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Environmental Analysis of the Valorization of Woody Biomass Residues: A Comparative Study with Vine Pruning Leftovers in Portugal

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Abstract: Evaluating Global Warming Potential (GWP) in waste management scenarios is crucial, especially in light of the escalating global concern for climate change and the pivotal role that waste management plays in mitigating this crisis. This research examines the GWP of three distinct waste management scenarios, each with a unique approach: (1) open burning, a method involving direct combustion with a GWP of 1600.1 kg·CO_2eq, chiefly attributed to direct emissions without any mitigation tactics; (2) energy recovery, which capitalizes on converting waste into energy, yielding a GWP of 1255.4 kg·CO_2eq, the reduction resulting primarily from avoided heat production; and (3) pyrolysis, an advanced thermal decomposition process that remarkably registers a negative GWP of −1595.1 kg·CO_2eq, mainly credited to the carbon sequestration capacity of biochar production and optimal energy conversion efficiency. These outcomes emphasize the ecological merits of waste management approaches that produce lower, or even better, negative GWP values. In particular, pyrolysis emerges as a powerful way of transforming waste management into a potential carbon sink, proving crucial for climate change counteraction. Nevertheless, for effective real-world deployment, the study highlights the importance of addressing technical, economic, and societal challenges, underscoring the need for holistic, interdisciplinary research.

Keywords: pruning residues; combustion; pyrolysis; carbon sequestration; life cycle assessment (LCA)

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1. Introduction

Woody biomass residues such as forest leftovers, agricultural remnants, and pruning waste pose a significant environmental challenge [1]. These residues, often generated in substantial volumes, pose threats to air and soil pollution while exacerbating fire hazards [2]. Managing these leftovers sustainably is beneficial for various reasons. It reduces environmental pollution and cuts greenhouse gas emissions. By repurposing woody biomass residues instead of sending them to landfills or burning them, harmful pollutants and carbon dioxide emissions are greatly curbed [1,3]. Sustainable management also helps conserve natural resources, for example, by using residues as renewable energy sources. This approach lessens our dependence on non-renewable fossil fuels and fosters an eco-friendlier energy mix [4,5].

Transforming these residues into energy not only recycles valuable resources but also opens opportunities for job creation and local economic growth. At the same time, it enhances energy security, diversifies energy sources, and lessens our dependence on imported fossil fuels [6–8]. The sustainable management of these leftovers also contributes to tackling climate change. By converting the residues into energy, the carbon dioxide emissions are balanced by the carbon-sequestering ability of the biomass feedstock, which in turn helps reduce greenhouse gas emissions and furthers the global efforts to combat climate change and achieve sustainability targets [9].

A circular economy approach is promoted through the sustainable management of woody biomass residues [10]. Rather than treating these leftovers as waste, they can be used as valuable resources, integrating them into various value chains [11,12]. With effective waste-to-energy technologies such as combustion, torrefaction, pyrolysis, gasification, and anaerobic digestion, among others, these residues can be converted into heat, electricity, biofuels, or even bio-based products [13,14]. This process promotes resource efficiency and reduces reliance on new materials.

Vineyard pruning leftovers offer a significant case study on the need for proper management of woody residues [15]. Often burned in open fields, releasing carbon dioxide without using the energy within these residues efficiently, this method significantly contributes to the risk of rural fires occurrence. Instead, these materials can be used as a renewable energy source, lessening our reliance on fossil fuels and aiding the transition to a greener energy matrix. With suitable conversion technologies such as controlled combustion or biochar production, heat, electricity, or even charcoal can be harnessed from these residues, avoiding unregulated open burning.

From an environmental point of view, the right use of vineyard pruning leftovers may have a substantial positive impact [16]. Open, uncontrolled burning directly emits CO_2, a major greenhouse gas, but by using biomass as energy, it is possible to curb net CO_2 emissions, as the carbon released during burning is balanced by carbon sequestration by the growing vines [17]. In addition, as previously stated, this mishandling of vineyard pruning leftovers increases rural fire risks [18]. Figure 1 shows the occurrence of rural fires in the period from 1 January 2023 to 30 April 2023. As can be seen, there are a significant number of occurrences in the NW region of Portugal, which can be justified by the vineyard pruning season and the burning of the leftovers being the preferred method to dispose of the residues. Therefore, it's vital to adopt sustainable measures to prevent careless disposal of vineyard pruning leftovers and reduce fire risks.

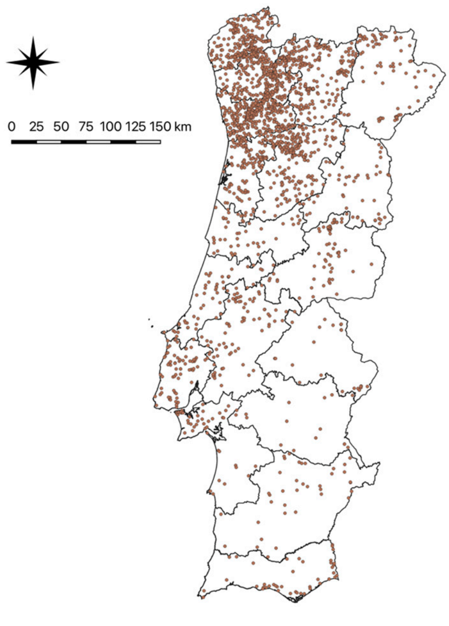

Figure 1. Occurrence of rural fires in Portugal during the period from 1 January 2023 to 30 April 2023 (adapted from the information available on https://fogos.icnf.pt/localizador/mostragooglemapsheatmaps.asp, accessed on 5 May 2023).

