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Circular viticulture: transforming grapevine waste into sustainable fibers

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Abstract. Annually, around 31.95 million tonnes of grapevine prunings are produced worldwide as agricultural waste. These prunings are mostly underutilized and are typically either burnt or left to decompose, contributing to greenhouse gas (GHG) emissions, air pollution, and resource inefficiency. Burning grapevine prunings releases particulate matter (PM), carbon monoxide, methane, and volatile organic compounds (VOCs), all of which contribute to air pollution and global warming. Meanwhile, decomposition emits methane (CH_4), carbon dioxide (CO_2), and nitrous oxide (N_2O). Overall, these disposal methods result in greenhouse gas (GHG) emissions ranging from 3.05 to 58.44 million tonnes of CO_2-equivalent CO_2-equivalent (CO_2e) annually. Aimed at tackling environmental challenges through valorization of lignocellulosic pruning biomass, this study introduces an innovative cradle-to-cradle approach- by using vineyard waste as raw material for production of high-performance natural fibers. Fibres were extracted using an optimised sodium sulphide (Na_2S) treatment and further refined through peroxide bleaching and hydro treatments. The fibres obtained were analysed for their morphological and physio-mechanical properties. With a tenacity of 3.50–4.84 g/d, bark fibres exhibited good mechanical properties comparable to those of jute, flax, and banana. Additionally, their moderate fineness suggested suitability in textiles and spinning. In contrast, the coarser and weaker core fibres indicate potential for use in nonwovens, composites, insulation, and packaging applications. Substituting 9.93–22.43 million tonnes of common cultivation based cellulosic fibres with agro waste based grapevines fibers has the potential to save 7.94–40.37 million hectares of land, conserve up to 201.87 billion gallons of water, and avert 2.68–42.62 billion tonnes of extra CO_2-equivalent emissions. Moreover, valorization of waste grapevine prunings offers rural employment opportunities and supports climate as well as economic resilience in grape-growing regions. This study contributes to circular viticulture and aligns with Sustainable Development Goals 8, 9, 12, 13, and 17, along with COP 29's objective of bridging the finance gap and COP 30's agenda of sectoral decarbonization.

1. Introduction

Fresh grapevine prunings represent a substantial yet underutilized lignocellulosic biomass generated annually across vineyards worldwide. Estimates of fresh pruning biomass vary depending on grape variety, training system, vineyard age, and regional practices, but typically range between 3 and 6 tonnes per hectare (t/ha). For instance, Pike et al. (2023) documented incorporation rates of 3.4 t/ha for Shiraz and 5.5 t/ha for Semillon in Australian vineyards. Similarly, Sun et al. (2020) reported an average yield of 2.35 kg per vine, translating to approximately 6.27 t/ha at standard planting densities. Velázquez-Martí et al. (2011) quantified average dry pruning yields of 0.8 t/ha in standard trellis wine grape systems and up to 4.2 t/ha in horizontal trellis systems used for table grapes, highlighting the influence of cultivation architecture. Earlier, Ntalos and Grigoriou (2002) observed that Greek vineyards produced up to 5 t/ha of pruning biomass annually, which they noted exceeds average wood yields from temperate forests. Based on these figures, a global average of 4.5 t/ha can be assumed. Additionally, according to the latest report by the International Organisation of Vine and Wine (OIV, 2024), the global vineyard area stands at approximately 7.1 million hectares, suggesting that around 31.95 million tonnes of grapevine pruning waste are generated annually worldwide, representing a vast and renewable resource for sustainable material applications.

Despite being produced in large volumes, grapevine prunings have limited economic value and are typically repurposed as fertilizer or fuel.

2. Environmental Impact of Grapevine Pruning Waste Disposal (Addition of Emissions)

2.1. Usage as fertilizer

Pruned grapevine biomass is typically left to decompose in open air or composted under controlled conditions to produce fertilizer. Figure 1 shows how some vineyards leave the grapevine shoots to decay near the pillars after pruning.

Figure 1 Pruned off shoots dumped near the pillars in the vineyard.

Although these methods are widely prevalent, grapevine prunings present specific challenges for both composting and decomposition that are listed below:

Environmental Issues**:** Grapevine prunings pose environmental challenges due to their high lignin and cellulose content, which makes them resistant to microbial breakdown and slows down composting unless pretreatment is applied (Nkoa, 2014; Czekała et al., 2016). Although composting reduces methane emissions, it still produces significant amounts of biogenic CO_2 as microbes degrade organic matter, contributing to local CO_2 levels even if not counted in net GHG emissions (IPCC, 2006). Additionally, improper compost pile management can create anaerobic conditions that lead to nitrous oxide (N_2O) emissions. N_2O is far more potent than CO_2 and requires proper aeration and moisture control (Andersen et al., 2010; IPCC, 2019).

