmental impact (Zhang and Wu, 2025). In this context, green solvents emerge as a key strategy to reduce or eliminate the use of harmful solvents, owing to their non-toxic, non-volatile, recyclable, and biodegradable nature, as well as their lower energy demand during synthesis. These alternative solvents can generally be grouped into four categories: supercritical fluids, neoteric solvents, bio-based solvents, and supramolecular solvents. However, replacing a conventional solvent with a greener alternative is not a trivial step, as new physicochemical constraints and operational challenges may arise (Liberal et al., 2022).

Supercritical CO_2 extraction is widely regarded as a benchmark green technology due to the use of a non-toxic, recyclable solvent and operation under relatively mild temperatures, which preserve bioactive compounds and enable high-purity extracts. However, high capital investment, elevated pressure requirements, and technical complexity may restrict large-scale implementation, particularly for low-value biomass streams such as vine-pruning residues (Zhang and Wu, 2025). Likewise, subcritical water extraction replaces organic solvents with pressurized water, fulfilling principles of safer solvent use and waste reduction, although elevated temperatures and possible degradation reactions require careful optimization to ensure extract stability and quality (Ferreira et al., 2023).

Emerging process-intensified technologies, including ultrasound-assisted extraction combined with deep eutectic solvents, further align with green extraction principles by enhancing mass transfer, shortening extraction times, and reducing energy input. The adoption of biodegradable and low-toxicity solvent systems improves extraction efficiency and environmental compatibility; however, challenges related to solvent recovery, regulatory acceptance, and industrial scalability remain critical barriers (Xu et al., 2025). Within the wine sector, integrating these technologies into vine-pruning wood valorization pathways strengthens circular bioeconomy strategies, yet comprehensive techno-economic assessment and life-cycle analysis are essential to validate their real environmental advantage (Peña-Portillo et al., 2024). Therefore, the transition from conventional extraction to green and sustainable strategies represents not only an environmental imperative but also a technological challenge that requires integrated optimization of solvent systems, energy inputs, and process scalability.

3.2. Methods and process intensification

Building upon green chemistry principles, intensification strategies applied to the valorization of vitivinicultural residues aim to enhance extraction efficiency while reducing processing time, solvent consumption, and energy demand. Unlike conventional solid–liquid extraction, intensified technologies rely on physical mechanisms that improve mass transfer and promote structural disruption of lignocellulosic matrices, enabling higher recovery of phenolic compounds under optimized conditions (Tumminelli et al., 2025). In vine shoots and pruning residues, response surface methodology and energy-consumption monitoring have been successfully applied to optimize extraction variables, demonstrating the integration of efficiency and sustainability criteria in process design (Muñoz-Realpe et al., 2025).

Ultrasound-assisted extraction enhances mass transfer through acoustic cavitation. The formation and collapse of microbubbles generate localized high-pressure and high-temperature zones, leading to cell wall disruption and improved diffusion of intracellular bioactive compounds (Liberal et al., 2022). In vine shoots, probe-type ultrasound systems have shown higher efficiency compared to conventional extraction, significantly reducing extraction time while maintaining high phenolic yields, particularly for trans-resveratrol and trans--ε-viniferin (Muñoz-Realpe et al., 2025). The optimization of operational parameters, such as amplitude, extraction time, ethanol concentration, and temperature, plays a critical role in maximizing yield and antioxidant capacity (Liberal et al., 2022). Probe systems, compared to ultrasonic baths, offer improved energy transmission and shorter treatment times, suggesting potential advantages for industrial implementation, although scale-up requires careful control of energy distribution and continuous-flow configurations (Muñoz-Realpe et al., 2025; Xu et al., 2025).

Microwave-assisted extraction operates via dielectric heating, where electromagnetic radiation induces dipole rotation and ionic conduction within the solvent and biomass matrix, resulting in rapid and volumetric heating (Xu et al., 2025). This mechanism accelerates solvent penetration and solute diffusion, enabling efficient extraction within significantly reduced processing times (Peña-Portillo et al., 2024). In vine-pruning wood, microwave extraction has demonstrated higher phenolic concentration under optimized temperature and solvent conditions, with energy efficiency considered as a key parameter during optimization (Muñoz-Realpe et al., 2025).

Microwave-assisted solvent extraction (MASE) has also been applied to vine-pruning wood for the recovery of (E)-resveratrol and (E)-ε-viniferin, combining short extraction cycles with environmental impact assessment tools such as the Environmental Factor (EF) and AGREE metrics to evaluate process greenness (Tumminelli et al., 2025). Furthermore, the integration of microwave heating with eutectic solvent systems has enabled high polyphenol yields under relatively mild conditions. Choline chloride-based eutectic mixtures, combined with controlled water addition, were shown to reduce solvent viscosity and enhance extraction performance, although solvent recovery and downstream handling remain technological challenges (Mattonai et al., 2024).

Supercritical fluid extraction (SFE), particularly using supercritical CO_2, represents a pressure-driven intensified technology with tunable solvating power. Above its critical point, CO_2 combines gas-like

diffusivity and liquid-like solvency, enabling deep penetration into lignocellulosic matrices and selective solubilization of bioactive compounds (Zhang and Wu, 2025). The addition of ethanol as a co-solvent improves the extraction of polar phenolics, enhancing recovery while maintaining low solvent residues and high extract purity (Peña-Portillo et al., 2024).

From an engineering perspective, SFE requires careful control of pressure, temperature, solvent-to-feed ratio, and bed geometry. A pilot-scale study demonstrated successful scale-up criteria for supercritical extraction of grape-derived byproducts, maintaining extraction yields at industrial volumes while providing techno-economic validation. The economic assessment confirmed the feasibility of a 500 L industrial SFE plant with competitive production costs (Da Porto et al., 2022). Although capital investment remains higher compared to ultrasound or microwave systems, SFE offers advantages in solvent recyclability, product purity, and industrial robustness.

In contrast to intensified technologies, percolation represents a conventional dynamic extraction approach. It is a solid–liquid extraction technique in which solvent is continuously passed through a packed bed of finely ground plant material contained in a percolation vessel. As the solvent percolates through the matrix, soluble compounds are progressively dissolved and carried downward, being collected at the outlet of the system. This continuous renewal of solvent enhances mass transfer compared to static techniques and allows the extract to be obtained directly in liquid form, typically followed by solvent removal for concentration. Because the system includes an integrated filtration base, an additional filtration step is generally unnecessary. However, this technique still presents several limitations, including relatively long processing times, high solvent consumption, and dependence on parameters such as particle size, solute solubility, solvent–matrix contact time, and flow rate. Therefore, although percolation represents an advancement over static extraction approaches, its operational constraints can limit its applicability in large-scale or highly sustainable extraction processes (Liberal et al., 2022).

Ultrasound- and microwave-assisted extraction technologies intensify the process primarily through enhanced matrix–solvent interaction and rapid volumetric heating mechanisms, leading to significant reductions in extraction time, solvent consumption, and overall energy input (Muñoz-Realpe et al., 2025). In contrast, supercritical fluid extraction operates through pressure- and temperature-modulated solvent density, enabling selective solubilization and the production of high-purity extracts with minimal solvent residues (Zhang and Wu, 2025). Percolation, although more dynamic than maceration due to the continuous renewal of solvent through the packed bed, relies mainly on diffusion-driven mass transfer and therefore typically requires longer processing times and higher solvent volumes compared to intensified techniques (Liberal et al., 2022). While ultrasound and microwave systems generally involve lower capital expenditure and offer operational flexibility at laboratory and pilot scales, SFE provides superior scalability, process standardization, and solvent recyclability, albeit with higher equipment investment and more complex high-pressure infrastructure (Da Porto et al., 2022). A comparative overview of operational conditions and performance metrics is summarized in Table 2.

3.3. Applications of green extraction to vine-pruning wood

Vine-pruning residues, particularly grape cane, have demonstrated strong potential as multifunctional bioinputs within sustainable viticulture. Stilbenoid-rich grape cane extracts obtained via microwave-assisted hydro-ethanolic extraction showed significant antifungal and antimycotoxigenic activity against *Fusarium graminearum, Aspergillus flavus*, and *Penicillium expansum*, reducing deoxynivalenol (DON) and AFB1 production in a dose-dependent manner (Aznar et al., 2025). Complementarily, field trials confirmed that grape cane extract formulations effectively reduced *Plasmopara viticola* severity under vineyard conditions, achieving disease control comparable to copper-based treatments without inducing relevant phenolic residues in musts (Besrukow et al., 2024). Comparative extraction studies further demonstrated that microwave-assisted systems improve stilbenoid recovery relative to water-only extraction, reinforcing the technological feasibility of vine-pruning wood valorization (Andlauer et al., 2025).

Beyond direct antifungal applications, plant-derived biostimulants and protein hydrolysate formulations have shown the capacity to prime grapevine defense metabolism. In vitro assays demonstrated that biostimulation enhances responsiveness to elicitors, increasing resistance to downy mildew through modulation of metabolomes and phytohormonal balance (Jacquens et al., 2022). Transcriptomic analyses revealed activation of MAPK cascades, ROS signaling, hormone cross-talk, and phenylpropanoid pathways following preventive biostimulant application (Mostacci et al., 2026). Similarly, high-throughput RNA-seq approaches confirmed broad transcriptional reprogramming associated with stress tolerance and growth regulation in treated grapevine leaves (Mostacci et al., 2026). Previous investigations with soybean-derived protein hydrolysates further demonstrated induction of stilbene biosynthesis and

Table 2
Comparative overview of green extraction technologies applied to grapevine pruning residues.

Solvent Type	Biomass	Extraction Technology	Main Compounds Recovered	Reported Application	Scale / Notes	References
Water (Hydrothermal)	Vine-pruning residue	Sequential autohydrolysis	Xylo-oligosaccharides + phenolics	Biorefinery cascade approach	Integrated fractionation	(Jesus et al., 2017)
Water (LHW)	Grapevine shoots	Liquid Hot Water (LHW) fractionation	Resveratrol (stems), quercetin (leaves)	Cascading valorization	Biorefinery concept	(Serna-Loaiza et al., 2022)
Ethanol/ Hydroethanolic	Grape canes	Hydroethanolic extraction (750 L reactor)	44 phenolic compounds	Industrial extract production	Pilot-scale reactor	(Escobar-Avello et al., 2021b)
Ethanol (UAE)	Vine canes	Ultrasound-assisted extraction (UAE)	Stilbenes	Process intensification	Lab to pilot scale	(Dorosh et al., 2020)
Ethanol (MAE)	Pruning wood	Microwave-assisted extraction (MAE)	Resveratrol, ε-viniferin	High-value bioactive recovery	Optimized extraction	(Tumminelli et al., 2025)
Ethanol (UAE vs MAE)	Vine shoots	Probe-UAE vs Microwave extraction	Stilbenoids	Energy-efficient extraction	Energy consumption evaluated	(Muñoz-Realpe et al., 2025)
Ethanol (Encapsulation)	Grape cane extract	Spray-drying encapsulation	Phenolic compounds	Stability enhancement	Shelf-life improvement	(Escobar-Avello et al., 2021a)
DES	Vine shoots	Levulinic acid-based DES + UAE	Polyphenols	Sustainable extraction	Green solvent alternative	(Duarte et al., 2024)
NADES	Grapevine canes	Selective NADES extraction	Resveratrol & viniferin	Targeted bioactive recovery	Selectivity study	(Kiene et al., 2023)
SFE (CO_2)	Grape cane	Supercritical CO_2 extraction	Stilbenes	High-purity extract	Compared with PLE	(Zachová et al., 2018)
SFE (Formulated)	Cane extract	SFE + agricultural formulation	Phenolic compounds	Antifungal crop protection	Pilot production	(Besrukow et al., 2023)

pathogenesis-related proteins, reinforcing their role as metabolic priming agents (Mostacci et al., 2026).

Collectively, these findings indicate that grapevine by-products and plant-based hydrolysates can function both as biofungicidal agents and as resilience-enhancing biostimulants, integrating pathogen control with stress tolerance modulation. This dual functionality supports a circular viticulture model in which vine-pruning wood is revalorized into high-value bioinputs, reducing reliance on synthetic pesticides and copper-based fungicides while maintaining crop productivity and quality (Besrukow et al., 2024; Andlauer et al., 2025; Aznar et al., 2025).