Effective use of vineyard pruning leftovers demands investment in proper infrastructure and technologies, as well as policies and regulations to promote their sustainable use [19]. For example, wine producers and local authorities must be incentivized to adopt responsible management practices, such as selective collection and routing the residues to biomass-to-energy recovery plants or other energy conversion facilities [20]. On the other hand, sustainable management of vineyard pruning leftovers demands teamwork among wine producers, government authorities, researchers, and other stakeholders in the biomass supply chain [21]. Awareness needs to be raised about the importance of repurposing these residues, alongside financial incentives and suitable regulations to stimulate the adoption of sustainable practices, as well as investment in research on more efficient technologies for converting these residues into energy and biomass supply chain management [22]. Managing this residual biomass sustainably exemplifies the need to rethink entirely the supply chain of woody residues [23]. Instead, a comprehensive approach must be adopted that values these resources as a viable source of renewable energy, paving the way for a more circular economy, benefiting not only the environment but the entire society as well [24].

As previously stated, vineyard pruning leftovers can be managed through different approaches, including burning, energy recovery, or charcoal production [18,25,26]. Burning the leftovers is a commonly employed method, where the residues are set on fire without harnessing the released energy. This practice, however, poses several environmental and safety concerns once the uncontrolled combustion not only leads to the release of greenhouse gases and air pollutants but, and this is a major question, also increases the risk of rural fires. To mitigate these issues and optimize resource utilization, alternative approaches for managing these residues have been suggested.

One alternative method is energy recovery involving combustion to generate thermal or electrical energy. By harnessing the energy content, this approach offers a more sustainable and efficient way to use the biomass. The energy produced can be used for heating purposes, or it can be converted into electricity [27]. This valorization pathway not only reduces the environmental impact associated with the burning of leftovers but also provides a renewable energy source, contributing to the transition towards a low-carbon economy. Another approach is the production of charcoal by pyrolysis, which involves heating the biomass in the absence of oxygen and converting the material into a solid carbon-rich material [28]. The charcoal can then be used for various applications, such as soil amendment (biochar) or as a renewable fuel source (charcoal). Incorporating biochar into the soil can enhance its fertility, improve water retention, and contribute to long-term carbon sequestration, thereby mitigating climate change [29,30]. Alternatively, the charcoal can be used as a fuel for thermal or electrical energy production, providing a renewable and carbon-neutral energy source [31].

Each of these management approaches has its own advantages and considerations. The burning of vineyard pruning leftovers without energy valorization is a simple and cost-effective method, but it leads to environmental pollution and fire hazards [32]. Energy recovery offers a more sustainable approach by using the energy content of the residues, reducing environmental impacts, and providing renewable energy [33]. The production of charcoal through pyrolysis allows for carbon sequestration and offers versatile applications, such as soil improvement and energy production. However, the production of charcoal requires additional processing and may involve higher costs [34,35].

The purpose of this study is to apply the Life Cycle Assessment (LCA) methodology to compare and evaluate the environmental impacts and sustainability of different options for woody biomass valorization. The study aims to provide insights into the most viable and environmentally friendly approaches for managing vineyard pruning residues, specifically focusing on the burning of residues without energy valorization, energy valorization through combustion, and charcoal production for soil deposition. By conducting a comprehensive LCA analysis, the study intends to assess the greenhouse gas emissions, energy consumption, and other environmental indicators associated with each option. The relevance of this study lies in addressing the urgent need to find sustainable solutions for woody biomass valorization. With the increasing recognition of the environmental impact of traditional practices such as burning and the importance of transitioning towards renewable energy sources, it becomes crucial to identify and promote more environmentally friendly alternatives. By implementing the LCA methodology, this study provides a systematic and holistic assessment of the available options, enabling decision-makers to make informed choices based on reliable and quantifiable data.

2. Literature Review

LCA has been widely used to assess the environmental impacts and viability of different woody biomass valorization options. Valente et al. [36] and Pérez-Fortes et al. [37] explored the use of woody biomass for thermal and electrical energy production, with positive results in terms of greenhouse gas emissions reduction and cost-effectiveness compared to fossil fuels.