Operational and Practical Barriers: Processing grapevine prunings requires mechanical shredding to enhance microbial access, which adds to energy and labor expenses (Czekała et al., 2016). Their inherently high carbon-to-nitrogen (C:N) ratio, often over 40:1, requires blending with nitrogen-rich materials like manure to support decomposition (Nkoa, 2014). Furthermore, composting systems for grapevine biomass demand significant space, regular turning, and consistent moisture management, among other factors that increase the complexity and operational burden (Andersen et al., 2010).

Biological and Pathogen Concerns: There is a risk of disease transmission, as prunings can harbor fungal pathogens such as *Eutypa lata* and *Botryosphaeria* species, which may survive if composting temperatures stay below 55°C. Inadequate composting also attracts pests like termites, beetles, and rodents, which can compromise both vineyard structures and compost quality.

Economic and Logistical Downsides: The high cost of composting infrastructure including shredders, turners, and sensors can be limiting factors, particularly for small-scale vineyards (Czekała et al., 2016). Moreover, grapevine residues decompose far more slowly than other organic materials, potentially taking months or even years, which delays compost availability and complicates waste management schedules (Nkoa, 2014).

2.2. Comparison of Emissions caused by Decomposition and Composting

This section gives a comparison of emissions caused by decomposition and composting of one ton of freshly pruned grapevine shoots:

Decomposition: Natural decomposition of grapevine prunings, often happening in unmanaged piles or as residue left in the field, results in significant greenhouse gas (GHG) emissions. This process is typically anaerobic or partially anaerobic, especially in compact or moist environments, which promotes the generation of methane (CH_4) and nitrous oxide (N_2O). These two gases have high global warming potentials. Emissions are estimated at 4.5 kg CH_4 and 0.7 kg N_2O per ton of fresh prunings, translating to 121.5 kg CO_2-eq and 191.1 kg CO_2-equivalent (CO_2e), respectively. This results in a total of approximately 312.6 kg CO_2-equivalent emissions per ton (IPCC, 2006; Brown et al., 2008). Although biogenic CO_2 is also released (~1000 kg), it is not counted in net totals due to its short-cycle nature. The high lignin and cellulose content in grapevine wood slows microbial degradation, further prolonging the process (Nkoa, 2014; Czekała et al., 2016). From an environmental perspective, decomposition is a less sustainable method of waste management due to its higher climate impact and slower breakdown of woody biomass.

Composting: In contrast, composting grapevine prunings under controlled aerobic conditions results in remarkably lower greenhouse gas emissions. Aerobic microbial activity minimizes methane formation, and while some nitrous oxide is produced, the quantity is relatively insignificant. For every ton of prunings composted, emissions are estimated at 0.5 kg CH_4 and 0.3 kg N_2O, contributing to 13.5 kg CO_2-eq and 81.9 kg CO_2-eq, respectively. The total GHG output is approximately 95.4 kg CO_2-equivalent per ton (IPCC, 2019; Andersen et al., 2010). Though biogenic CO_2 (~1000 kg/ton) is released during composting, it is not included in GHG totals under standard protocols. Despite these benefits, composting grapevine waste has its own limitations. The high lignin content and low nitrogen levels slow down the process and may require additional inputs or pre-processing for efficient breakdown (Nkoa, 2014). Nevertheless, composting remains the climate-preferred strategy, especially when implemented at scale with proper oxygenation and moisture control.

2.3. Usage as fuel

Using fresh grapevine prunings as fuel presents several environmental, technical, and economic challenges listed below:

Open burning : It is highly inefficient due to the high moisture content (~50–60%) of fresh grapevine prunings, which leads to incomplete combustion and poor energy recovery (Johansson et al., 2004; Díaz et al., 2011). This method emits significant amounts of carbon monoxide (CO), methane (CH_4), particulate matter ($PM_{2.5}$), and volatile organic compounds (VOCs), contributing to air pollution and climate change (IPCC, 2019; Rogers & Brammer, 2012). Due to its harmful environmental and health impacts, open burning is banned or restricted in many regions (EEA, 2021; MoEFCC, 2019).

Pelletized or biofuel combustion : Offers better efficiency but requires energy-intensive pre-processing such as drying and pelletizing. While it emits lower amounts of CO_2 (and trace gases like CH_4 and N_2O) compared to open burning (Chatham House, 2021; Johansson et al., 2004), the high mineral content (especially chlorine and potassium) in grapevine wood can lead to fouling and corrosion in combustion systems (Nussbaumer, 2003).

Bioethanol production : It involves fermentation and distillation processes that vary in yield and energy efficiency depending on the technology used (Díaz et al., 2011). Although the resulting CO_2 is biogenic and often excluded from GHG inventories, fossil-based energy inputs during processing can still contribute to CO_2e emissions (IPCC, 2019). This method is considered climate-efficient only if renewable energy or the prunings themselves power the conversion process (Díaz et al., 2011).