3.4. Industrial potential and challenges for scale-up

The industrial valorization of vine-pruning wood represents a technically promising yet operationally demanding opportunity within circular bioeconomy systems. The high annual availability of pruning wood and their richness in stilbenoids support their positioning as feedstock for high-value extracts in food, cosmetic, and agricultural applications (Noviello et al., 2022; Peña-Portillo et al., 2024). However, industrial scalability depends on managing intrinsic biomass heterogeneity, including seasonal variation, variety-dependent metabolite profiles, moisture content, and storage conditions. These factors directly affect extraction kinetics, solvent performance, and product standardization. Upstream preprocessing strategies such as controlled drying, particle size optimization, and batch traceability become critical to ensure reproducibility at industrial throughput. Pretreatment is a key step in the valorization of vine-pruning wood, as the recalcitrant lignocellulosic structure limits the accessibility of cellulose and hemicellulose for downstream conversion processes. Among the available strategies, steam explosion offers one of the best compromises between efficiency, operational cost, and environmental performance, as it effectively disrupts the biomass structure while minimizing chemical consumption (Buratti et al., 2015; Jesus et al., 2022). Dilute acid pretreatment generally achieves higher hemicellulose solubilization and sugar recovery but requires acid neutralization and corrosion-resistant equipment, increasing both costs and environmental burdens (Kumar et al., 2009; Haghighi Mood et al., 2013). Conversely, alkaline pretreatment is particularly effective for lignin removal in woody biomasses such as vine-pruning residues, although its sustainability depends on efficient alkali recovery and wastewater management (Haghighi Mood et al., 2013; Jesus et al., 2022). Biological pretreatments are environmentally friendly due to their low energy demand and reduced chemical inputs, but their slow processing rates and limited scalability currently restrict industrial application (Sindhu et al., 2016). Therefore, the selection of the most appropriate pretreatment should balance technical efficiency, economic feasibility, and environmental performance according to the intended biorefinery pathway.

While intensified extraction technologies such as microwave- and ultrasound-assisted systems demonstrate improved yields and reduced solvent use at pilot scale (Muñoz-Realpe et al., 2025; Tumminelli et al., 2025), their transition to continuous industrial operation requires careful evaluation of energy efficiency, equipment durability, and process control. Downstream processing remains a decisive bottleneck, particularly when high-value positioning demands compositional standardization and selective purification. Continuous adsorption systems and molecularly imprinted materials offer promising selectivity under hydroalcoholic conditions, yet challenges related to fouling, regeneration cycles, and long-term operational stability must be validated at scale (Bzainia et al., 2024).

Industrial feasibility ultimately depends not only on extraction performance but on integrated techno-economic and environmental validation. This trend is consistent with broader assessments of agro-food biorefineries, which identify feedstock logistics, process integration, and market diversification as key factors governing industrial feasibility (Ragini et al., 2025). Techno-economic assessment and life cycle assessment indicate that solvent recovery efficiency, energy integration, and downstream separation costs are often the dominant factors determining profitability and environmental performance (Arias et al., 2023). Although supercritical CO_2 extraction offers advantages in solvent recyclability and extract purity, its higher capital expenditure and infrastructure requirements significantly influence break-even scale and investment risk (Da Porto et al., 2022; Zhang and Wu, 2025). Furthermore, regulatory positioning as food ingredient, cosmetic active, or agricultural bioinput imposes strict constraints on solvent residues, contaminant control, and compositional consistency. Therefore, successful scale-up will likely require hybrid and modular process architectures integrating intensified extraction, continuous purification, solvent recycling loops, and digital monitoring systems to ensure reproducibility, economic resilience, and regulatory compliance.

Despite the promising laboratory-scale results reported for many vine-pruning wood valorization processes, their industrial implementation remains challenging. Scale-up requires the optimization of reactor and extraction system design, heat and mass transfer, and process integration to ensure stable product yields under continuous operation. In thermochemical processes, reactor configuration and operating conditions strongly influence product distribution and energy efficiency, whereas biochemical conversion routes require efficient biocatalytic performance and downstream processing. In addition, equipment fouling, operational stability, and process reproducibility remain important operational challenges that directly affect economic viability and industrial feasibility. Overcoming these engineering constraints through pilot-scale validation and integrated techno-economic and environmental assessments will be essential for the successful deployment of vine-pruning wood biorefineries (Da Porto et al., 2022; Arias et al., 2023; Ragini et al., 2025; Zhang and Wu, 2025).

Addressing these interconnected engineering, economic, and regulatory challenges is essential for transitioning grapevine pruning valorization from pilot demonstration to commercially viable biorefinery platforms (Fig. 2).

4. Current management practices and valorization pathways for vine-pruning wood

4.1. Conventional disposal routes and limitations

Although vine-pruning wood is increasingly recognized as a versatile lignocellulosic feedstock, conventional management practices in many viticultural systems still remain dominated by low-value or suboptimal disposal routes. From a technical perspective, however, its chemical composition, wide availability, and low economic cost make it suitable for valorization through multiple processing routes (Fig. 3). These approaches enable the recovery of a broad range of value-added products, including hemicellulose-derived oligosaccharides, lignin-based antioxidant compounds, organic acids and bioethanol obtained via cellulose saccharification, as well as ashes, proteins and other extractives, in line with an integrated biorefinery concept (more details in Section 3) (Dávila et al., 2016; Jesus et al., 2017). Within this context, the current European regulatory framework mandates the recovery and reuse of winemaking by-products through approved pathways, such as industrial processing, energy recovery (e.g., biogas or combustion systems) and agronomic recycling via composting, thereby discouraging uncontrolled disposal practices (Bignami et al., 2023).

4.2. Agronomic reuse of vitivinicultural residues through soil application and amendment

Among the most immediate management options, the return of vine-pruning wood to the soil represents one of the most direct and agronomically relevant valorization pathways. This strategy enables the reintegration of organic biomass into vineyard systems, contributing to soil quality improvement while reducing the environmental burdens associated with conventional disposal practices.

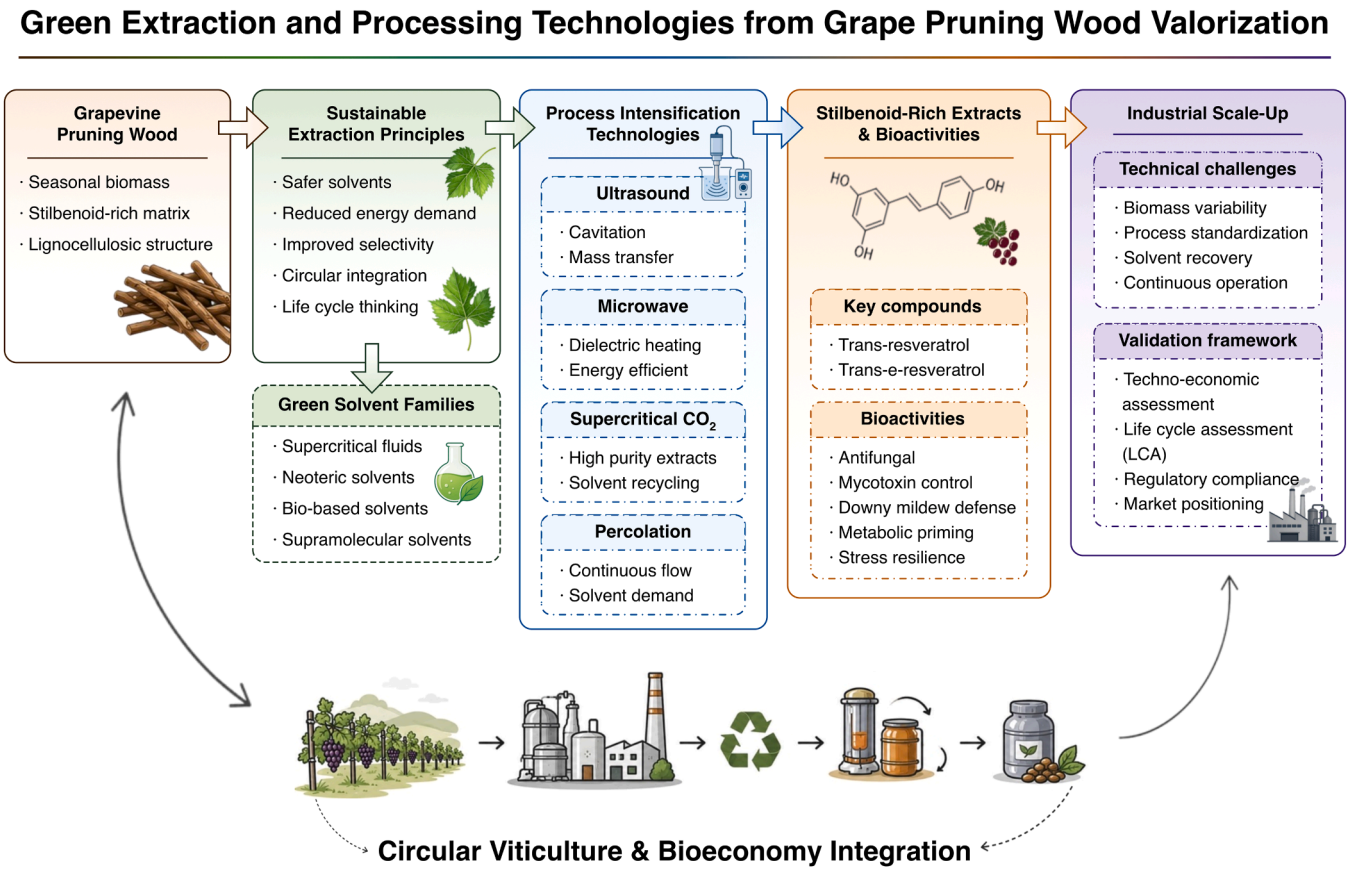


Fig. 2. Conceptual framework integrating green chemistry principles, intensified extraction technologies, functional applications, and industrial scale-up considerations for grapevine pruning wood valorization within a circular bioeconomy model.

Biological treatments such as composting and vermicomposting are widely recognized as effective methods for transforming vine-pruning wood into stabilized organic amendments with enhanced agronomic value (Kolbe et al., 2019; Jesus et al., 2019; Azevedo et al., 2025). These processes promote the degradation of lignocellulosic biomass and the formation of humified organic matter enriched with essential nutrients, contributing to improved soil fertility and structural stability. Vermicompost, in particular, has demonstrated the ability to enhance soil physicochemical and microbiological properties, including increased organic matter content, improved nutrient retention and availability, and stimulation of beneficial microbial activity (Rehman et al., 2023; Oyege and Balaji Bhaskar, 2023). These improvements support plant growth, increase resilience to abiotic and biotic stresses, and reduce dependence on synthetic fertilizers, reinforcing the sustainability of viticultural systems (Nascimento-Gonçalves et al., 2024). The application of compost derived from vine-pruning wood has been shown to provide significant long-term benefits in vineyard soils. These include improvements in soil organic matter content, enhanced microbial activity and improved nutrient cycling, without negative effects even at application rates corresponding to annual pruning biomass production ($\approx$2 t ha^{-1} yr^{-1}) (Morlat and Chaussod, 2008; García-Orenes et al., 2016; Mondini et al., 2018). Such improvements in soil health have been associated with enhanced grapevine performance, including increased yield and improved fruit quality, highlighting the agronomic potential of vine-pruning-derived amendment (Gaiotti et al., 2017; Karimi et al., 2020).

A further agronomic route is the thermochemical conversion of vine-pruning wood into biochar. As a stable carbon-rich material characterized by high porosity and adsorption capacity, which improves soil structure, enhances nutrient retention and increases water-holding capacity (Tag et al., 2016; Guo et al., 2019). Recent characterization of biochar produced from vine-pruning wood at 400°C demonstrated a substantial increase in fixed carbon content (from $\approx$19.6% to 58.8%) and total carbon concentration (from $\approx$46% to 73%), accompanied by a marked reduction in oxygen content (to $\approx$20%), indicating enhanced aromaticity and structural stability (Nunes et al., 2021b). These compositional shifts reflect a lower O/C ratio and greater carbon recalcitrance, supporting long-term carbon persistence in soils. Moreover, pyrolysis significantly increased the higher heating value (from $\approx$19 to $\approx$30 MJ kg^{-1}), while chlorine content was almost eliminated during the process, reducing potential environmental risks linked to soil contamination or combustion emissions (Nunes et al., 2021b). From an agronomic perspective, the elevated fixed carbon fraction and the relative concentration of mineral elements after carbonization may contribute to improved cation exchange capacity and nutrient retention, while the porous structure supports microbial habitat formation. Together, these characteristics position vine-pruning-derived biochar as both a soil amendment and a climate mitigation tool within vitivinicultural circular systems.