These studies highlighted the importance of innovative biomass systems in climate change mitigation. Moret et al. [38] and Homagain et al. [39] examined the integration of woody biomass with other renewable energy sources such as geothermal energy and biochar. Both studies found synergies and benefits in terms of cost reduction and environmental impacts. The combination of different renewable energy sources showed promise for improving energy efficiency and reducing environmental impacts. Hamedani et al. [40] and Cheng et al. [41] specifically analyzed the production of woody biomass pellets and biochar. Hamedani et al. [40] compared different types of woody biomass and found differences in environmental impacts and energy efficiency. Cheng et al. [41] used machine learning to optimize the pyrolysis process and found promising results in terms of energy efficiency and climate impact. Both studies highlighted the importance of considering different biomass types and conversion processes to achieve the best results. Froese et al. [42] and Cavalcanti et al. [43] examined the mitigation of CO_2 emissions through woody biomass utilization. Froese et al. [42] compared different mitigation options and concluded that burning forest residues was the most effective option. Cavalcanti et al. [43] analyzed the energy efficiency and environmental impacts of forest biomass, emphasizing the importance of biomass moisture content in efficiency and environmental impact. Lu and Hanandeh [44] and Jackson et al. [45] explored the use of biochar as a low-carbon alternative. Lu and Hanandeh [44] analyzed different biochar utilization scenarios and found that pyrolysis temperature significantly affected efficiency and life cycle cost. Jackson et al. [45] compared different pathways for processing woody biomass and found economic and environmental benefits in ethanol production. Cheng et al. [46] and Hammar et al. [47] analyzed the economic and environmental feasibility of different biomass conversion technologies. Cheng et al. [46] investigated thermochemical technologies for negative CO_2 emissions and concluded that slow pyrolysis of woody residues and crops is economically viable as a negative emissions technology. Hammar et al. [46] explored fast pyrolysis, ethanol production, and charcoal production from woody biomass and identified differences in energy efficiency and climate impact. Both studies highlighted the importance of considering different conversion technologies and biomass sources to achieve energy sustainability.

Other studies, such as Kanematsu et al. [48], Pergola et al. [49], and Muñoz et al. [50], addressed specific aspects of the woody biomass supply chain. Kanematsu et al. [48] assessed the performance of biomass cogeneration systems for urban heating and cooling, considering appropriate scale and wood supply. Pergola et al. [49] compared the environmental impacts and production costs of wood pellets using different feedstocks [49]. Muñoz et al. [50] examined the transport performance of woody biomass with different pre-treatment options [50]. These studies emphasized the importance of optimizing the supply chain and considering different variables such as transport, pre-treatment, and feedstock to improve efficiency and reduce environmental impacts. Lastly, Ahmadi [51] and Boschiero et al. [52] investigated the use of different woody biomass sources for biogas and bioenergy production. Ahmadi [51] compared the energy efficiency and climate impact of maize-based anaerobic digestion (AD) and willow-based pyrolysis as an emerging technology. The study encompassed the entire technical system, from biomass production to biomethane delivery. Additionally, the study explored the climate impact when biochar was applied to soil as a carbon sequestration agent or used as an energy source. Results showed that substituting fossil gas with biomethane significantly reduced the climate impact, particularly in the case of willow pyrolysis. The willow pyrolysis system acted as a carbon sink, resulting in a negative climate impact and mitigating global warming. Boschiero et al. [52] conducted a study on the use of woody residues from apple orchards for bioenergy production using the LCA methodology. The study included the harvesting and chipping of an apple orchard's woody residues (AWRs), their transport, and their conversion into heat and power through gasification. Field measurements and chemical analysis were used for life cycle inventory (LCI) data. The study considered environmental impact categories such as climate change, acidification, and fossil depletion in the life cycle impact assessment (LCIA). The outcomes were compared with two reference systems based on fossil fuels, serving as benchmarks for the environmental performance of AWRs as a bioenergy source.

The analyzed studies addressed various aspects related to woody biomass valorization, including the evaluation of environmental impacts, energy efficiency, economic feasibility, and supply chain optimization. The results indicated that woody biomass could play an important role in mitigating climate change by replacing fossil fuels and reducing greenhouse gas emissions. Furthermore, the studies emphasized the importance of considering different biomass types, conversion technologies, and supply chain variables to maximize the environmental and economic benefits of woody biomass. The conclusions of the studies highlighted the need for integrated and sustainable approaches that consider technical, environmental, and economic aspects when assessing woody biomass valorization options. The previous studies have demonstrated the importance of LCA as a valuable tool for evaluating the environmental impacts and sustainability of woody biomass valorization. The different research efforts complemented each other, providing insights into different aspects of the supply chain, conversion technologies, and biomass types. This ongoing discussion of the topics, results, and conclusions of the studies reflects the evolution of knowledge and the continued interest in the sustainable utilization of woody biomass as a renewable energy source. However, from the previous studies, several research gaps concerning the LCA of residual biomass recovery can be identified. Firstly, and analyzing more recent studies such as the one presented by George et al. [53], while the characterization of groundnut shell and pinewood chip biomass was conducted using various tests, a comprehensive environmental impact assessment using LCA was not performed. The environmental implications of the use of these biomass sources for gasification, particularly in the context of Uganda, were not explored. While the calorific values of the biomass were mentioned, there was no comparison of these values to other potential biomass sources, making it challenging to understand their relative effectiveness. No information on the potential renewability of these biomass sources was provided. The potential economic and social implications, vital components of a comprehensive LCA, were also not addressed. Lastly, potential mitigation measures for the identified challenges, such as the high char deposit in groundnut shells (GNS) gasification, were not discussed.

3. Materials and Methods

3.1. LCA Methodology

In this study, a comprehensive LCA methodology was applied to evaluate the environmental impacts of different vineyard pruning leftovers management approaches. The LCA is a well-established methodology to evaluate the environmental performance of products and processes throughout their life cycle, from raw material extraction to end-of-life disposal, as schematized in Figure 2. It provides a systematic framework for quantifying and analyzing the environmental inputs and outputs associated with several other activities and enables the comparison of different systems or scenarios.