2.4. Comparison of Emissions Caused Under Different Combustion Scenarios

This section gives a comparison of emissions caused by using one ton of freshly-pruned grapevine shoots in different combustion scenarios:

Open Burning: Open burning of fresh grapevine prunings is the most polluting option in terms of greenhouse gas emissions. It releases approximately 1,518 kg of CO_2, along with significant amounts of methane (CH_4: ~4.4 kg) and nitrous oxide (N_2O: ~0.07 kg) per ton of biomass (IPCC, 2019; U.S. EPA, 2025). Due to the high moisture content of fresh prunings (>50%), combustion is often incomplete. The result is high emissions of carbon monoxide (CO: ~88 kg) and particulate matter ($PM_{2.5}$: ~8–12 kg) (Johansson et al., 2004). These incomplete combustion products not only have elevated global warming potentials but also contribute to air quality degradation and respiratory health risks (Rogers & Brammer, 2012). The total carbon dioxide equivalent (CO_2e) emissions from open burning amount to roughly 1,829 kg per ton.

Pelletized/Biofuel Combustion**:** When grapevine prunings are processed into pellets or briquettes and combusted in controlled systems like biomass boilers, emissions go down significantly. Though CO_2 emissions stay high, around 1,500–1,800 kg per ton, methane and nitrous oxide are much lower, usually under 1.0 kg CH_4 and 0.03–0.07 kg N_2O, due to more complete combustion at higher temperatures (Chatham House, 2021; Johansson et al., 2004). Emissions of CO and VOCs are also reduced, and $PM_{2.5}$ emissions drop to ~2–6 kg, depending on fuel quality and combustion efficiency (Rogers & Brammer, 2012). The total CO_2e emissions range from 1,544 to 1,944 kg per ton, which is still high but preferable to open burning when renewable combustion technologies are used.

Bioethanol Combustion: Converting grapevine prunings into bio-ethanol via fermentation and distillation results in the lowest net greenhouse gas emissions. While combustion of ethanol emits around 475 kg of CO_2 per tonne of prunings (Díaz et al., 2011), this carbon is considered biogenic, meaning it was recently absorbed from the atmosphere by the plant and is therefore excluded from CO_2e under standard life cycle assessment protocols (IPCC, 2019; U.S. EPA, 2025). Only non-CO_2 gases, such as CH_4 and N_2O, and process-related emissions from fermentation and distillation (especially when powered by fossil energy), contribute to the CO_2e total, which ranges between 173–278 kg per ton, depending on energy sources used (Díaz et al., 2011). Bioethanol combustion is thus the most climate-efficient reuse of grapevine biomass, among those listed above, particularly when process energy is derived from the biomass itself.

2.4.1. Comparative Assessment of Current Grapevine Waste Disposal Practices

As discussed above, the global annual generation of grapevine prunings is estimated at approximately 31.95 million tonnes. The method of disposal significantly influences the greenhouse gas emissions produced. Table 1 presents a comparative analysis of emissions resulting from five commonly used disposal methods: natural decomposition, composting, open burning, pelletized/biofuel combustion, and bioethanol combustion, calculated for this total pruning volume.

Table 1. Comparative Assessment of Current Grapevine Waste Disposal Practices (Emissions Added).

Waste Disposal Method	CO_2e per ton (kg)	Total CO_2e estimated for 31.95 Mt prunings globally (Million Tons)
Decomposition	312.6 kg	9.99 Mt
Composting	95.4 kg	3.05 Mt
Open Burning	1,829 kg	58.44 Mt
Pelletized/Biofuel Combustion	1,544–1,944 kg (avg ≈ 1,744 kg)	55.72 Mt
Bioethanol Combustion	173–278 kg (avg ≈ 225.5 kg)	7.21 Mt

2.5. Proposed Solution and Significance of the Study

The annual production of 31.95 million tonnes of grapevine prunings contributes an estimated 3.05 to 58.44 million tonnes of recurring CO_2e emissions, depending on the disposal method used. This is an alarmingly high volume of greenhouse gases, primarily driven by uncontrolled decomposition, open burning, and inefficient composting practices. The urgent need to mitigate this environmental burden calls for sustainable and value-added alternatives to conventional waste disposal.

While traditional disposal methods contribute to CO_2, CH_4, and N_2O emissions, these lignocellulosic residues remain a largely untapped source of renewable material. Previous studies have demonstrated that agro-waste-derived fibers, such as those from corn husks, sugarcane bagasse, and banana stems, have effectively reduced emissions in the textile sector by replacing synthetic fibers with biodegradable, low-carbon alternatives (Tursi 2019; Eerhart et al. 2012). These bio-based fibers not only help lower environmental pollution but also address the growing concerns of fossil fuel dependency and microplastic contamination. In line with these advancements, this study proposes the valorization of grapevine prunings through the extraction of natural fibers suitable for textile and composite applications. By converting this abundant agricultural waste into functional bio-based fibers, the process offers dual benefits: lowering the carbon footprint of the viticulture sector and contributing to a more sustainable and circular textile economy.

Therefore, this study was aimed at exploring valorization with the objectives of: extraction and enhancement of fibers from grapevine shoots; evaluating the morphological, mechanical, and physical properties of these fibers under varying levels of alkaline treatment; comparison of extracted grapevine fibers with other lignocellulosic fibers for assessing their suitability for potential applications.