Recent studies further demonstrate that pyrolysis temperature and residence time jointly modulate key physicochemical and biological properties of vineyard-pruning biochars, indicating that these materials should be considered process-engineered amendments rather than uniform products. Increasing temperature generally reduces the water-extractable organic carbon (WEOC) fraction, shifting the material from a more labile, microbially available carbon pool to a highly condensed and recalcitrant structure. This transition influences not only carbon sequestration potential but also short-term soil–microbe interactions and nutrient dynamics (Cárdenas-Aguiar et al., 2023).

Alternative mild thermochemical routes have also been proposed. In contrast to conventional pyrolysis, which primarily targets biochar stability and soil functionality, torrefaction aims to balance energy

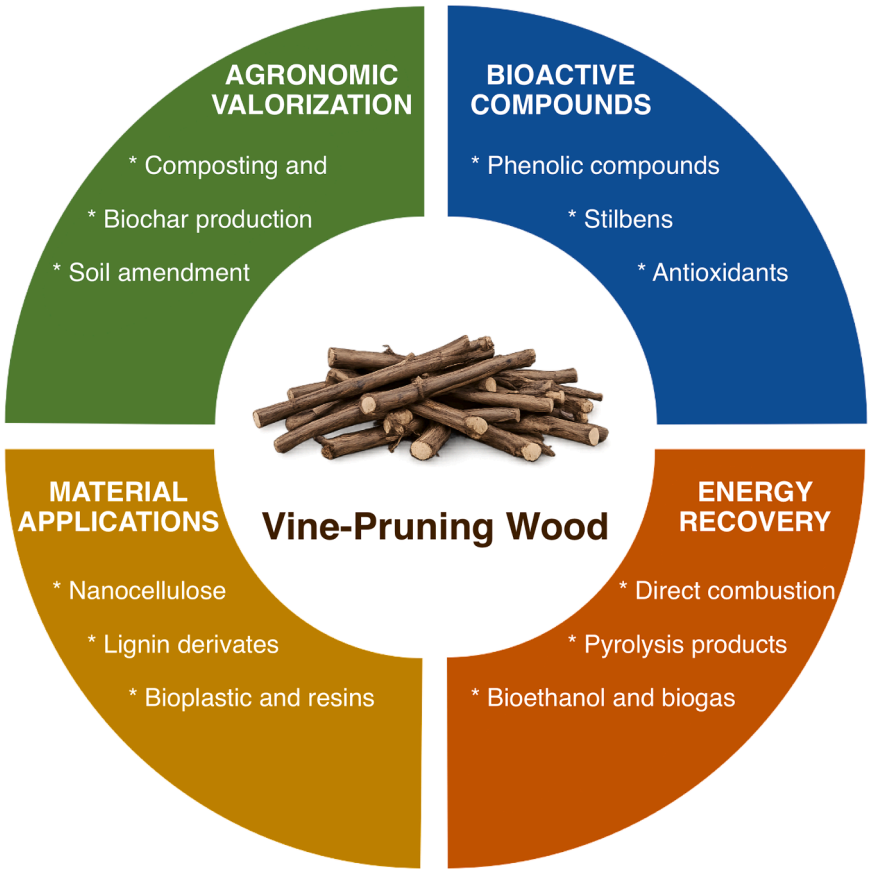


Fig. 3. Vine-pruning wood valorization: A comprehensive review of sustainable pathways.

densification with structural preservation. Oxidative torrefaction has been proposed as an energy-efficient and scalable alternative to conventional inert pyrolysis. Özer and Duranay demonstrated that vine-pruning wood subjected to oxidative torrefaction (220–280°C) produced a carbon-enriched solid with improved fuel properties while maintaining structural integrity suitable for soil applications. At 220°C, solid yields of approximately 80% were achieved, with a higher heating value (HHV) increase from 17.79 MJ kg^{-1} (raw biomass) to 19.77 MJ kg^{-1}, corresponding to an energy yield above 88%. Importantly, the process can operate under controlled oxygen atmospheres and utilize flue gases as a heat source, reducing external energy demand and enhancing process sustainability (Özer and Duranay, 2025).

Despite these advantages, the agronomic performance of thermochemically derived materials depends on process severity, soil type, and application rate, and excessive inputs may alter soil pH or nutrient dynamics. Furthermore, germination assays reported for vineyard-pruning biochars indicate that phytotoxic responses may occur depending on residence time and pyrolysis severity, reinforcing the need for optimization and quality control prior to field-scale application. In this context, monitoring of polycyclic aromatic hydrocarbons (PAHs) and compliance with international standards such as the European Biochar Certificate (EBC) are essential to ensure environmental safety (Cárdenas-Aguiar et al., 2023). Therefore, further long-term field evaluations are required to fully validate their soil functionality.

Direct application of vine-pruning wood as an organic mulch also represents an effective agronomic management strategy. Organic mulching contributes to soil moisture conservation, temperature regulation and reduced soil evaporation, while simultaneously increasing soil organic matter over time. Under semi-arid vineyard conditions, vine-pruning wood mulch has been shown to reduce evapotranspiration by approximately 16–18% compared with bare soil, improving water use efficiency without increasing vine transpiration (López-Urrea et al., 2020). These findings highlight its potential as a sustainable alternative to synthetic mulching materials, contributing to improved vineyard resource efficiency and environmentally responsible residue management.

Collectively, these agronomic pathways illustrate that vine-pruning wood can transition from a disposal liability to a multifunctional resource within regenerative viticulture systems, provided that transformation parameters, environmental safety thresholds, and soil-specific responses are carefully aligned.

4.3. Bioactive applications: viticulture, oenology, food, cosmetic and pharmaceutical sectors

Beyond soil-oriented uses, vine-pruning wood has gained relevance as a source of bioactive compounds for direct use in multiple high-value applications. Its complex chemical profile underpins a wide range of antioxidant, antimicrobial, and signaling functions, enabling applications in viticulture, food preservation, cosmetics and biomedical fields.

4.3.1. Viticultural and oenological applications

Aqueous extracts derived from vine-pruning wood have demonstrated considerable potential as foliar biostimulants, positively influencing vine physiology, grape composition and resulting wine characteristics. For example, aqueous extracts obtained from vine-pruning wood have been shown to act as effective foliar fertilizers, increasing amino acid concentrations in the resulting wines and improving their nutritional and sensory profile (Sánchez-Gómez et al., 2017b). Similarly, foliar application of aqueous extracts from toasted vine-pruning wood resulted in increased grape yield and modifications in wine composition, including lower alcoholic content and higher concentrations of aroma-active compounds such as norisoprenoids, volatile phenols and vanillin derivatives, which contribute to enhanced

wine aroma complexity (Sánchez-Gómez et al., 2016a). These physiological responses are likely associated with elicitor-like effects of phenolic compounds, which may modulate plant secondary metabolism and stress-response pathways, enhancing resilience to abiotic stress conditions.

The same biomass has also been investigated as an oenological additive during winemaking. Studies have demonstrated that roasted and unroasted vine-pruning wood can release significant amounts of phenolic and aromatic compounds when applied during vinification processes. During hot maceration in model wine systems, vine-pruning wood showed efficient transfer of bioactive compounds, with concentrations of key aroma compounds exceeding sensory perception thresholds, highlighting their potential to enhance wine sensory properties and functional quality (Cebrián-Tarancón et al., 2019). Further research has confirmed the ability of vine-pruning wood to modulate wine chemical composition and improve key quality parameters. Indeed, the application of vine-pruning wood in pellet or granular form during vinification has been associated with increased concentrations of flavan-3-ols and other phenolic compounds, contributing to improved antioxidant capacity and color stability (Cebrián-Tarancón et al., 2018). Similarly, the incorporation of vine-pruning wood-derived compounds has been shown to enhance wine color intensity, stabilize anthocyanins and improve aromatic complexity, while also preserving glutathione levels and influencing important oenological parameters such as pH, total acidity and volatile compound composition (Raposo et al., 2016; Sánchez-Gómez et al., 2016a; Sánchez-Gómez et al., 2016b; Raposo et al., 2018; Cruz et al., 2018; Ruiz-Moreno et al., 2018; Sánchez-Gómez et al., 2020). These effects contribute to improved wine stability, sensory quality and shelf life.

From a regulatory perspective, the use of alternative wood materials in oenology must comply with international standards and guidelines (e.g., OIV specifications) governing oenological practices, particularly regarding safety, compositional limits and absence of undesirable contaminants. Consequently, process control (degree of toasting, particle size, extraction conditions) and compositional fingerprinting are critical to ensure reproducibility and regulatory acceptance, especially when positioning vine-pruning wood as an alternative to traditional oak chips.

In addition to their biostimulant and oenological applications, vine-pruning wood extracts have demonstrated promising bioactivity in plant protection. Antifeedant effects against herbivorous insect pests have been reported, highlighting their potential as natural plant protection agents. Furthermore, these extracts have shown positive effects on root development in plant model species such as Lolium perenne and Lactuca sativa, indicating their capacity to promote plant growth and enhance plant resilience (Sánchez-Gómez et al., 2017a). These multifunctional properties support the use of vine-pruning wood-derived products as sustainable alternatives to synthetic agrochemicals, contributing to environmentally friendly vineyard management practices. However, variability in phenolic composition depending on grape variety, pruning age, storage conditions and thermal treatment intensity may influence bioactivity, requiring optimization of extraction protocols and standardization strategies prior to large-scale agricultural deployment.

Taken together, these applications represent a high-value valorization route within which extractable bioactive fractions are first recovered for direct use in viticulture and oenology, while the residual lignocellulosic matrix may subsequently be directed towards other downstream pathways.

4.3.2. Food preservation applications and antifungal applications

Within food-related applications, the strongest interest in vine-pruning wood extracts is linked to their antifungal and antioxidant functionality. The growing demand for natural food preservatives, driven by regulatory restrictions and consumer concerns regarding synthetic additives, has intensified research into plant-derived bioactive compounds with antimicrobial properties. In this context, vine-pruning wood extracts have attracted increasing attention due to their high content of phenolic compounds and associated antifungal and antioxidant activities. These compounds play a key role in plant defense and exhibit strong antimicrobial properties, making them promising candidates for food preservation applications and the prevention of postharvest spoilage. Stilbenes, flavonoids and phenolic acids present in vine-pruning wood are particularly relevant due to their documented capacity to interfere with fungal metabolism and oxidative balance.

The antifungal activity of vine-pruning wood extracts has been experimentally demonstrated against several foodborne pathogenic fungi associated with postharvest fruit deterioration. Jesus and collaborators evaluated the inhibitory effects of vine-pruning wood extracts against five fungal strains, including *Alternaria* sp., *Cladosporium cladosporioides, Phoma violacea, Penicillium italicum* and *Penicillium expansum*, which are among the most relevant spoilage fungi affecting fruit quality and safety. At a concentration of 1000 μg mL^{-1} and after 96 h of exposure, the extracts inhibited fungal growth by at least 41%, confirming their potential as natural antifungal agents. These findings demonstrate the ability of vine-pruning wood extracts to suppress the development of foodborne fungal pathogens, supporting their application in strategies aimed at extending shelf life and preserving food quality (Jesus et al., 2020a).

Mechanistically, phenolic compounds may disrupt fungal cell wall integrity, interfere with ergosterol biosynthesis in fungal membranes, alter membrane permeability and inhibit mitochondrial function, ultimately impairing hyphal growth and spore germination. In some cases, phenolics also reduce mycotoxin production by affecting secondary metabolic pathways, which is particularly relevant for species such as *Penicillium expansum*.

The antifungal efficacy of vine-pruning wood extracts is closely linked to their phenolic composition, particularly stilbenes, flavonoids and phenolic acids. These compounds exert antimicrobial activity through multiple complementary mechanisms, as previously described, including disruption of fungal membranes, interference with cellular metabolism and induction of oxidative stress, ultimately impairing fungal growth and viability (Farhadi et al., 2016; Gullón et al., 2017). In addition, the strong antioxidant activity of these extracts contributes to the inhibition of oxidative degradation processes in food systems, which are often associated with quality loss, lipid oxidation and reduced product stability. By scavenging reactive oxygen species and chelating pro-oxidant metal ions, these compounds help preserve sensory attributes such as color, flavor and texture.

Beyond their direct antifungal effects, vine-pruning wood extracts also offer broader functional benefits relevant to food preservation. Their combined antioxidant and antimicrobial properties enable the simultaneous inhibition of spoilage microorganisms and reduction of oxidative deterioration, thereby contributing to improved food stability, safety and shelf life. This multifunctional bioactivity highlights their potential as natural alternatives to synthetic preservatives commonly used in the food industry, such as sorbates and benzoates, whose use is increasingly scrutinized due to potential health and environmental concerns.