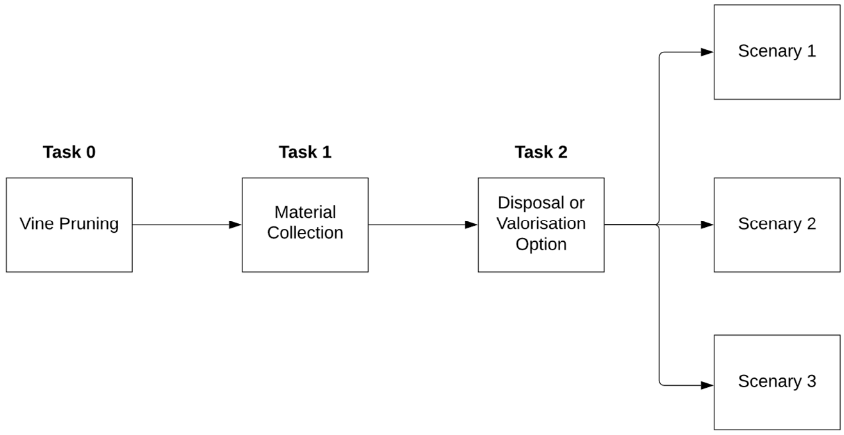

Figure 2. Vineyard pruning leftovers management tasks. Task 0, corresponding to vine pruning, is not considered in the LCA analysis because it is assumed that it is a mandatory task of the vine management system and must be conducted in any circumstances.

The LCA methodology employed in this study involved several steps. First, a functional unit (FU) was defined, which represents the functional output of the vineyard pruning management system under evaluation. This allowed for a standardized basis for comparing different management options. The FU of this LCA is the treatment of 1000 kg of vine pruning as a unit capable of comparing waste recovery in the wine industry. Next, the system boundaries were established, delineating the stages of the life cycle to be included in the assessment. This included activities such as pruning, collection, transportation, and disposal or utilization of the pruning residues. Data collection played a crucial role in this study, as it involved gathering accurate and representative data on the inputs and outputs of each stage in the life cycle of the vineyard pruning management systems. The data collection process encompassed various sources, including primary data from field measurements, interviews with stakeholders, and secondary data from literature, databases, and industry reports. Special attention was given to ensuring the quality and reliability of the collected data to ensure the robustness of the LCA results.

To conduct the LCA analysis, SimaPro (version 8.5) software was used, which is a widely recognized and widely used LCA software tool that facilitates the compilation, organization, and calculation of the life cycle inventory data, providing a comprehensive database of life cycle inventory data for different materials, processes, and energy sources, allowing for accurate modeling and assessment of the environmental impacts. The LCA methodology used in this study adhered to internationally recognized standards and guidelines, following the four phases of LCA as described in the ISO 14040 standards and in several previous studies [54,55]. These standards provide a framework for conducting and reporting LCA studies, ensuring consistency, transparency, and comparability of results.

3.2. Scenario Selection

For this study, three scenarios for the management of woody biomass were selected for the LCA evaluation, as follows:

- Scenario 1: Vineyard pruning leftovers open burning.
- Scenario 2: Vineyard pruning leftovers for energy recovery.
- Scenario 3: Charcoal production for soil deposition.

The first scenario involves the disposal of vineyard pruning leftovers through open burning without harnessing the released energy. This traditional method is commonly used due to its simplicity and low cost. However, it is associated with significant environmental concerns, such as the emission of greenhouse gases and air pollutants, as well as the risk of wildfires in rural areas. Figure 3 presents the input-output balance for Scenario 1.

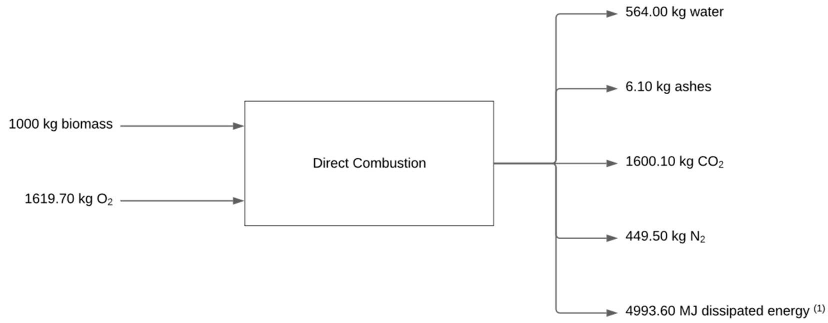

Figure 3. Inputs and outputs for Scenario 1, where (1) represents the remaining energy after the use of 1415.60 MJ to evaporate the 15% moisture content.

The second scenario, with energy recovery, focuses on the combustion of the leftover materials to harness thermal energy or generate electricity. This approach aims to maximize the energy potential of the biomass while minimizing environmental impacts. Biomass is used as a renewable energy source, replacing fossil fuels and reducing greenhouse gas emissions. Figure 4 presents the input-output balance for Scenario 2.