3. Materias and Methodology

3.1. Materials

Grapevine shoots were collected as pruning waste during the post-harvest season in October from a vineyard in Bengaluru, Karnataka. The shoots were then defoliated to prepare them for further processing.

3.2. Fiber Extraction and Refinement

3.2.1. Pretreatment and Separation

Initial processing involved overnight soaking protocol established in a previous study by Rana (2025). The shoots were soaked overnight at room temperature and subsequently pounded with a soft-faced hammer to mechanically separate the bark and core layers.

3.2.2. Fiber Extraction

Based on the optimization findings from Rana (2025), sodium sulfide (Na_2S) was identified as the most effective chemical treatment. Therefore, bark and core were treated using 15 g/L Na_2S solution at boiling temperature (≈100 °C) for 1 hour (bark) and 1.5 hours (core), with a material-to-liquor ratio (MLR) of 1:40. After that, fibers were rinsed, neutralized using 5% acetic acid, and manually extracted through mechanical loosening.

3.2.3. Bleaching Treatment

After fiber extraction using the optimized sodium sulfide (Na_2S) method described by Rana (2025), a peroxide-based bleaching treatment was applied to improve the brightness and separation of individual fibers. The bleaching solution was prepared with a material-to-liquor ratio (MLR) of 1:30. The bath comprised 1 g/L EDTA, 4 g/L sodium silicate, 8 g/L sodium carbonate, and 10 g/L sodium hydroxide. To this alkaline base, 10 g/L of 30% (w/v) hydrogen peroxide (H_2O_2) was added immediately prior to fiber immersion. The bleaching process was conducted at boiling temperature for 45 minutes.

This chemical combination was chosen for its proven effectiveness in enhancing fiber purity and promoting delignification. Prior research by Cheng et al. (2017) and Rana (2021) showed that using sodium hydroxide along with hydrogen peroxide significantly improved the extraction and refinement of fibers from lotus stems and banyan aerial roots. The dual action of alkali-induced swelling and oxidative bleaching was found to increase the convenience and efficiency of fiber isolation, which guided its application in the present study.

3.2.4. Dithionite (Hydro) Treatment

Following the peroxide bleaching, the fibers underwent a hydro-treatment using sodium dithionite to further improve their whiteness and facilitate greater fiber separation. Sodium dithionite is also known as sodium hydrosulfite, and is often referred to as "hydro" in the textile industry. Hydro treatment is a reduction-based process used to lighten or remove colors from fabrics and other materials. The fibers were bleached in a solution of 10 g/L sodium dithionite and 10 g/L sodium hydroxide. The treatment was conducted at boiling temperature for 30 minutes for bark fibers and 45 minutes for core fibers, respectively.

After treatment, the fibers were thoroughly washed with distilled water and neutralized using a diluted acetic acid solution to remove residual alkalinity. This process, commonly referred to as hydro treatment, is widely recognized in fiber processing for its ability to reduce chromophores and soften the fiber mass, thereby aiding in both whitening and individualization.

3.3. Analysis and Characterisation of Extracted fibers

The extracted grapevine bark and core fibers were evaluated for key physical and morphological characteristics using the following standardized procedures:

- Morphological Analysis: Conducted using Scanning Electron Microscopy (SEM)
- Fiber Length: Measured using the IS 10014-1
- Fiber Diameter: Measured through microscopic imaging
- Fineness (Linear Density): ASTM D1577-07 (Cut and Weigh method)
- Tensile Strength, Tenacity, and Elongation (Individual Fibers): Tested according to ASTM D3822/D3822M-14
- Bundle Strength and Elongation: IS 3675:1966
- Yield Percentage: Calculated as the percentage of the dry weight of extracted fibers to the initial dry weight of raw material, evaluated separately for bark and core to compare extraction efficiencies.

4. Results and Discussion

After the preparatory step of overnight soaking and subsequent separation, grapevine shoots were found to consist of 27% bark and 70% core by mass as shown in Figure 2.

Figure 2. Components of Grapevine Shoots.

4.1. Fiber extraction and Refinement

The Na_2S treatment resulted in visibly clean, pliable fibers. This improvement is attributed to effective lignin breakdown and partial hemicellulose removal. Bark fibers [Fig. 3(a)] appear visibly finer than core fibers [Fig. 3(c)]. Peroxide bleaching, followed by hydro treatment markedly improved fiber brightness and helped in loosening residual non-cellulosic matter, improving fiber individualization. There was improvement in the visual whiteness [as can be seen when comparing bark fibers after Na_2S treatment (Fig. 3a) to bark fibers after hydro treatment (Fig. 3b) ; with similar thrend in core [Fig. 3(c), 3(d)]. Additionally, softness of the fibers also increased, which is an indicator of successful chromophore reduction and additional purification.