Recent studies have explored the incorporation of plant-derived phenolic extracts into edible coatings, biodegradable films and active packaging systems. In this context, vine-pruning wood extracts may be integrated into biopolymer matrices such as chitosan, starch or PLA, enabling controlled release of antifungal compounds and extended postharvest protection. Such active packaging strategies may reduce reliance on synthetic fungicides and improve sustainability in fresh produce supply chains.

From a regulatory perspective, the application of plant extracts in food systems requires compliance with food safety frameworks, including toxicological evaluation and assessment of migration limits when used in packaging materials. Authorization under food additive or novel food regulations (e.g., EFSA frameworks in the European Union) may be necessary depending on the intended application and concentration levels. Therefore, standardization of extract composition and

demonstration of safety at effective doses are essential steps towards industrial implementation.

From a sustainability perspective, the valorization of vine-pruning wood as a source of natural antifungal and antioxidant compounds aligns with circular bioeconomy principles by transforming an abundant agricultural residue into high-value functional ingredients for food applications. This approach not only enhances the economic value of vitivinicultural by-products but also contributes to the development of sustainable food preservation strategies based on renewable and environmentally friendly resources.

Nevertheless, challenges remain, including potential variability in phenolic composition across varieties and seasons, possible sensory impacts on treated foods, stability during storage and cost-effectiveness at industrial scale. Addressing these aspects through process optimization, encapsulation technologies and life-cycle assessment will be crucial to ensure technical feasibility and environmental benefit.

Consequently, vine-pruning wood extracts represent a promising and sustainable solution for the development of natural food preservation systems, with potential applications in postharvest protection, active packaging and functional food formulations. Within an integrated biorefinery framework, recovery of food-grade phenolic extracts may constitute a high-value upstream pathway prior to material or energy valorization of the residual biomass, maximizing overall resource efficiency and economic return.

4.3.3. Cosmetic and dermocosmetic applications

In dermocosmetic contexts, the value of vine-pruning wood lies primarily in its antioxidant, enzyme-modulating, and skin-protective properties. Vine-pruning wood extracts have emerged as promising sources of bioactive ingredients for cosmetic and dermocosmetic applications due to their high phenolic content and associated antioxidant activity, which plays a central role in protecting skin cells against oxidative stress and preventing premature ageing. Stilbenes such as resveratrol and viniferins, together with flavonoids like quercetin, are particularly relevant due to their well-documented capacity to modulate oxidative and inflammatory pathways at the cellular level. Oxidative stress promotes the formation of reactive oxygen species (ROS), which induce lipid peroxidation, protein oxidation and degradation of structural components such as collagen and elastin, ultimately contributing to loss of skin elasticity, wrinkle formation and overall skin ageing (Almeida et al., 2018; Matos et al., 2019). Mechanistically, inhibition of matrix metalloproteinases (MMPs) limits collagen breakdown, while suppression of tyrosinase activity interferes with melanogenesis pathways, reducing excessive melanin production and uneven pigmentation. In this context, phenolic compounds derived from vine-pruning wood have been shown to inhibit key enzymes involved in skin ageing processes, including tyrosinase, collagenase and elastase, thereby contributing to the preservation of skin structure, prevention of hyperpigmentation and maintenance of dermal integrity (Rodrigues et al., 2013; Matos et al., 2019).

The extraction method significantly influences the phenolic profile and biological activity of vine-pruning wood extracts. Subcritical water extraction has been demonstrated as an effective and environmentally friendly approach for recovering bioactive compounds with high antioxidant potential. Moreira and collaborators evaluated vine-pruning wood extracts from six grapevine varieties and reported total phenolic contents ranging from approximately 27 to 33 mg GAE g^{-1} dry weight, alongside strong radical scavenging activity against biologically relevant ROS. This high antioxidant capacity highlights their potential to protect skin cells from oxidative damage and prevent premature ageing, reinforcing their suitability for incorporation into cosmetic formulations (Moreira et al., 2020). In addition to their antioxidant properties, vine-pruning wood extracts have demonstrated a favorable safety profile for dermal application. Cytotoxicity assays using human keratinocyte (HaCaT) and fibroblast (HFF-1) cell lines, which represent the main cellular components of the epidermis and dermis, respectively, showed no cytotoxic effects at concentrations relevant for cosmetic use, confirming their biocompatibility and suitability for topical applications (Moreira et al., 2020). Such findings are critical for compliance with cosmetic safety assessment requirements under regulatory frameworks such as the European Cosmetics Regulation, which mandates toxicological evaluation and demonstration of consumer safety prior to market placement. These findings support their potential as safe natural alternatives to synthetic cosmetic ingredients.

Furthermore, vine-pruning wood extracts have been successfully incorporated into topical gel formulations, exhibiting appropriate physicochemical characteristics, including compatible pH, suitable rheological behavior and microbiological stability, which are essential parameters for the development of effective and stable cosmetic products (Pinto et al., 2017; Moreira et al., 2020). Stability studies indicate that phenolic-rich formulations maintain antioxidant activity over time when protected from light and excessive heat, although encapsulation strategies (e.g., liposomes or polymeric nanoparticles) may further enhance stability and skin penetration efficiency.

Beyond their antioxidant and safety properties, vine-derived extracts also contribute to skin regeneration and functional performance in cosmetic formulations. The presence of amino acids and other bioactive molecules supports skin hydration, cellular regeneration and maintenance of skin barrier function, enhancing overall skin health and resilience (Wasilewski et al., 2025). Additionally, their incorporation into cosmetic products has been associated with improved formulation stability, enhanced antioxidant protection and reduced irritation potential, reinforcing their suitability as multifunctional cosmetic ingredients (Barbulova et al., 2015; Wasilewski et al., 2025).

From a market and sustainability perspective, vine-pruning wood extracts align with the growing demand for natural, plant-based and upcycled cosmetic ingredients within the clean beauty sector. Their utilization valorizes agricultural residues, reduces waste generation and contributes to the development of low-carbon cosmetic supply chains under circular bioeconomy principles.

Their multifunctional bioactivity, combined with favorable safety and formulation properties, reinforces the potential of vine-pruning wood extracts as high-value ingredients for next-generation cosmetic and dermocosmetic applications. Nevertheless, further in vivo efficacy studies, dermatological testing and long-term stability assessments are required to fully substantiate performance claims and support large-scale industrial adoption.

4.3.4. Pharmaceutical and biomedical applications

Building on this diversity of material applications, vine-pruning wood also represents a valuable source of bioactive compounds with significant potential for high-value applications in pharmaceutical and biomedical fields, as discussed in the following section. The increasing prevalence of antimicrobial resistance has significantly reduced the effectiveness of conventional antibiotics, highlighting the urgent need for alternative sources of bioactive compounds with antimicrobial and therapeutic potential (Jesus et al., 2022). In this context, vine-pruning wood has emerged as a promising source of high-value phytochemicals, particularly phenolic compounds, flavonoids and stilbenes, which exhibit a wide range of biological activities relevant to pharmaceutical and biomedical applications. Notably, stilbenes such as resveratrol and viniferins, together with flavonoids including quercetin and apigenin, are well-documented for their antioxidant, anti-inflammatory and cytoprotective properties, positioning vine-pruning wood as a secondary source of pharmacologically relevant grapevine metabolites.

Several studies have demonstrated the antimicrobial potential of vine-pruning wood extracts obtained through different extraction strategies. For instance, hydrothermal treatment followed by ethyl acetate extraction has been shown to produce extracts with significant antimicrobial activity against both Gram-positive and Gram-negative bacteria, with minimum inhibitory and bactericidal concentrations ranging from 5 to 20 mg mL^{-1} (Gullón et al., 2017). These antimicrobial effects are

largely attributed to the presence of phenolic compounds capable of disrupting microbial cell membranes, altering membrane permeability and interfering with essential metabolic and enzymatic processes, ultimately leading to microbial growth inhibition or cell death (Dorosh et al., 2022). Mechanistically, phenolic hydroxyl groups may destabilize lipid bilayers, induce oxidative imbalance in microbial cells and inhibit quorum sensing pathways, thereby reducing virulence and biofilm formation. In addition to antibacterial activity, these extracts also exhibit strong antioxidant capacity, which further contributes to their protective effects by reducing oxidative stress and preventing cellular damage.

The extraction method plays a critical role in determining the biological activity and functional properties of vine-pruning wood extracts. Advanced extraction techniques such as microwave-assisted extraction and subcritical water extraction have demonstrated superior efficiency in recovering bioactive compounds compared with conventional extraction methods. Extracts obtained from Touriga Nacional vine-pruning wood using these techniques showed particularly high antioxidant activity, as evidenced by elevated FRAP and DPPH values, as well as strong antimicrobial activity against bacteria and yeasts, including drug-resistant strains. Minimum inhibitory concentrations ranged from 0.6 to 4.0 mg mL^{-1}, highlighting their potential as effective antimicrobial agents (Moreira et al., 2018). Moreover, these extracts exhibited protective effects against oxidative hemolysis, indicating their potential to protect cellular structures from oxidative damage and supporting their relevance in biomedical applications. Such findings suggest that extraction selectivity and solvent polarity directly influence phenolic profile, bioavailability and functional potency, reinforcing the need for process optimization and compositional fingerprinting.

Beyond antimicrobial and antioxidant activities, vine-pruning wood extracts have also demonstrated inhibitory effects on key enzymes associated with metabolic and neurodegenerative disorders. In particular, inhibition of α-amylase suggests potential applications in glycemic regulation and the management of metabolic diseases such as diabetes, while inhibition of acetylcholinesterase is associated with neuroprotective strategies and the potential prevention or mitigation of neurodegenerative conditions such as Alzheimer's disease (Moreira et al., 2018). These enzyme-modulating activities indicate possible applications in nutraceutical formulations targeting metabolic syndrome and cognitive decline, although dose–response relationships and in vivo validation remain necessary. These multifunctional bioactivities highlight the potential of vine-pruning wood extracts as sources of bioactive compounds for nutraceutical and pharmaceutical development.

In addition to their antimicrobial and enzyme inhibitory properties, vine-pruning wood extracts have shown promising antiproliferative and anticancer activities. Extracts obtained through autohydrolysis demonstrated antifungal activity against phytopathogenic fungi and significant antiproliferative effects against various cancer cell lines, with growth inhibition dependent on extract concentration and exposure time (Jesus et al., 2020b) These effects have been associated with phenolic compounds such as quercetin, apigenin, ellagic acid and hesperidin, which are known to induce oxidative stress modulation, apoptosis and cell cycle arrest in cancer cells. Furthermore, vine-pruning wood extracts have been shown to inhibit colorectal cancer cell proliferation, induce DNA damage and enhance the sensitivity of cancer cells to chemotherapeutic agents such as 5-fluorouracil, suggesting potential applications as complementary therapeutic agents or sources of lead compounds for drug development (Jesus et al., 2020b; Dorosh et al., 2022). Synergistic interactions between phenolic compounds may further enhance cytotoxic selectivity against tumor cells while minimizing damage to healthy tissues, although comprehensive toxicological profiling is still required.

The observed biological activities are closely linked to the complex phenolic profile of vine-pruning wood, as previously discussed, reinforcing their multifunctional role in antimicrobial, antioxidant and therapeutic applications. These compounds can act through multiple complementary mechanisms, including reactive oxygen species scavenging, modulation of cellular signaling pathways, disruption of microbial membranes and induction of programmed cell death, reinforcing their potential as multifunctional bioactive agents. However, most current evidence remains based on *in vitro* assays, and translation into in vivo models and clinical studies is still limited, indicating an early technological readiness level (TRL) for pharmaceutical application.

Despite these promising findings, the pharmaceutical application of vine-pruning wood extracts remains at an early stage of development. Several challenges must be addressed before clinical or commercial implementation, including extract standardization, optimization of extraction and purification processes, evaluation of bioavailability and pharmacokinetics, and comprehensive safety and toxicity assessments. Regulatory approval pathways for botanical extracts require rigorous characterization, reproducibility and demonstration of safety under frameworks such as EMA or FDA botanical drug guidelines, which may pose additional development barriers. Additionally, the variability in chemical composition associated with grapevine variety, environmental conditions and extraction techniques highlights the need for process optimization and quality control to ensure reproducibility and efficacy (Jesus et al., 2022).