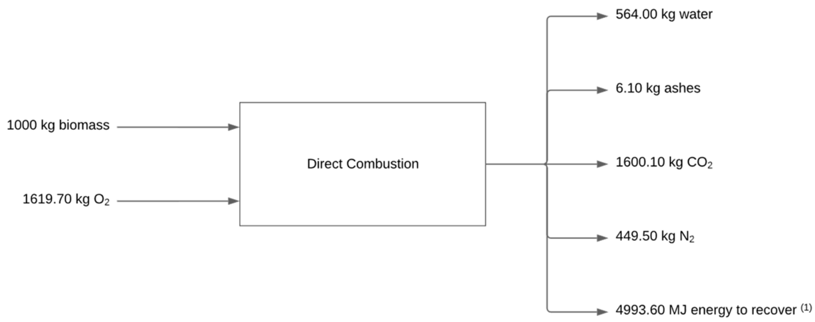

Figure 4. Inputs and outputs for Scenario 2 where (1) represents the remaining energy to be recovered after the use of 1415.60 MJ to evaporate the 15% moisture content.

The third scenario involves the production of charcoal from vineyard pruning leftovers. Charcoal can be used as a valuable carbon sequestration measure when incorporated into the soil, contributing to long-term carbon storage. It is recognized as a NET (negative emissions technology) by the IPCC (Intergovernmental Panel for Climate Change). Figure 5 presents the input-output balance for Scenario 3.

Each scenario presents distinct characteristics and trade-offs that must be analyzed. The residue burning scenario, although inexpensive, has adverse environmental effects and contributes to air pollution. The energy valorization scenario offers the advantage of using the renewable energy carbon neutral potential of the biomass. However, it requires appropriate combustion technologies and infrastructure. The charcoal production scenario offers the potential for carbon sequestration and long-term storage, but it requires additional processing and may have implications for soil quality and nutrient cycling, which must be properly cautioned.

3.3. System Limits

In the life cycle analysis of vineyard pruning management, as illustrated in Figure 2, the study encompasses the entirety of the management process, aiming to detail both the environmental and economic consequences inherent to each scenario. To provide a thorough understanding of the environmental consequences, several environmental aspects were assessed, namely greenhouse gas emissions, energy consumption, and air pollutants. To ensure the replicability and clarity of the study's data sources, Table 1 presents a detailed breakdown. Primary data, which were procured through field measurements, stakeholder interviews, and on-site observations, provided specific insights into vineyard pruning management practices. This primary data captures specifics such as the volume of vineyard pruning leftovers, energy prerequisites, emissions, and waste management routines associated with each scenario. Concurrently, secondary data was derived from an array of sources, including literature reviews, specific databases (such as EcoInvent or Agri-footprint), and bibliographic databases. These datasets supplemented the primary information, ensuring that our inventory data remains exhaustive and holistic.

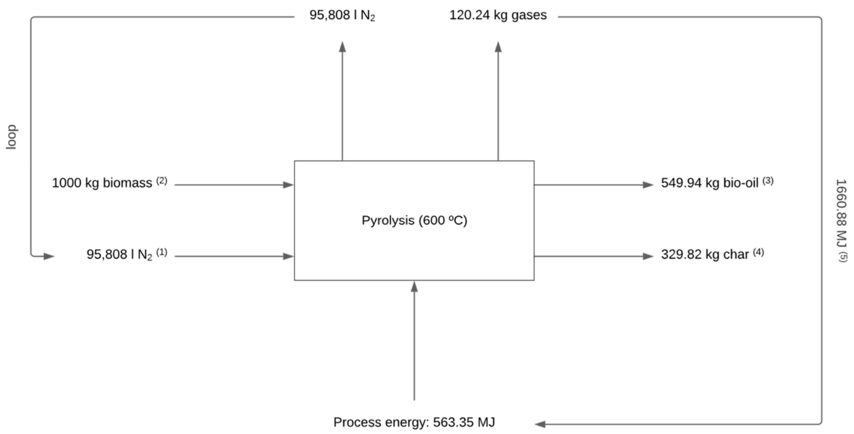

Figure 5. Inputs and outputs for Scenario 3, where (1) this N_2 does not participate in the reaction but is only used to inertize the reactor's interior and ensure an O_2-poor environment. It can be produced from a N_2 generator using PSA technology from atmospheric air; (2) it is assumed the use of conventional biomass with a moisture content < 15%, yielding a low heating value of 18.5 $MJ \cdot kg^{-1}$; (3) bio-oil is a product that can either be energetically valorized or marketed; (4) the char contains a total energy quantity of 9659.39 MJ and a fixed carbon content of 90%; (5) after the energetic valorization of the pyrolysis gases in the process, 1097.53 MJ are dissipated. In other words, in a perfect system, pyrolysis can be considered self-sustaining in terms of energy.

Table 1. Data source and values for environmental aspects in vineyard pruning management scenarios.

Environmental Aspect	Primary Data Value	Database/Secondary Source	Annotations/Metrics
Greenhouse gas emissions	25 $kg \cdot CO_2eq \cdot ha^{-1}$	EcoInvent v3.5	Based on average emission factors for vineyard pruning
Energy consumption	50 $kWh \cdot ha^{-1}$	Agri-footprint v4.0	Includes energy for machinery and processing
Vineyard pruning leftovers	3 to 3.5 $tons \cdot ha^{-1}$	Field measurements	Based on the average yield in sampled vineyards [18]
Waste management practices	As described in the text	On-site observations	Practices employed post-pruning

In Table 1, for each environmental aspect, we've itemized the relevant primary data value, the particular database or secondary source utilized, and any supplementary annotations or metrics that would aid in the analysis's replicability. The rigor in data collection and the adherence to established LCA protocols ensure that the insights are not only accurate and consistent across scenarios but also support comparability and the replicability of this study.