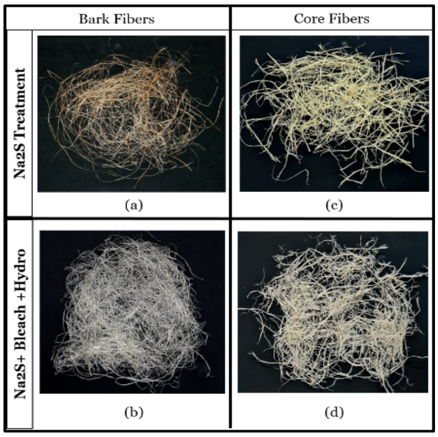


Figure 3. Visual analysis of extracted bark and core fibers at both levels of treatments.

4.2. Analysis and Characterization of extracted fibres

4.2.1. SEM Analysis

The surface morphology of grapevine bark and core fibers was examined using Scanning Electron Microscopy (SEM) at 55X and 550X magnifications, as shown in Figure 4. Na_2S-treated bark fibers had an uneven surface, with residual matrix materials, indicative of incomplete removal of lignin and hemicellulose and partial fiber bundle separation. At higher magnification (550×), compact layers and some adhered amorphous materials were visible. Following bleaching and hydro treatment, the bark fibers exhibited a cleaner, smoother surface with clear fibrillation and less matrix residue, indicating a more effective removal of non-cellulosic components and improved access to the cellulose-rich core.

Core fibers treated with Na_2S showed thicker, rough structures, with patches of lignified material at 550×. After bleaching and hydrotreatment, core fibers showed significant improvements in surface cleanliness and fibril separation. But, due to the inherently denser and more lignified structure of core fibers, the degree of refinement remained lower than that of bark fibers.

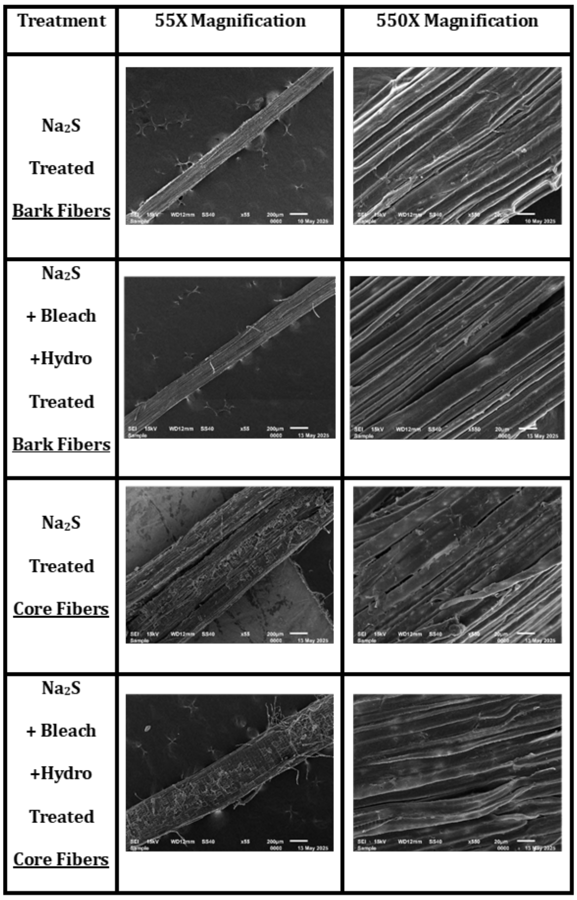


Figure 4. SEM micrographs of Grapevine bark and core fibers.

4.2.2. Characterisation of Extracted Fibers

As shown in Table 2, bark fibers extracted by Na_2S treatment were moderately long (80.9mm) and fine (170.20 µm) but exhibited good tenacity (3.50 g/denier) and bundle strength (3.18 g/denier), which points to strong individual fiber performance. With further bleaching and hydro treatment, the fibers became finer (66.04 denier) andstronger individually (4.84 g/denier), although bundle strength dropped to 2.14 g/denier. It is important to note that, overall, in bark fibers, individual tensile strength is higher than bundle strength due to their finer, more separated structure. When bundled, these fine fibers may not align perfectly, leading to less efficient load distribution and slippage, thus reducing overall bundle strength.

Core fibers extracted by Na_2S treatment produced shorter (59.6 mm), coarse (294.98 µm), weak (1.13 g/denier) fibers but with high yield (85.3%), reflecting their bulkiness. After hydro treatment, fineness improved

Table 3. Comparison of Physical Properties with other Natural Cellulosic Fibers.

Fiber	Physical Parameters				Source
	Diameter (µm)	Fineness (denier)	Strength(g/d)	Breaking Elongation (%)	
Jute	40-350	27-36	3.33-3.38	1.0-2.0	(Rana & Sethi, 2024)
Flax	12-27	22.5-27	3.33-4.44	1.5-5	
Hemp	25-50	16-50	3.0-7.0	1.5-5	
Ramie	50	16-125	4.5-8.8	1.5-5	
Kenaf	70-250	14-33	2.4-3.33	1.6	
Sisal	50-300	100-400	3.11-3.33	3.02	
PALF	20-80	31.5-38.5	2.55-3.33	2.4-3.4	
Coir	100-450	450-495	1.22-1.33	30	
Banana	50-250	90-140	3.47- 3.87	1.8-2.4	
Bamboo	240-330	1.37	2.2	21.1	
Grapevine Bark (Na_2S extraction - Hydro treatment)	126.58-170.20	66.04-97.55	Tenacity: 3.50–4.84 Bundle Strength: 2.14-3.18	1.97-2.01	Present Study
Grapevine Core (Na_2S extraction - Hydro treatment)	249.65-294.98	307.50-343.33	Tenacity: 0.87-1.13 Bundle Strength: 1.10-1.88	2.07-2.86	

Table 2. Physical Properties of Extracted Grapevine Bark and Core Fibers.