From a circular bioeconomy perspective, the recovery of pharmaceutical-grade phytochemicals from vine-pruning wood may represent a high-value upstream step within integrated biorefinery schemes, where bioactive fractions are first isolated for nutraceutical or pharmaceutical development before residual biomass is directed towards material or energy applications.

4.4. Energy recovery and bioenergy production

For energy-oriented valorization, vine-pruning wood offers a combination of high carbon content, low ash fraction, and suitable calorific value that makes it attractive for conversion into multiple energy carriers. Structurally, it is composed predominantly of cellulose, hemicellulose, and lignin, with lignin fractions often exceeding 20–25%, which confer both energetic density and thermochemical suitability (Jesus et al., 2022; Florindo et al., 2022).

Direct combustion is one of the most immediate and technically mature valorization pathways. Vine-pruning wood exhibits a lower heating value of approximately 17.6–18.9 MJ kg^{-1} (dry basis), comparable to conventional woody biomass fuels such as pine pellets and other lignocellulosic feedstocks, supporting its use in medium- and large-scale biomass combustion systems (Giorio et al., 2019; Florindo et al., 2022). Laboratory characterization has confirmed average carbon contents of approximately 46%, volatile matter around 78%, fixed carbon near 20% and low ash content (~1.4%), indicating favorable combustion behavior and energy recovery efficiency (Florindo et al., 2022). These characteristics support its integration into existing bioenergy infrastructures as a renewable alternative to fossil fuels. However, elevated concentrations of copper resulting from vineyard phytosanitary treatments may accumulate in combustion ashes, potentially limiting their reuse in agricultural applications. In addition, increased particulate matter emissions during combustion may require the implementation of appropriate emission control systems, particularly in industrial-scale applications (Giorio et al., 2019). Furthermore, variability in moisture content, pruning storage conditions and particle size distribution may influence combustion efficiency and emission profiles, necessitating preprocessing steps such as drying, palletization or size homogenization for optimized performance.

This biomass also holds potential in decentralized energy systems. Its recovery and utilization can support local biomass value chains, enhance energy security in agricultural regions and reduce dependence on fossil fuels. Furthermore, its combustion performance and calorific properties are comparable to those of traditional firewood, supporting its use in domestic heating applications and contributing to improved resource efficiency and sustainability within vitivinicultural production systems (Zhang et al., 2010; Nunes et al., 2021a; Florindo et al., 2022).

In this context, decentralized biomass systems may reduce transport-related emissions and enhance regional circularity, although economic feasibility depends on collection logistics and seasonal biomass availability.

Densification processes such as pelletization and briquetting further strengthen its bioenergy potential. In these approaches, the biomass is dried, ground, and mechanically compressed to produce solid biofuels with improved handling, storage, and combustion characteristics. Several studies reported the production of vine-pruning pellets with heating values ranging from approximately 15.98 to 18.87 MJ/kg, demonstrating their suitability as a renewable energy source (Pizzi et al., 2018; Nunes et al., 2021a). Similarly, briquettes produced through mechanical densification processes exhibited comparable calorific values and high mechanical durability, highlighting the potential of vine-pruning residues as a feedstock for solid biofuel production (Ţenu et al., 2021; Ţenu et al., 2024).

In addition to direct combustion, vine-pruning wood is a promising feedstock for the production of liquid biofuels due to its lignocellulosic composition, which is rich in cellulose and hemicellulose. However, the recalcitrant structure of lignocellulosic biomass requires pre-treatment to enhance enzymatic accessibility and improve sugar release. Several pre-treatment strategies, including alkaline, hydrothermal and steam explosion processes, have been successfully applied to improve saccharification efficiency and enable microbial fermentation into bioethanol and biobutanol (Cotana et al., 2015; Dávila et al., 2017a; Jesus et al., 2017; Jesus et al., 2019). For example, alkaline pre-treatment followed by enzymatic hydrolysis enabled efficient sugar recovery and subsequent biobutanol production by Clostridium strains, achieving concentrations of up to 8.0 g L^{-1} (Garita-Cambronero et al., 2021). Similarly, hydrothermal and steam explosion treatments have enhanced cellulose conversion, yielding up to 8.9kg of ethanol per 100 kg of vine-pruning wood (Buratti et al., 2015). These results highlight the suitability of this residue as a renewable feedstock for advanced biofuel production.

Nevertheless, the economic competitiveness of second-generation biofuels derived from vine-pruning wood remains highly sensitive to enzyme costs, pre-treatment energy demand and process integration efficiency. Techno-economic assessments (TEA) and life-cycle assessments (LCA) are therefore essential to determine whether net greenhouse gas reductions and positive energy balances are achieved under realistic industrial scenarios. Similar conclusions have been reported for agro-food residues in general, where process integration, feedstock logistics, and downstream processing are recognized as the main determinants of the economic viability of sustainable biorefineries (Ragini et al., 2025).

Thermochemical conversion through pyrolysis enables the production of multiple energy carriers, including biochar, bio-oil and syngas, supporting integrated and multiproduct valorization strategies. This structural composition supports efficient thermochemical processing, particularly due to the lignin fraction, which contributes to higher energy density and char yield (Fytili and Zabaniotou, 2018). Biochar can be used as a renewable solid fuel and as a partial substitute for fossil coal, contributing to greenhouse gas emission reductions and improved energy sustainability. In addition, activated biochars derived from vine-pruning wood exhibit high surface area and CO_2 adsorption capacity, enabling applications in gas purification, biogas upgrading and carbon capture technologies (Azuara et al., 2017; Manyà et al., 2018). The simultaneous production of solid, liquid and gaseous fuels through pyrolysis significantly enhances overall energy recovery efficiency and supports multiproduct valorization strategies. Process parameters such as temperature, heating rate and residence time strongly influence product distribution and quality, allowing targeted optimization towards either energy densification or material-oriented applications. This flexibility reinforces the strategic role of vine-pruning wood within integrated thermochemical platforms.

Representative quantitative case studies further illustrate the differences among energy-oriented valorization pathways. Mechanical densification into briquettes primarily improves biomass bulk density, transportability and storage while largely preserving its original fuel properties, whereas hydrothermal carbonization produces hydrochar with higher carbon content, increased energy density and improved combustion characteristics, particularly for wet feedstocks (Kambo and Dutta, 2015). Among thermochemical routes, biochar production provides additional climate-change mitigation through long-term carbon sequestration. Life-cycle assessment studies have reported net greenhouse gas savings of approximately 864–885 kg CO_2 eq per tonne of dry biomass, with 62–66% of these benefits attributed to stable carbon sequestration in biochar (Roberts et al., 2010). Similar results have been obtained specifically for vine-pruning biomass, where charcoal production achieved negative net emissions of up to −522.74 g CO_2 eq for the production of approximately 10–12 g of charcoal (Los Santos-Ortega et al., 2024). Furthermore, the incorporation of vine-pruning biochar into mortar reduced global warming potential by 76.83% under a consequential life-cycle assessment, highlighting that the environmental performance of biochar-based valorization strongly depends on system boundaries and carbon accounting assumptions (Los Santos-Ortega et al., 2024).

Biological conversion pathways also offer promising opportunities for renewable energy production. Anaerobic digestion of vine-pruning wood, following appropriate pre-treatment, has demonstrated methane yields of up to 200 L CH_4 kg^{-1} biomass, highlighting its suitability for biogas production and decentralized energy generation (Pérez-Rodríguez et al., 2016; Contreras et al., 2022). This approach contributes to improved waste management, renewable energy production and greenhouse gas emission reduction within vitivinicultural systems. However, lignin recalcitrance may limit biodegradability, and co-digestion strategies with more labile substrates may be required to optimize methane yields.

Importantly, vine-pruning wood is particularly well suited for integrated biorefinery schemes, which enable the sequential recovery of energy carriers and high-value bioproducts from a single feedstock. During pre-treatment and conversion processes, valuable compounds such as phenolics and other bioactive molecules can be simultaneously recovered alongside energy products, improving overall process efficiency and economic viability (Oksman et al., 2011; Romaní et al., 2012; Romaní et al., 2016a; Domínguez et al., 2017; Costa et al., 2017). Such cascade valorization models prioritize high-value extractives (e.g., antioxidants or specialty chemicals) before directing the residual lignocellulosic matrix towards bioenergy or biochar production, thereby maximizing carbon utilization efficiency and economic return per unit biomass.

Energy valorization through combustion, densification, thermochemical conversion, biological processes, and integrated biorefinery platforms represents a technically robust pathway for the management of vine-pruning residues, although its long-term deployment depends on supply-chain optimization, carbon footprint quantification, and regional integration.

A practical implementation of this concept involves a sequential cascade valorization strategy in which vine-pruning wood is processed through complementary conversion routes rather than a single end-use application. Initially, high-value bioactive compounds, including phenolics and stilbenes, can be recovered for food, cosmetic or pharmaceutical applications. Subsequently, the carbohydrate-rich fraction may be converted into biofuels, platform chemicals or other biobased products through biochemical or thermochemical processes, while the remaining lignin-rich fraction can be further valorized through pyrolysis to produce biochar, activated carbon, bio-oil and syngas. Finally, residual streams may be recovered for heat and power generation, minimizing waste production and maximizing carbon utilization and economic value. Such integrated cascade biorefineries are increasingly recognized as one of the most promising approaches for maximizing the sustainability and resource efficiency of vine-pruning wood within

circular bioeconomy systems (Romaní et al., 2012; Romaní et al., 2016b; Domínguez et al., 2017; Costa et al., 2017; Jesus et al., 2022; Arias et al., 2023).

4.5. Material and industrial applications

From a materials engineering perspective, vine-pruning wood represents a versatile lignocellulosic feedstock that can be transformed into a wide range of value-added industrial products. Its composition, characterized by high contents of cellulose, hemicellulose and lignin, provides favorable mechanical, thermal and physicochemical properties that support its conversion into bio-based materials, functional polymers and engineered composites (Romaní et al., 2016b; Jesus et al., 2022).

In addition to its use as a source of structural biopolymers, vine-pruning wood can be directly utilized as a lignocellulosic raw material for pulp and paper production, as well as for the manufacture of engineered wood products such as particleboards, fiberboards and structural composites. Studies have demonstrated that these materials exhibit mechanical and structural properties comparable to those produced from conventional wood species, confirming their suitability for industrial material applications and construction-related uses (Ntalos and Grigoriou, 2002; Jiménez et al., 2006; Pereira et al., 2023). Parameters such as internal bond strength, modulus of rupture and dimensional stability have been reported within acceptable industrial ranges, indicating technical feasibility. These applications contribute to resource diversification, reduce pressure on forest resources and support the substitution of non-renewable raw materials.

Building on these conventional applications, more advanced material valorization pathways have emerged, focusing on the fractionation of vine-pruning wood into its main structural components. The recovery of cellulose enables the production of nanostructured materials such as cellulose nanocrystals and nanofibrils, which can be incorporated into polymer matrices to enhance mechanical performance, barrier properties and durability. Similarly, lignin fractions can be valorized into bio-based resins, polymer modifiers and functional nanoparticles, while hemicelluloses can be converted into films, hydrogels and other functional biopolymers with tailored properties. As a result, they contribute to improved mechanical resistance, barrier performance and durability of bioplastics, packaging materials and structural biocomposites, supporting the development of lightweight, high-performance and biodegradable material systems (El Achaby et al., 2018; Verdini et al., 2021).

Hemicellulose fractions obtained during biomass fractionation also offer important industrial opportunities. These polysaccharide-rich fractions can be converted into functional biopolymers, hydrocolloids and other bio-based materials with applications in industrial formulations, coatings and biodegradable material systems (Dávila et al., 2017b; Dávila et al., 2019). Lignin recovered from vine-pruning wood represents another key industrial precursor. Its complex aromatic structure and functional groups enable its use in bio-based resins, adhesives, polymer modifiers and antioxidant stabilizers, contributing to reduced dependence on fossil-derived chemicals (Romaní et al., 2016b; Jesus et al., 2022). Recent studies have further demonstrated the production of lignin nanoparticles with controlled size, high stability and strong antioxidant activity, enabling applications in coatings, polymer reinforcement and advanced functional materials (Pereira et al., 2023).

Table 3 provides an overview of representative studies reporting the conversion of vine-pruning wood into different material systems, highlighting the materials produced, processing routes and resulting properties.

Beyond these primary material applications, vine-pruning wood has also been extensively explored as a reinforcing phase in composite systems. Cellulose nanocrystals derived from vine-pruning biomass have been incorporated into carboxymethyl cellulose (CMC) films to produce reinforced nanocomposites with improved mechanical properties (El Achaby et al., 2018). Similarly, lignocellulosic particles have been combined with acrylic resins to manufacture composite panels with thermal and acoustic insulation properties (Maderuelo-Sanz et al., 2022).