3.4. Inventory

All material and energy flow data within the system boundary were identified based on the treatment of 1000 kg of vine pruning. The Ecoinvent database was used as a secondary data source. Direct combustion (open burning) involves the disposal of vineyard pruning leftovers through open burning in loco (therefore it is assumed that there are no collection and transport processes) without harnessing the released energy. Direct combustion (energy recovery) focuses on the combustion of the leftover materials to harness thermal energy (it is assumed that the production of heat using natural gas is avoided). Pyrolysis involves the production of biochar from vineyard pruning leftovers that is incorporated into the soil, the production of bio-oil (calorific value 13.06 $MJ \cdot kg^{-1}$) that is also used to harness thermal energy (it is assumed that the production of heat using light fuel oil is avoided), and the production of pyrolysis gases (calorific value 13.81 $MJ \cdot kg^{-1}$) that are also used to harness energy that feeds the pyrolysis process (the remaining energy is dissipated). In these two last treatment options, the collection and transport of the vineyard pruning leftovers were considered. Capital goods were excluded.

Biochar can be used as a valuable carbon sequestration measure when incorporated into the soil, contributing to long-term carbon storage. Therefore, the biochar produced by the pyrolysis of 1000 kg of vine pruning could be incorporated into the soil to achieve stable carbon storage of 980.5 $kg \cdot CO_2eq$. Carbon sequestration in soil (CCS) can be calculated using the following equation [56]:

$$\mathrm{CCS} = -\,\mathrm{B_{mass}} \times \mathrm{B_{carbon}} \times \mathrm{B_{stable\ carbon}} \times 3.67 \quad (1)$$

where CCS is the carbon sequestration in soil ($kg \cdot CO_2eq$); B_{mass} is the biochar mass (kg); B_{carbon} is the carbon content in biochar (%); $B_{stable\ carbon}$ is the stable carbon content in biochar (%); and 3.67 is the C-CO_2 conversion coefficient.

4. Results and Discussion

One of the major challenges that demands attention and intervention today is the mounting apprehension surrounding the probable influence of Global Warming Potential (GWP) [57]. This importance arises from the prevalent global emphasis on environmental preservation and sustainability goals [58]. Given the grave implications of global warming on diverse aspects of human life, GWP merits a thorough analysis, particularly in the context of varying environmental scenarios [59]. To provide a comprehensive and credible evaluation of GWP, we used the characterization factors from the Intergovernmental Panel on Climate Change (IPCC) method [60]. The importance of leveraging the IPCC method in this analysis is underscored by its comprehensiveness, which encompasses the complex facets of climate change dynamics [61]. This IPCC method is crucially based on climate change factors—elements that exert a profound impact on climatic trends and conditions [62]. These factors, integrated into the method, serve as the foundation for assessing GWP [63]. Furthermore, the IPCC method affords a significant advantage in our analysis due to its application over a 100-year timeframe [64]. This temporal parameter provides a long-term perspective that is essential for understanding the sustained impact of different environmental scenarios on GWP [65].

Figure 6, which portrays the relative contributions of these potential impacts on GWP, is a representation of the variations in climate change factors across different scenarios. In essence, it serves as a guide for interpreting the effects of environmental scenarios on GWP, providing a visual demonstration of their comparative implications where and interpreting the range of possible outcomes on global warming as influenced by distinct environmental and sustainability parameters. Each scenario represented in Figure 6 encapsulates a set of factors and conditions, each contributing in its own way to GWP. By analyzing these scenarios in detail, the key drivers of GWP within each context can be identified, helping to better understand the intricate relationship between environmental changes and global warming. The scenarios collectively enable us to recognize the complexities of GWP, necessitating a nuanced and dynamic approach to addressing climate change and environmental sustainability. Thus, the evaluation of GWP, rooted in the application of the IPCC method and an examination of the scenarios illustrated in Figure 6, allows us to understand the global warming dynamics. This detailed analysis provides insights that can guide new strategies and interventions in pursuing environmental and sustainability goals.