Part of the Grapevine Shoot	Treatment	Length (mm)	Diameter (µm)	Fineness (denier)	Tenacity (g/denier)	Bundle Strength (g/denier)	Elongation at Break (%)	Yield %
Bark	Na_2S	80.9	170.20	97.55	3.50	3.18	2.01	38.9
	Na_2S+ Bleach+Hydro	82.2	126.58	66.04	4.84	2.14	1.97	13.5
Core	Na_2S	59.6	294.98	343.33	1.13	1.88	2.86	85.3
	Na_2S+ Bleach+Hydro	64.6	249.65	307.50	0.87	1.10	2.07	39.2

slightly, but both individual strength (0.87 g/denier) and bundle strength (1.10 g/denier) declined. Elongation also decreased, and yield dropped to 39.2% after bleaching and hydrolysis. Interestingly, in the case of core fibers, the bundle strength is overall higher than tensile strength of individual fibers. This is because the coarser and stiffer morphology promotes better mechanical interlocking within the bundle. This improves collective load-bearing capacity, rendering bundle strength higher than individual fiber strength, despite the lower tenacity per filament.

So, further treatment of Na2s extracted fibers by bleaching and hydro treatment boosts the length and fineness but the strength and yield are reduced, especially in the finer bark fibers.

4.3. Comparison with Other Lignocellulosics and Potential Applications

4.3.1. Grapevine Bark Fibers

Grapevine bark fibers exhibit favorable mechanical characteristics, including moderate fineness (66.04–97.55 denier), high tenacity (3.50–4.84 g/d), and low elongation (1.97–2.01%). As presented in Table 3, these properties place them close to ramie, flax, banana, hemp, and jute, and superior to coarser fibers such as coir, sisal, and kenaf in several respects.

In line with the COP 30 agenda of 'Accelerating Sectoral Decarbonization Efforts', grapevine bark fibers may find potential applications across multiple sectors:

- *Yarn and Textile Applications*: With fineness and tensile strength comparable to ramie, banana, and jute, grapevine bark fibers can be spun into pure or blended yarns. Ramie-banana blended yarns, for instance, have demonstrated high tenacity and spinnability (Soraisham et al., 2021).
- Reinforced Composites (Automotive Sector): The bark's high tenacity aligns it with flax and hemp, making it suitable for reinforcement in automotive interiors such as dashboards, rear shelves, and door panels (Li et al., 2008; Liang et al., 2014).
- Bio-Packaging Solutions: Its biodegradability and mechanical strength make it ideal for molded packaging materials, trays, and containers, similar to banana and pineapple leaf fibers in similar use cases (Jose et al., 2016; Ngo, 2017).
- Nonwoven Textiles and Technical Felts: The moderate fineness and strength of bark fibers enable their use in needle-punched felts and technical nonwovens for insulation, agro-textiles, and acoustic insulation, akin to rice straw and sugarcane bagasse-based fabrics (Agirgan & Taskin, 2018; Sakthivel et al., 2021).
- Specialty Paper and Cigarette Papers: Given its high tensile strength and low elongation, grapevine bark fibers may also be suitable for cigarette paper, specialty pulp, and high-strength paper products, much like flax and banana fibers (Ferdous et al., 2021)
- Ballistic and Structural Panels: With tenacity exceeding coir and kenaf, bark fibers can be considered for ballistic composites or impact-resistant panels, drawing on research showing kenaf's competitiveness with synthetic aramids (Yahaya et al., 2014, 2016).
- Thermal and Acoustic Insulation: The moderate fiber volume and strength suggest potential use in building insulation panels, mirroring applications of sugarcane bagasse and corn husk fibers (Mehrzad et al., 2022; Fattahi et al., 2023).