Biocomposites based on biodegradable polymers such as poly(3-hydroxybutyrate-co-3-hydroxyvalerate) (PHBV) and polylactic acid (PLA) have also been developed using vine-pruning residues as fillers. These works typically involve the extraction of polyphenols or other compounds from vine particles followed by melt mixing with PHBV to produce films or molded specimens. The results indicate that vine-derived fillers can be successfully integrated into PHBV matrices while maintaining adequate mechanical properties, demonstrating the potential of vine-pruning biomass as a sustainable filler for biodegradable packaging materials (David et al., 2019; David et al., 2020; David et al., 2021b). Regarding PLA-based composites, studies report the incorporation of vine-pruning residues as reinforcing fillers in PLA matrices through melt mixing or twin-screw extrusion followed by compression molding, producing biocomposites with improved stiffness and adequate mechanical performance. These materials have been proposed for applications such as biodegradable agricultural accessories, plastic components, and alternatives to disposable plastic products (Battegazzore et al., 2019; Huang et al., 2023; Majka et al., 2024; Chang et al., 2024).

In parallel, vine-pruning particles have been used as alternative lignocellulosic feedstocks in the production of particleboards and fiberboards. These materials, obtained through hot pressing or compression molding using adhesives such as urea–formaldehyde resins, exhibit mechanical and thermal properties comparable to conventional wood-based panels, demonstrating their suitability for construction and furniture applications (Ferrandez-Villena et al., 2020; Wong et al., 2020; Auriga et al., 2022; Ferrández-Villena et al., 2022; Almeida et al., 2026).

Additionally, the incorporation of vine-pruning residues into cementitious composites has been investigated. In these systems, lignocellulosic particles or derived ash are integrated into cement matrices, influencing hydration reactions and improving material compactness. Reported results indicate adequate compressive and flexural strength, together with enhanced density and thermal stability, supporting their use in more sustainable construction materials (Scurtu et al., 2022; Scurtu et al., 2023; Kallou et al., 2025; Scurtu et al., 2025)

Beyond structural composites, vine-pruning biomass has also been successfully converted into film-based materials for packaging and agricultural applications. Cellulose and lignocellulosic fractions extracted from vine residues have been used to produce bio-based films with different functionalities. For example, nanocellulose-reinforced films obtained using agar or other biopolymer matrices have demonstrated promising mechanical and barrier properties for food packaging applications (Benito-González et al., 2020). Similarly, incorporation of vine-derived fillers into PHBV and PLA matrices has enabled the production of biodegradable composite films suitable for packaging applications (Monari et al., 2020; David et al., 2021a). Other approaches include the production of films from liquefied biomass using plasticizers such as polyethylene glycol and glycerol, as well as cellulose acetate-based films derived from vine biomass, highlighting the potential for bioplastic development (Briones et al., 2015; Lettieri et al., 2025).

Aerogel-based materials have also been developed from vine-pruning biomass. Hybrid cellulose–polymer aerogels produced through freeze-drying and polymer impregnation exhibit low density and high porosity, enabling applications in packaging, cosmetics and biomedical fields (Reyes et al., 2023; García-Abril et al., 2025).

In addition to packaging applications, vine-pruning wood has shown strong potential in the development of environmental and functional materials. Thermochemical processing enables the production of activated carbon with high surface area and adsorption capacity, which has demonstrated excellent performance in filtration systems, gas purification and pollutant removal (Nabais et al., 2010; Pereira et al., 2023). In water treatment applications, lignocellulosic fractions and biochar derived from vine-pruning biomass have been incorporated into

Table 3
Summary of material-based valorisation pathways for vine-pruning wood reported in the literature, including material type, binders or matrices, processing routes, key properties, and applications.

Material type	Binder	Experimental procedure	Properties	Application	REF.
Composite	CMC	• Fiber treatment • Extraction of crystalline nanocellulose • Production of CMC-CNC films (1, 3, 5, and 8 wt%), by solvent casting	E=1445.5–2422.6 MPa σ= 66.5–90.0 MPa ε= 11.2–19.1%	Nanocomposite materials	(El Achaby et al., 2018)
Composite	HDPE	• Premixing of vine-pruning with HDPE granules • Twin-screw extrusion to produce composite strands • Compression molding of granules to form composite plates (5–20% VS content)	E= 500–800 MPa σ= 15-22 MPa E_f= 600–1000 MPa σ_f= 13-22 MPa	New reinforcement for composites	(Kılınc et al., 2016)
Composite	Polybutylene succinate (PBS)	• Preparation of grapevine char by pyrolysis (500°C, 2 h) • Synthesis of maleic anhydride grafted PBS (MAPBS) through melt mixing and reflux grafting • Surface modification (silane coupling agent) • Drying and melt mixing of PBS, MAPBS, modified char • Composite fabrication, by compression molding	E= 513–1730 MPa σ= 27.02–41.04 MPa IS= 29.37–51.93 (J/m)	New filler for composites	(Huang et al., 2024)
Composite	Water-based acrylic resin	• Composite production: Mixing with water-based acrylic resin binder and molding with controlled binder percolation	E= 3.62 MPa E_f= 0.24 MPa λ = 0.0917 W/(m*K) α = 0.479	Acoustic Panels	(Maderuelo-Sanz et al., 2022)
Composite (fillers)	PHBV	• Solvent extraction of the particles to obtain exhausted fillers • Preparation of PHBV/vine shoot biocomposites by melt mixing (20 wt% filler)	E= 2.5 MPa Deg_{max}= 87–102%	Food packaging	(David et al., 2019)
Composite (fillers)	PHBV	• Solvent extraction of polyphenols • Preparation of PHBV/vine biocomposites by melt mixing (5–20 wt% filler), by compression molding (films) and injection molding (dog-bone specimens)	E= 2212–2500 MPa σ= 35.5–40.3 MPa ε= 2.6–3.7 %	Food packaging	(David et al., 2020)
Composite (fillers)	PHBV	• Gas-phase esterification treatment of fillers (palmitoyl chloride) • Preparation of PHBV/vine composites by twin-screw extrusion (5–30 wt%) • Film production by compression molding	E= 2.9–3.3 GPa σ= 26.3–35.4 MPa ε= 1.08–1.71 %	Food packaging	(David et al., 2021b)
Composites	PLA	• Preparation of PLA composites (10–50 wt%), using twin-screw melt extrusion • Composite plates production, by compression molding	E= 3016–3880 MPa σ= 39.5–68.7 MPa ε= 1.4–4.2%	Biodegradable biocomposites	(Battegazzore et al., 2019)
Composite	PLA	• Grapevine pyrolysis (500°C, 2 h, N_2) to produce biochar • Grinding and sieving (120 and 200 mesh) • Drying of PLA and biochar and melt mixing (175°C) • Compression molding at 175°C to produce PLA/biochar composites (1–10 wt%)	E= 4.802–5.422 GPa σ= 29.30–79.79 MPa IS= 17.11–22.67 J/m	Biodegradable agricultural accessories	(Huang et al., 2023)
Composite	PLA	• Synthesis of PBS-MA and PLA-MA via grafting with maleic anhydride • Drying of all components (<1 wt% moisture) • Melt mixing at 175°C to produce composites (10–50 wt%)	σ= 15.40–29.70 MPa IS= 17.11–22.67 J/m	Replace disposable plastic products	(Chang et al., 2024)
Composite	PLA	• Chemical treatment of fibers (10% NaOH) • Extrusion processing using twin-screw extruder • Production of biocomposites (5–15 wt%)	TTI=223–301 s TOF= 280–373 s $Comb_{time}$= 56–75 s	Plastic components	(Majka et al., 2024)
Composite	Resin	• Processing into smaller particles • Production of three-layer particleboards, by compression molding	E= 2673–3163 MPa σ= 12.8–20.2 MPa	Particleboard	(Wong et al., 2020)
Composite	Urea–formaldehyde (UF) resin	• Production of one- and three-layer particleboards using UF resin, by compression molding (180°C, 5min)	E= 1048–2833 N/mm^2 σ= 8.0–19.1 N/mm^2	Particleboard	(Ntalos and Grigoriou, 2002)
Composite	UF resin	• Mixing of vine and pine particles for three-layer particleboards and application of UF resin (8–10%) by spraying • Compression molding (150°C, 7 min)	E= 2409.1–5151.9 N/mm^2 σ= 7.96–13.36 N/mm^2	Particleboard	(Yorioka et al., 1990)
Composite	UF resin	• Blending with UF resin (9%) and ammonium nitrate hardener • Formation of single-layer particleboards, by hot-pressing (140°C, 2–2.6 MPa)	E= 743–1810 N/mm^2 σ= 6.58–16.5 N/mm^2 λ = 0.0642–0.0676 W/(m*K) R = 0.1036–0.1090 (m^2*K/W)	Particleboard	(Ferrandez-Villena et al., 2020)
Composite	Water	• Manual mat formation with vine particles and water addition (10%) • Hot pressing (130°C, 2.6 MPa)	E= 419.6–1806.3 N/mm^2 σ= 3.61–11.24 N/mm^2 λ = 0.0692–0.0751 W/(m*K)	Particleboard	(Ferrández-Villena et al., 2022)

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Table 3 (*continued*)

Material type	Binder	Experimental procedure	Properties	Application	REF.
Composite	UF Resin	• Adhesive application (10–12%) in vine-pruning waste • Production of three-layer particleboards, by hot pressing (180°C, 2.5 MPa)	E= 1040–3055 N/mm^2 σ= 4.58–14.74 N/mm^2	Particleboard	(Auriga et al., 2022)
Composite	UF, mUF, MUF	• Blending particles with adhesive system (resin, catalyst, paraffin) • Production of single-layer particleboards by hot pressing (190 °C)	σ= 3.8–6 MPa Internal bond = ~0.8 N/mm^2	Particleboard	(Almeida et al., 2026)
Composite	Sodium alginate	• Acid hydrolysis • Preparation of alginate–vineyard biocomposite mixture (cellulosic residue + sodium alginate) • Formation of biocomposite spheres by drop-wise dripping into a $CaCl_2$ crosslinking solution	Dye Removal ~77%	Water treatments	(Vecino et al., 2015)
Composite	rGO	• Preparation of rGO–vine-pruning biochar suspensions with different compositions (50–90 wt%) • Formation of composite membranes by deposition on a PVDF supporting membrane • Identification of optimal composition (rGO/VBC = 40/60) for self-standing membranes	Adsorption capacity (Cu^{2+}) = 2.19 mmol/g Adsorption capacity (Zn^{2+}) = 19.12 mmol/g	Water treatments	(Dotti et al., 2025)
Film	PEG, glicerol	• Liquefaction of agricultural residues (PEG, glycerol, sulfuric acid) at 180°C, 60 min • Separation of liquefied product by dilution, filtration, and solvent evaporation • Preparation of biopolymer films, by solvent casting	E'= 42–47 MPa Tg = 103–112°C	Agricultural applications	(Briones et al., 2015)
Film	Agar	• Purification of vine shoot cellulose via extraction, delignification, and alkaline treatment • Production of cellulose nanocrystals by sulfuric acid hydrolysis • Preparation of pure nanocellulosic films by dispersion and vacuum filtration • Fabrication of hybrid films using nanocellulose and agar	E= 2.9–7.8 GPa σ= 42.1–68.3 MPa ε= 1.1–9.0 %	Food Packaging	(Benito-González et al., 2020)
Film	PHBV	• Melt mixing with PHBV to produce composites (5–20 wt% residue) (200 °C, 5 min)	E= 1638–1728 MPa σ= 24.1–33.2 MPa ε= 2.5–3.1 %	Packaging	(Monari et al., 2020)
Film	Carboxymethyl cellulose (CMC)	• Production of cellulose and lignocellulose nanofibers from vine shoots • Pretreatments: soda pulping, TEMPO oxidation or mechanical refining • Preparation of CMC-based films reinforced with nanofibers (1–10 wt%) by solvent casting • Production of active films containing gallic acid	E= 1450.80–2807.07 MPa σ= 29.36–49.31 MPa	Packaging	(Rincón et al., 2023)
Film	—	• Extraction of cellulose • Removal of lipids and alkaline treatment • Bleaching with sodium chlorite solution • TEMPO-mediated oxidation of cellulose fibers, sonication and purification • Preparation of films by solvent casting	WVP= 0.25–0.3 g/day*cm^2	Conservation of heritage buildings	(Araújo et al., 2023)
Film	Glycerol and acetone	• Biomass pretreatment (microwave, ultrasound, or autoclave) and ethanol–water extraction • Bleaching/acetylation of cellulose to produce cellulose acetate • Preparation of films by solvent casting	Biodegradation: rapid fragmentation within the first week (~20% weight loss) with fungal colonization	Bioplastics	(Lettieri et al., 2025)
Eletrospun nanofibers	Polyacrylonitrile (PAN)	• Production and purification of biochar • Preparation of PAN/biochar electrospinning solutions (DMF solvent) • Electrospinning process to produce nanofiber mats	Morphological analysis showed good dispersion of biochar grains within the fiber mat	Electrospun Fiber Production	(Schirra et al., 2022)