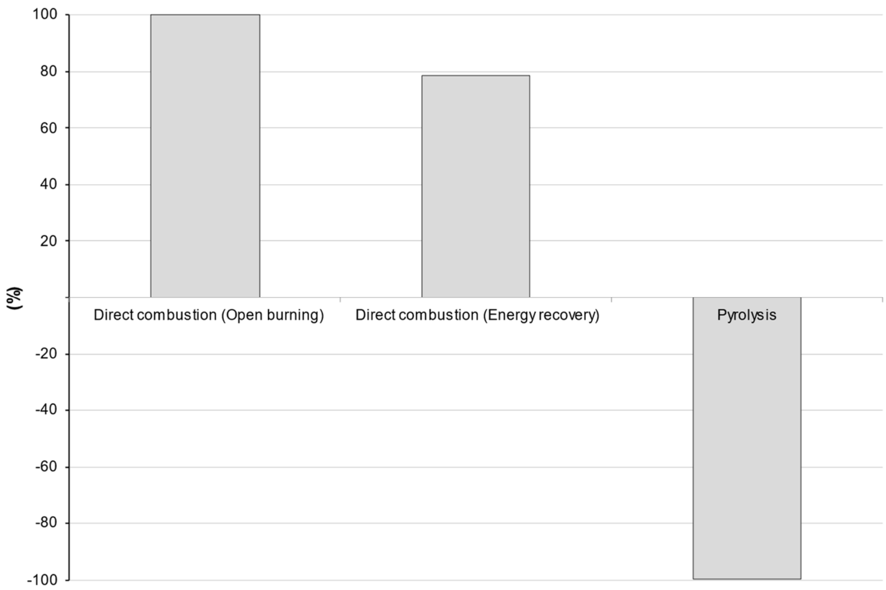

Figure 6. Relative contribution (in %) of the GWP for the different scenarios.

The assessment of the results illustrates that the pyrolysis system brings about a beneficial environmental impact, represented by negative values, in terms of GWP, particularly when juxtaposed with the direct combustion in open burning of vine pruning residues or even when compared to direct combustion with energy recovery. The investigation indicates that direct combustion, accompanied by energy recovery, carries distinct environmental benefits over open burning, as it shows a decrease in GWP of 21.5%. Nevertheless, the results highlight that the benefits of direct combustion with energy recovery do not quite reach the advantages offered by the pyrolysis system. The underlying reason for the superiority of the pyrolysis system over the other alternatives is attributed to the carbon sequestration capabilities provided by biochar, a product of pyrolysis. The integration of biochar into the soil serves as stable carbon storage, with the ability to sequester a noteworthy 980.5 kg·CO_2eq. In addition, the use of bio-oil, another output of the pyrolysis process, offers an opportunity to avoid the production of heat and, consequently, further reduces greenhouse gas emissions, amounting to an additional 620.1 kg·CO_2eq.

Figure 7 presents an overview of the relative contribution towards the potential impact on the GWP from different flows within the pyrolysis scenario. The visualization emphasizes the role of each element in the pyrolysis process, further underscoring the value of this environmentally friendly technology as a sustainable alternative to traditional combustion methods. The figure shows compelling evidence of how various elements within the pyrolysis process work in tandem to lower the GWP, thus making a substantial contribution to mitigating climate change.

Table 2 presents the GWP values, quantified in kilograms of carbon dioxide equivalent (kg·CO_2eq), associated with specific processes across three different scenarios: direct combustion via open burning, direct combustion via energy recovery, and pyrolysis. The processes under consideration are direct combustion (split into open burning and energy recovery), avoided heat production, transport, collection, and biochar production. The table exhibits the cumulative GWP value of each scenario, which is obtained by the sum or subtraction of the respective process values.

The data in Table 2 clearly elucidates the disparate environmental impacts of the three waste management scenarios. In the direct combustion with open burning scenario, the GWP value is noticeably high at 1600.1 kg·CO_2eq. This value represents the direct emissions from open burning, offering no mitigation strategies or benefits, such as energy recovery or biochar production, hence its significantly high value. In the direct combustion scenario with energy recovery, the GWP value is less at 1255.4 kg·CO_2eq, with the reduction attributed to the process of avoided heat production (−350.1 kg·CO_2eq). Avoided heat production signifies the energy recovered from combustion, which can offset the need for energy production elsewhere, thus lowering the overall carbon footprint of the process. Further, transport and collection processes contribute minor values of 0.8 and 4.6 kg·CO_2eq respectively, further contributing to the overall GWP value. The third scenario, pyrolysis, demonstrates a remarkable reversal in GWP, with the total per scenario value at −1595.1 kg·CO_2eq. Notably, this scenario includes biochar production, which is seen to have a significant carbon sequestration potential of −980.5 kg·CO_2eq, thereby offsetting other sources of emissions. Similar to the previous scenario, transport and collection contribute minor quantities to the total. However, the negative GWP of the avoided heat production here (−620.1 kg·CO_2eq) is more pronounced than in the energy recovery scenario, reflecting the higher efficiency of pyrolysis in converting waste into useful energy.

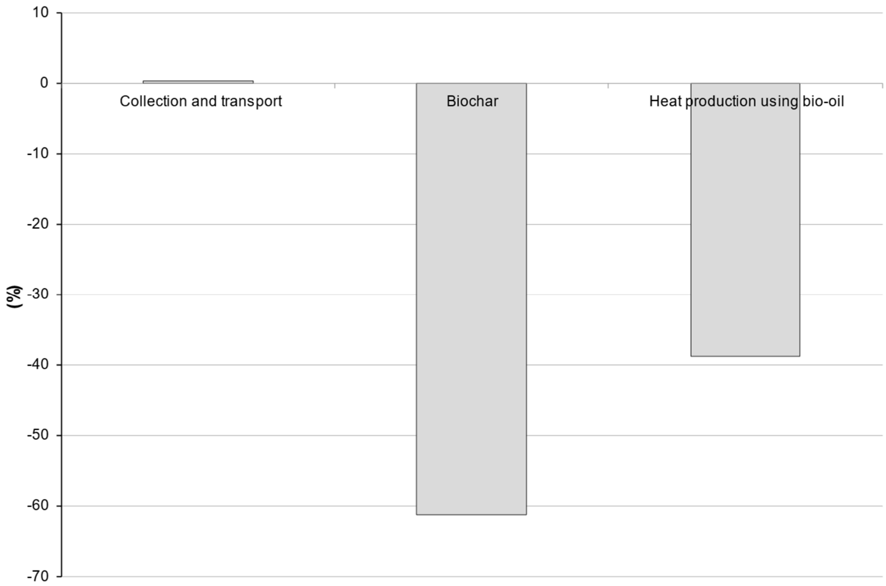

Figure 7. Relative contribution (in %) of the GWP per flow in the overall pyrolysis process.