4.3.2. Grapevine Core Fibers

Grapevine core fibers are coarse (307.5–343.33 denier) with low tenacity (0.87–1.13 g/d) and moderate elongation (2.07–2.86%), aligning them with coir, sisal, and bamboo (as seen in Table 3). They outperform coir in fineness, although they remain lower in strength than traditional textile-grade fibers. Based on these properties, grapevine core fibers may potentially find applications like:

- *Eco-Packaging Materials*: With fineness better than coir, grapevine core fibers may be used in the production of biodegradable packaging, trays, and protective casings using binders like latex or thermoplastics (Ngo, 2017).
- *Nonwoven Mats and Technical Felt:* The relatively coarse diameter and moderate elongation make core fibers ideal for needle-punched nonwoven materials in applications like floor mats, geo-textiles, or agro-fabric liners, similar to sugarcane and rice-straw derived products (Agirgan & Taskin, 2018; Sakthivel et al., 2021).
- *Impact-Resistant and Automotive Components*: While lower in strength, their fineness and elongation make core fibers suitable for filler material in hard composites, as seen in the use of banana fiber composites to enhance hardness in automotive interiors.
- *Paper and Pulp Products:* With adequate fiber length and moderate crystallinity, core fibers may be processed into molded pulp forms, cardboard, or fiber-reinforced paperboard, similar to the use of okra and corn stalk in fiber-cement and packaging (Jarabo et al., 2013; Ferdous et al., 2021).
- *Thermal and Sound Insulation Panels*: The coarseness and bundle strength, along with flexibility, of grapevine core fibers, make them promising for acoustic boards and eco-insulation panels, much like sugarcane bagasse and sunflower stalks (Mehrzad et al., 2022; Binici et al., 2013).

Table 4. Comparison of Resources spent in cultivating raw material for 1 million ton of fiber.

Fiber Crop	Land (Mha)	Water (km³)	Fertilizer (Mt)	Pesticide (kt)	Labor (Million man-days)	Energy Consumption (PJ)	CO_2 Emissions (Mt CO_2e)	References
Cotton	1.8	9.0	175.0	7500.0	225.0	17.5	1900.0	Cotton Inc. (2016)
Jute	0.9	2.75	65.0	3500.0	165.0	11.0	566.0	Singh et al. (2018)
Flax	1.35	3.5	125.0	5000.0	200.0	13.0	520.0	Dissanayake et al. (2009)
Hemp	0.8	2.5	75.0	2000.0	125.0	9.0	385.0	Zampori & Dotelli (2014)
Sisal	1.75	0.15	30.0	1500.0	275.0	4.2	270.0	Dellaert (2014)
Ramie	1.1	1.75	100.0	3000.0	200.0	11.0	316.0	Zhou & Wang (2018)

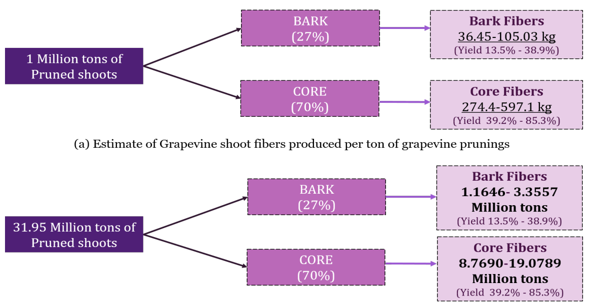
4.4. Impact of Grapevine Fibers

4.4.1. Environmental Impact: Resource conservation and Emissions Reduction

Estimation of potential global grapevine fiber yield

As discussed above, grapevine shoots, comprise approximately 27% bark and 70% core by weight. Since the fiber yield of bark fibers varies from 13.5% to 38.9% depending on the level treatment applied, the yield ranges from 36.45 kg (for Na_2S + bleach + hydro treatment) to 105.03 kg per tonne (for basic Na_2S treatment). Similarly, for core fibers, the yield ranges from 39.2% to 85.3% , meaning 274.4 kg to 597.1 kg per tonne, respectively. Figure 5(a) illustrates the estimate of grapevine shoot fibers produced per ton of grapevine prunings.

When scaled to the estimated 31.95 million tons of annual grapevine pruning biomass, bark fiber yield ranges from 1.16 million tons to 3.36 million tons, while core fiber yield ranges from 8.77 million tons to 19.08 million tons. Therefore, the total potential global yield of grapevine fibers is 9.93 million tons to 22.43 million tons, highlighting the substantial potential of this agro-waste for sustainable fiber recovery. Figure 5(b) illustrates the estimate of grapevine shoot fibers produced from 31.95 mt of prunings.



(a) Estimate of Grapevine shoot fibers produced per ton of grapevine prunings

(b) Estimate of Grapevine shoot fibers produced from 31.95 Million Tons of grapevine prunings

Figure 5 Estimate of grapevine shoot fibers produced by 1 ton and 31.95 mt of prunings respectively.

Comparison of resources used by cultivated fiber crops

As per United Nations, the world population is projected to reach 9.7 billion by 2050. Meeting the nutritional needs of this growing population, especially with limited resources, demands a 70% increase in food production (Rana et al., 2024). Cultivation of fiber crops further intensifies this challenge, as they compete with food crops for essential resources such as land, water, and other resources. For production of common cellulosic fibers such as cotton, jute, flax, hemp, sisal, and ramie, substantial resources are spent during the cultivation phase, from sowing to harvest. These include arable land, freshwater, fertilizers, pesticides, human labor, energy, and the release of significant amounts of greenhouse gases (CO_2e). Table 4 presents the resources consumed solely for cultivating the raw material required to produce 1million ton of fiber from commonly used cellulosic crops such as cotton, jute, flax, hemp, sisal, and ramie.