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Table 3 (*continued*)

Material type	Binder	Experimental procedure	Properties	Application	REF.
		• Thermal stabilization and carbonization			
Nanocellulose	Lineboard sheets	• Szentesi, M.; Kažimírová, V.; Kubík, Ľ. MECHANICAL PROPERTIES OF BIOMASS PELLETS.; Prague, 2022.	E= 1.20–1.50 GPa ε= 1.50–2.75 mm Drainage =30–75 °SR	Linerboard Recycling Processes	(De Haro-Niza et al., 2022)
Pellets	—	• Processing of biomass into pellets	HHV= 15.98 MJ/kg	Renewable energy	(Pizzi et al., 2018)
Pellets	—	• Preparation of ash through controlled combustion for fusibility tests • Chemical digestion of samples for ICP-OES elemental and chlorine analysis	HHV= 18.58–18.87 MJ/kg	Renewable energy	(Nunes et al., 2021a)
Pellets	—	• Production of biomass pellets	E= 70.83 MPa ε= 0.12 mm	Renewable energy	(Kubík and Kažimírová, 2015)
Briquette	—	• Briquetting of biomass using a screw-type densification machine	HHV= 18.358–19.27 MJ/kg LHV= 16.92–17.95 MJ/kg DU= 97.34–99.14 %	Biofuel	(Ţenu et al., 2021)
Briquette	—	• Convective artificial drying of biomass • Sieving and grinding of biomass particles • Briquetting to produce densified biomass fuel	LHV= 16.92–17.94 MJ/kg	Biofuel	(Ţenu et al., 2024)
Aerogel	PLA, PHB	• Produce cellulosic nanocrystals (delignification and acid hydrolysis) • Preparation of cellulose suspensions • Freezing and freeze-drying to obtain cellulosic aerogels • Impregnation with PLA or PHB solutions aerogels	σ_c= 2.0- 52.2 N λ= 0.035–0.041 W/(m*K)	Packaging, cosmetics, or biomedical field	(Reyes et al., 2023)
Aerogel	PLA	• Preparation of cellulose pulp and production of aerogels by freeze-drying • PLA coating of aerogels using two techniques: pipette impregnation or spray coating • Development of aerogel packaging structures (wine bottle mould)	E= 0.033–4.707 (N/cm^2) σ= 0.04 – 1.54 (N/cm^2) λ = 0.0305–0.0364 W/(m*K)	Packaging	(García-Abril et al., 2025)
Hydrochar	—	• Hydrothermal carbonization (HTC) of biomass in pressurized autoclaves with different solid–liquid ratios and temperatures • Cooling, filtration, and separation of hydrochar and liquid phase after HTC	Elemental composition and structure indicate potential for soil conditioning, environmental remediation, and energy production	Energy storage and water treatments	(Armanu et al., 2025)
Cement Composites	Cement paste	• Mixing of vine shoot waste (10 wt%) with Portland cement • Preparation and casting of cement paste with water–cement ratio of 0.5	Addition of vine shoot waste improved hydration products, density, thermal stability, and structural properties of the cement paste	Construction sector materials	(Scurtu et al., 2022)
Cement Composites	Cement paste	• Preparation of cement mixtures, followed by the addition of vine shoot waste • Mixing, molding, and curing of cement-based composite samples	σ_F=13–14.64 (N/mm^2) σ_C= 45–54.03 (N/mm^2)	Construction sector materials	(Scurtu et al., 2023)
Cement Composites	Cement paste	• Preparation of cement mixtures incorporating vine shoot waste and ash (1 wt%) • Casting, curing, and conditioning of cement composite	σ_F= 9.5–15.96 (N/mm^2) σ_C= 40–49.45 (N/mm^2)	. Construction sector materials	(Scurtu et al., 2025)
Cement Composites	Cement paste	• Alkali treatment of vine shoot fibres, followed by neutralization, washing, and drying • Acrylic waterproofing treatment by immersion in polymer resin • Preparation of cement–soil blocks followed by molding and compaction (~3 MPa)	σ_C= 0.0734–0.3549 MPa λ = 0.8382–1.1615 W/m·K	Construction sector materials	(Kallou et al., 2025)

E= Young's Modulus; σ= Tensile Strength; ε= Strain; E_f= Flexural modulus of elasticity; λ= Thermal conductivity; α= Sound absorption coefficient; IS= Impact strength; Deg_{max}= percentage of degradation at infinite time; TTI= Time to Ignition; TOF= Time to Flameout; $Comb_{time}$= Combustion Time; E'= Storage Modulus; Tg= Glass transition temperature; WVP= Water vapor permeability; σ_f= Flexural Tensile Strength; HHV= Heating Value; LHV= Lower calorificValue; DU= Mechanical durability; σ_c= Compressive Tensile Strength.

composite systems such as alginate-based beads and reduced graphene oxide (rGO) membranes. These materials have demonstrated the ability to remove dyes and heavy metals from aqueous solutions, highlighting their potential for sustainable water purification technologies (Vecino et al., 2015; Dotti et al., 2025). Hydrothermal carbonization of vine-pruning biomass has also been explored to produce hydrochar materials with potential applications in energy storage, environmental remediation and soil conditioning, further expanding the range of functional applications (Armanu et al., 2025).

Additional advanced material applications have been reported. Vine-derived biochar has been incorporated into electrospun polyacrylonitrile (PAN) nanofibers, producing nanofiber mats with homogeneous particle dispersion and potential use in filtration or advanced material systems (Schirra et al., 2022). In another approach, nanocellulose extracted from vine shoots has been used to reinforce recycled linerboard, improving mechanical strength and drainage properties in paper-based materials (De Haro-Niza et al., 2022).

These studies demonstrate that vine-pruning wood can be transformed into a broad spectrum of material systems, ranging from conventional industrial products to advanced functional materials. This diversity reflects both the versatility of lignocellulosic biomass and the wide range of processing techniques available for its valorization. Within a circular bioeconomy framework, these material pathways contribute not only to resource efficiency and waste reduction but also to the substitution of fossil-based and conventional raw materials.

The diverse valorization pathways described in this section demonstrate that vine-pruning wood can be strategically repositioned from a low-value agricultural residue to a multifunctional and high-value resource within integrated circular bioeconomy systems. From immediate agronomic applications to the recovery of bioactive compounds, advanced material development, and energy production, these pathways reflect a cascade utilization logic in which high-value fractions are prioritized before directing the residual lignocellulosic matrix towards material and energy recovery. Such an approach maximizes resource efficiency, enhances economic return per unit biomass, and minimizes environmental impacts. However, the successful transition from isolated valorization routes to fully integrated biorefinery systems requires coordinated optimization of processing technologies, supply chain logistics, and product standardization, as well as alignment with regulatory frameworks and market requirements. In this context, the evaluation of environmental performance, economic feasibility, and regulatory compliance becomes essential to determine the real sustainability and scalability of these pathways, which are further explored in the following section through life cycle assessment, techno-economic analysis, and policy considerations.

5. Techno-economic, environmental, and regulatory considerations

5.1. Life cycle assessment and sustainability metrics

LCA is a standardized methodology used to evaluate the environmental impacts associated with a product or process throughout its entire life cycle, from raw material extraction to end-of-life management (Muralikrishna and Manickam, 2017). By accounting for upstream and downstream stages, LCA enables the identification of environmental hotspots, supports process optimization, and provides a robust basis for decision-making grounded in environmental, economic and social indicators (Pachón et al., 2020).

In the context of vine-pruning wood, LCA is critical to verify whether alternative uses generate genuine benefits or merely shift environmental burdens. The transition from traditional practices, such as in-field burning or soil incorporation (OIV, 2018), to industrial processing does not inherently guarantee improved sustainability performance. Only comparative LCA against clearly defined reference systems can substantiate claims of environmental superiority and guide investment toward structurally sound solutions.

Open-field burning of vine-pruning wood releases approximately 1.6 kg CO_2 per kg of biomass combusted (Alves et al., 2019). Alongside, combustion emits methane (CH_4), nitrous oxide (N_2O), and volatile organic compounds that contribute to ozone formation, increasing the overall climate impact (Alves et al., 2019; López-Caravaca et al., 2024). These baseline emissions establish an important reference scenario when evaluating alternative valorization pathways. However, system boundaries must also account for agronomic trade-offs: while systematic residue removal may deplete soil organic matter and nutrient cycling, incorporation can inadvertently introduce contaminants, such as pesticide residues or heavy metals (OIV, 2018).

Recent LCA evidence shows that technology choice drastically alters sustainability outcomes. For instance, vine-pruning wood pyrolysis has been reported to achieve net-negative greenhouse gas emissions, up to −522.74 g CO_2 eq per 40 g of biomass, through carbon sequestration in biochar (Los Santos-Ortega et al., 2024). Nevertheless, these results are highly sensitive to energy source, carbon stability assumptions, and system boundaries, reinforcing the need for validation at pilot and industrial scales (Los Santos-Ortega et al., 2024). Similarly, LCA of biochemical valorization through biorefinery configurations also demonstrates measurable benefits. Production of lactic acid from vine-pruning wood resulted in a reduction of climate change impacts from 4.67 to 3.26 kg CO_2 eq compared to fossil-based reference systems. In co-production scenarios of lactic acid and furfural, emissions decreased from 4.77 to 3.03 kg CO_2 eq, corresponding to reductions of 30–38.6%. Significant decreases in fossil resource depletion and toxicity-related indicators were also observed. However, the overall environmental performance depends strongly on process efficiency, solvent recovery, enzyme use, energy integration, and allocation factors used in the LCA methodology (Pachón et al., 2020). Material valorization also offers promising results: incorporation of 30 vol% vine-pruning wood particles into PHBV reduced global warming impact by 20% and production cost by 25% (David et al., 2021a). Interestingly, this assessment revealed that current bioplastics might carry higher environmental burdens than fossil-based polypropylene due to low technological maturity, underscoring the necessity of full life cycle evaluation over intuitive assumptions (David et al., 2021a).

Collectively, these studies demonstrate that environmental performance is highly sensitive to transport distances, drying energy demand, electricity mix, solvent use, purification intensity, and co-product allocation. When integrated with TEA, it further strengthens strategic decision-making by simultaneously identifying environmental and economic hotspots. Ultimately, potential environmental benefits must be demonstrated rather than assumed, and their robustness relies on coherent system design rather than the mere renewability of the feedstock alone.

5.2. Techno-economic assessment (TEA) of valorization pathways

Complementing environmental validation through LCA, TEA evaluates the financial feasibility of valorization pathways prior to full-scale implementation (Frey and Zhu, 2012). This framework integrates data on equipment specifications, labor, consumables, and construction costs, enabling comparison of alternative valorization routes (Frey and Zhu, 2012). Key metrics include Capital Expenditure (CAPEX), the upfront investment required to build and equip a facility, and Operational Expenditure (OPEX), encompassing ongoing costs such as utilities and raw materials. In a strategic context, TEA must move beyond static profitability estimates and explore structural configurations that enable long-term resilience.

Vine-pruning wood presents significant logistical constraints due to its seasonal availability, geographic dispersion and low bulk density. Collection, handling and transport may dominate OPEX, particularly in low-value applications such as combustion. Thus, economic viability is not solely a function of conversion efficiency, but of supply chain

organization and regional coordination. Studies on comparable residues, such as corn stover, indicate that accurate logistical cost modeling is a prerequisite for realistic economic evaluation (Becerra-Pérez et al., 2022); without this precision, TEA outcomes risk overestimating profitability. A recent case study in Northern Italy illustrated these structural challenges: while small-scale gasification for combined heat and power (CHP) could substitute 30% of a winery's electricity and 60% of its thermal demand, the system remained economically vulnerable to high CAPEX, biomass supply costs and fluctuating energy prices (Morselli et al., 2024). Indeed, TEAs are highly sensitive to energy market dynamics; a pathway that was economically viable in 2026 may face significant challenges by 2030 due to price volatility.