In contrast, grapevine prunings are a by-product of viticulture, already generated annually without the need for separate cultivation (or even harvesting) for fiber production. Substituting one million tons of conventional cellulosic fibers with grapevine pruning fiber can significantly reduce resource consumption, as grapevine prunings are an agricultural by-product and require no cultivation. This substitution can save approximately 0.8 to 1.8 million hectares of land, 150 million to 9 billion gallons of water, 30 to 175 million tons of fertilizers, 1,500 to 7,500 kilotons of pesticides, 125 to 275 million man-days of labor, 4.2 to 17.5 PJ of energy, and 270 to 1,900 Mt of CO_2e emissions. Table 5 presents both the per-million-ton and cumulative resource savings per million ton of grapevine fiber used as substitution for common cellulosic fibers; along with estimation of total potential savings when 9.93–22.43 Mt grapevine fiber is used to replace common cellulosic fibers.

Since the estimated total potential of grapevine fiber production ranges from 9.93 to 22.43 million tons, substituting this quantity in place of traditional fiber crops could result in substantial environmental and resource savings. This includes avoiding the use of 7.94 to 40.37 million hectares of agricultural land, 1.49 to 201.87 billion gallons of water, 297,900 to 3,925,250 tons of fertilizers, and 2,681.1 to 42,617 Mt of CO_2e emissions as listed in Table 5 among other inputs. These figures highlight the immense sustainability benefits of valorizing grapevine pruning waste as an alternative fiber source.

Table 5. Estimated Resource Savings from Grapevine Fiber Substitution (Emissions Reduced).

Resource	Savings per 1 Mt grapevine fiber used (as replacement)	Total potential savings when 9.93–22.43 Mt grapevine fiber used (as replacement)
Land (ha)	0.8 – 1.8 million ha	7.94 – 40.37 million ha
Water (gallons)	150 million – 9 billion gallons	1.49 – 201.87 billion gallons
Fertilizers (tons)	30,000 – 175,000 tons	297,900 – 3,925,250 tons
Pesticides (tons)	1,500 – 7,500 tons	14,895 – 168,225 tons
Labor (million man-days)	125 – 275 million man-days	1,241 – 6,168 million man-days
Energy (PJ)	4.2 – 17.5 PJ	41.7 – 392.5 PJ
CO_2 Emissions (Mt CO_2e)	270 – 1,900 Mt	2,681.1 – 42,617 Mt CO_2e (2.681 – 42.617 Billion ton CO_2e)

4.4.2. Social and Economic Impact : Aligning with COP 29's Goal of Bridging the Finance Gap

– *Empowering Vineyard Farmers* : Skilled vineyard farmers, or viticulturists, often face prolonged periods of unemployment during the off-season when grapevines lie dormant. This research introduces a novel income opportunity by monetizing pruned grapevine shoots ; turning what was once considered waste from the labor-intensive pruning process into a source of livelihood Additionally, the collection and processing of fibers can generate employment opportunities, promoting economic self-reliance.

– Boosting Local Economies : By enabling local processing of fibers, this initiative helps establish circular economies within grape-growing regions. Instead of discarding prunings as waste, small and medium enterprises (SMEs) in rural areas can participate in fiber production, leading to job creation and economic resilience. This approach aligns with global climate finance goals by making sustainable solutions more accessible to underserved communities.

5. Conclusion

To address the environmental challenges posed by the annual generation of over 31.95 million tonnes of grapevine pruning waste, this study introduces an innovative cradle-to-cradle approach by using discarded pruning waste from the vineyard as raw material for producing high-performance natural fibers. These grapevine fibers, derived from recurring agricultural waste, offer a sustainable, biodegradable alternative to conventional and synthetic fibers, without requiring additional land, water, or cultivation inputs.

Converting grapevine prunings into functional fibers, has the potential to directly reduce 3.05 to 58.44 million tons of CO_2-equivalent (CO_2e) emissions produced annually from conventional disposal in the viticulture sector. Moreover, substituting 9.93 to 22.43 million tons of grapevine fibers in place of common cellulosics such as cotton, jute, and flax could save up to 40.37 million hectares of land, 201.87 billion gallons of water, and 3.93 million tons of fertilizers, while preventing an additional 2.68 to 42.62 billion tons of CO_2e emissions in the textile and allied industries.

The valorization of prunings not only minimizes GHG emissions caused by burning and decomposition but also contributes to circular economy practices and climate resilience. Furthermore, substantial socio-economic benefits include empowering viticulturists with a new income stream, creation of rural employment in fiber collection and processing, and supporting the global transition toward low-carbon materials across textile, automotive, and packaging industries. By integrating waste valorization into viticultural systems, this research aligns with key Sustainable Development Goals 8 (Decent work and economic growth), 9 (Industry, Innovation and Infrastructure), 12 (Responsible Consumption and Production), 13 (Climate Action) and 17 (Partnerships for the Goals) as well as aligns with COP 29’s Goal of Bridging the Finance Gap ; and supports global decarbonization agendas under COP 30.

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