Beyond energy recovery, high-value compound production introduces additional complexity. A recent modeling study on resveratrol production using engineered yeast showed that while vine-prunings are technically feasible substrates, the pathway remains constrained by scale-up uncertainty, downstream processing complexity and capital intensity (Arias et al., 2023). Furthermore, an often-underestimated factor in TEA is the relevance of avoided disposal costs. Traditional pruning management (e.g. shredding or removal) costs farmers approximately 25 € t^{-1} (Silvestri et al., 2011). When these avoided expenses are subtracted from harvesting and forwarding costs, the net cost of biomass at the farm gate can drop to 30–40 € t^{-1}. This compares favorably with historical Italian energy biomass prices (50–55 € t^{-1}), although long-term stability may require contractual arrangements that prevent price escalation once residues acquire market value (Silvestri et al., 2011).

External incentives, including carbon credits or bioenergy subsidies, can significantly shift TEA outcomes. From a strategic perspective, the central question is not whether a pathway is currently profitable, but under which institutional and market conditions it becomes viable and scalable. Bridging the "Valley of Death" between pilot success and commercialization, therefore, requires demonstration projects capable of validating economic assumptions under real operating conditions.

5.3. Legislative frameworks and policy context

Regulatory frameworks act simultaneously as catalysts and constraints for residue valorization. In the European Union, the transition toward a circular sector is framed by the European Green Deal promoted by the European Commission (European Commission, 2019) and legally anchored in the European Climate Law (Regulation (EU) 2021/1119), which mandates climate neutrality by 2050. Recent provisional agreements (December 2025) have further intensified these targets, aiming for a 90% net GHG reduction by 2040. This policy landscape creates a strong incentive to move away from traditional in-field burning, towards more sustainable pathways.

5.3.1. Waste classification and the circular economy

A central legal challenge concerns residue classification. Under the Waste Framework Directive (DIRECTIVE 2008/98/EC), "waste" is defined as any substance or object which the holder discards or is required to discard. For vine-pruning wood to circulate without full waste-management constraints, they must meet "by-product" criteria. This requires that: (a) further use is certain; (b) the substance can be used directly without non-standard industrial processing; (c) it is produced as an integral part of a production process; and (d) further use is lawful and fulfills all environmental and health requirements. Harmonization of End-of-Waste interpretations across Member States is strategically essential to avoid regulatory fragmentation and enable cross-border valorization chains.

5.3.2. Phytosanitary constraints and local implementation

In wine-producing countries like Portugal, national regulations introduce specific constraints. Guidelines from DGAV (Direção-Geral de Alimentação e Veterinária) (DGAV, 2026) regarding the control of diseases such as Grapevine flavescence dorée phytoplasma and grapevine trunk diseases (e.g., Esca, Eutypa dieback) often mandate the rapid destruction of symptomatic wood. This creates a regulatory conflict: while circular economy policies promote valorization, phytosanitary laws may prioritize on-site destruction (burning or deep burial) to prevent spore dissemination. Thus, any valorization pathway must therefore demonstrate effective sanitization to prevent pathogen dissemination, ensuring that circular solutions do not compromise vineyard biosecurity.

5.3.3. Market access and safety standards

For high-value applications, the complexity increases significantly. Extracts destined for food, nutraceutical, pharmaceutical, or cosmetic markets must comply with stringent safety and traceability standards. This includes the REACH (Registration, Evaluation, Authorization and Restriction of Chemicals) Regulation (Regulation (EC) No 1907/2006) for chemical safety, EFSA (European Food Safety Authority) guidelines for food-chain risks, and other sector-specific legislation (European Food Safety Authority, 2026). While these frameworks ensure consumer protection, they can impose disproportionate compliance costs on small and medium-sized enterprises, potentially slowing innovation uptake.

5.3.4. International perspectives and policy coherence

The strategic framework provided by the European Green Deal (European Commission, 2019) aligns agricultural residue valorization with broader objectives of decarbonization, resource efficiency and bioeconomy development. Financial instruments under the Common Agricultural Policy (CAP) (European Commission, 2026) and innovation funding mechanisms may further incentivize deployment. However, regulatory coherence, linking environmental validation, economic incentives and administrative simplification, remains decisive for scaling beyond pilot initiatives.

Beyond the EU, sustainability standards and waste classifications vary across major wine-producing regions, limiting international harmonization and technology transfer. Therefore, policy alignment, rather than technological readiness alone, will largely determine whether vine-pruning wood valorization evolves from isolated projects into a structured component of the circular bioeconomy.

The scalability of vine-pruning wood valorization is not a purely technological question, but a systemic coordination challenge. Environmental validation through LCA, economic structuring through TEA, and regulatory alignment must interact coherently to reduce investment risk and attract industrial participation. Only when these three dimensions converge can vine-pruning wood transition from an underutilized by-product to a strategic resource within resilient and climate-aligned viticulture systems.

6. Research gaps and future perspectives

Despite significant advances in the valorization of vine-pruning wood (see section 4), their full potential within biorefinery schemes and the circular bioeconomy remains largely untapped. Relevant gaps persist regarding technological maturity, the integration of digital and biotechnological tools, and the creation of industrial symbiosis ecosystems that would enable "zero waste" models (Jesus et al., 2022; Rodrigues et al., 2022; Ratto et al., 2025).

6.1. Technological innovation and research priorities

Although numerous valorization pathways have been proposed for vine-pruning wood, ranging from the production of high value-added phenolic extracts to bio fuels, biopolymers and composite materials, most studies target a single step or product and do not consider integrated cascade biorefinery schemes in which the same biomass is successively convert into different products (Rodrigues et al., 2022). This limitation is particularly evident in works focusing on polyphenol

extraction that do not incorporate, within the same value chain, the subsequent use of the lignocellulosic fraction in energy or material production processes (Jesus et al., 2022; Echave et al., 2025; Ratto et al., 2025).

Furthermore, there is a clear gap between emerging processes evaluated at laboratory scale and their demonstration at pilot or industrial scale, including systematic techno-economic assessments and life-cycle evaluation, which are indispensable to support decision-making and investment (Mastellone et al., 2020; Rodrigues et al., 2022; Duarte et al., 2024; Tumminelli et al., 2025).

In addition, biomass variability (variety, vine age, training system, management practices and edaphoclimatic conditions) is seldom considered in process design, which undermines reproducibility and standardization of the resulting products (Jesus et al., 2022).

Comparative studies that systematically assess different physical, chemical and biological pretreatments of pruning biomass under realistic operating conditions, with integrated evaluation of yield, product quality, energy demand and carbon footprint, also remain scarce (Rätsep et al., 2021; Jesus et al., 2022; Rodrigues et al., 2022).

In this context, future priorities include: i) the development of modular and flexible biorefinery platforms able to rapidly adjust the portfolio of products (bioactives, fibers, energy, biofertilizers) according to biomass quality and market conditions (Jesus, 2019; Rodrigues et al., 2022); ii) the integration of process modelling and real-time optimization tools to support scale-up (Ploch et al., 2019; Gómez et al., 2023; Gómez and Correa, 2024); iii) the systematic incorporation of sustainability assessment (LCA, LCC, water and carbon footprints) from the early stages of technological design (Jesus et al., 2022; Rodrigues et al., 2022).

6.2. Integration of digital and biotechnological tools in valorization

Although viticulture has undergone intense digitization in recent years, the application of digital tools to residue management and valorization is still limited. Spatial and temporal monitoring of pruning biomass availability using remote sensing, geographic information systems or biomass prediction models rare, hindering the design of efficient logistics chains and the feasibility of regional biorefineries (Ratto et al., 2025).

In parallel, there is a lack of digital traceability systems linking biomass origin, storage conditions and the chemical profile of derived products, which is crucial to ensure quality, safety and regulatory compliance in food, cosmetic and pharmaceutical applications (Jesus et al., 2022; Rodrigues et al., 2022).

From a biotechnological standpoint, several studies demonstrated the potential of microorganisms and microbial consortia for polysaccharide hydrolysis, bioconversion of sugars into biofuels and biopolymers, and transformation of lignin into high value-added aromatic molecules, bit most of these processes remain confined to laboratory or bench scale (Rätsep et al., 2021; Echave et al., 2025).

The use of biological pretreatments, specific enzymes and genetically engineered microorganisms is still scarcely explored for the specific matrix of vine-pruning wood, despite its potential to reduce the severity of chemical treatments and overall energy consumption (Jesus et al., 2022; Rodrigues et al., 2022; Ratto et al., 2025).

Accordingly, future perspectives include: i) the development of digital twins and decision-support systems that integrate field, climate, logistics and biorefinery operation data to optimize the vine-pruning wood value chin in near real time (Millan et al., 2019); ii) the exploration of metabolic engineering and genome-editing tools to design microorganisms specialized in converting vitivinicultural sugars and lignin into high value bioproducts (Baptista et al., 2023); iii) the creation of bio-assisted biorefinery platforms in which microbial consortia and tailored enzymatic cocktails are adapted to the specific physicochemical characteristics of grapevine wood (Millan et al., 2019; Lin, 2022).

6.3. Opportunities for industrial symbiosis and circular economy models

Full implementation of the biorefinery concept in the wine value chain requires a systemic approach that goes beyond the boundaries of individual vineyards or wineries and promotes synergies with other agri-food, textile, cosmetic, packaging and energy sectors (Rodrigues et al., 2022; Rocha and Nodari, 2023; Provenzano et al., 2024; Ratto et al., 2025). Case studies have shown that integrating winemaking residues into production chains for bioethanol, biogas, oils, fertilizers, fibers and cosmetic ingredients can deliver significant environmental and economic benefits, but these examples remain isolated and are seldom replicated (Senila et al., 2020; Osete-Alcaraz et al., 2025).

Persistent gaps relate to business models, supply-chain governance, risk-and benefit-sharing mechanisms, and regulatory harmonization for products derived from residues, all of which limit the emergence of circular ecosystems and industrial symbiosis in the wine sector (ADVID, 2020). There is also a shortage of integrated assessments (LCA and socio-economic analyses) of eco-industrial parks or regional hubs that combine multiple vitivinicultural and agro-industrial residue streams, exploiting cross-flows of materials, energy, water and information (Marques et al., 2025).

In the future, it will be crucial to design and test industrial symbiosis models that use vine-pruning wood and other wine-sector residues as structuring feedstocks, articulating the production of fibers, bioactive extracts, organic fertilizers and bioenergy, and to develop circular-economy frameworks tailored to viticulture and aligned with decarbonization, biodiversity and rural-development goals. Likewise, public policies, financial instruments and certification schemes must be promoted to recognize and reward products originating from circular value chains based on vineyard and winery residues (Rodrigues et al., 2022; Agnusdei et al., 2026).

7. Conclusions

This review advances the understanding of vine-pruning wood not merely as an agricultural by-product, but as a structurally strategic node within the vitivinicultural circular economy. By situating vine-pruning wood within the entire annual production cycle, it becomes clear that its relevance extends beyond waste management, emerging instead as a leverage point for systemic sustainability transformation.

The evidence compiled demonstrates that the true value of vine-pruning wood lies not in isolated applications, but in its compatibility with cascade and integrated biorefinery configurations. Its lignocellulosic backbone enables energy and material recovery, while its phenolic and stilbenoid fractions support high-value bioactive extraction. This dual nature positions vine-pruning wood at the interface between bulk biomass valorization and specialty bio-based markets, a characteristic that few vitivinicultural residues simultaneously exhibit.

However, the pathway from technical feasibility to structural implementation remains incomplete. Environmental performance varies significantly depending on processing configuration, logistics and energy inputs, reinforcing the necessity of rigorous LCA integration from the design phase. Similarly, economic viability is strongly dependent on supply chain organization, avoided disposal costs and institutional incentives. Regulatory alignment, particularly regarding waste classification and phytosanitary constraints, emerges as a decisive enabling factor.

Beyond technological considerations, the major transition required is conceptual: shifting from residue-centric thinking to resource-centric system design. Vine-pruning wood should be embedded within coordinated regional value chains that integrate digital monitoring, modular processing and industrial symbiosis. Only through such systemic alignment can it contribute meaningfully to decarbonization, soil restoration, bio-based material substitution and rural economic resilience.

In this context, vine-pruning wood represents more than a biomass stream, it represents an opportunity to operationalize circular

bioeconomy principles in viticulture. Realizing this potential will depend less on discovering new applications and more on integrating existing knowledge into scalable, economically robust and environmentally validated systems.SFunding

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Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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