Table 2. GWP (kg·CO_2eq) values of processes in the three different scenarios per FU.

	Direct Combustion (Open Burning)	**Direct Combustion (Energy Recovery)**	**Pyrolysis**
		kg·CO_2eq	
Direct combustion (Open burning)	1600.1	-	-
Direct combustion (Energy recovery)	-	1600.1	-
Avoided heat production	-	−350.1	−620.1
Transport	-	0.8	0.8
Collection	-	4.6	4.6
Biochar	-	-	−980.5
Total per scenario	1600.1	1255.4	−1595.1

The discussion of these results underscores the imperative to shift waste management strategies towards those with lower GWPs and, ideally, negative values. The stark contrast between the GWP of open burning and pyrolysis underlines the potential for significant environmental benefits if waste management processes are optimized. The data presented show that pyrolysis, coupled with biochar production, can turn waste management from a significant source of GHG emissions into a carbon sink, thus playing a substantial role in efforts to mitigate climate change. It also draws attention to the need for comprehensive carbon accounting, considering not only direct emissions but also the benefits of energy recovery and carbon sequestration. However, the actual implementation of such strategies would require considering other factors, including technical feasibility, economic viability, and societal acceptance, necessitating further multidisciplinary research.

5. Sensitivity Analysis

Understanding the uncertainty and sensitivity of the GWP values presented in Table 2 is very important for assessing the robustness of the biomass waste management strategies under examination. Sensitivity analysis can reveal how alterations in certain input parameters impact the outcomes, while uncertainty analysis assesses the degree of confidence we can attribute to these outcomes [66]. Such knowledge aids in decision-making, particularly in terms of strategizing the optimization of waste management processes for future sustainability and resilience [67]. Given the complex nature of waste management systems, several key variables may influence GWP outcomes, such as the efficiency of energy recovery, the carbon sequestration potential of biochar, and the emissions associated with transportation and collection processes [68]. For instance, the GWP of direct combustion with energy recovery and pyrolysis could fluctuate considerably based on how much energy is successfully recovered and utilized or how effectively the carbon is sequestered in biochar.

In this study, sensitivity analysis was used to determine the most influential variables in the system, especially concerning GWP values. When analyzing the sensitivity of GWP values, Table 2 showcased that with an alteration in certain parameters, there was a notable change in the GWP outcomes. For instance, a 10% variation in the carbon sequestration potential of biochar resulted in a GWP change of ±150 kg·CO_2eq. Similarly, a 5% alteration in energy recovery efficiency led to a GWP variation of ±60 kg·CO_2eq. Such information suggests the pivotal nature of these parameters. Uncertainty analysis sheds light on the inherent ambiguities associated with the system. Consider the carbon sequestration potential of biochar; our analysis showed that the GWP value had a 95% confidence interval ranging from −1450 to −1740 kg·CO_2eq, capturing uncertainties from feedstock differences and pyrolysis conditions. This probabilistic representation provides a comprehensive view of possible outcomes and their likelihoods. Given these insights, optimization strategies should primarily target the pyrolysis scenario, especially enhancing energy recovery efficiency during pyrolysis. Potentially, integrating advanced technologies or using high-energy-yielding waste could improve GWP outcomes by 20%. Similarly, increasing the carbon storage efficiency of biochar by 15% through optimal feedstock and pyrolysis conditions could be transformative. Ancillary measures, such as optimizing waste transport and processing, can reduce associated environmental impacts by an estimated 10%. As the journey towards sustainable waste management progresses, it's vital to continuously refine our understanding through advanced research, reducing uncertainties, and enhancing the robustness of predictive system analyses.

The transition towards more sustainable and resilient waste management systems requires a comprehensive understanding of the system dynamics, including the sensitivity and uncertainty of the outcomes. The strategies outlined above for optimizing the pyrolysis process and associated activities represent a step in the right direction. However, they must be complemented with broader systemic changes, including policy support, stakeholder engagement, and consumer awareness, to realize a truly sustainable waste management future. Future research should also seek to refine and validate the GWP values, incorporating more detailed data and sophisticated modeling approaches to reduce the uncertainties and enhance the predictive capabilities of the system analysis.

6. Conclusions

The research has critically assessed the environmental impacts of three waste management strategies: open burning, energy recovery through combustion, and pyrolysis, as detailed in Table 2. Open burning, with its highest GWP of 1600.1 kg·CO_2eq, highlights the substantial environmental repercussions of uncontrolled waste combustion. Conversely, energy recovery lessened the GWP to 1255.4 kg·CO_2eq, signifying the role of efficient waste-to-energy approaches. Notably, pyrolysis, presenting a negative GWP of −1595.1 kg·CO_2eq, stands out, suggesting that waste management can evolve from being an environmental concern to a solution for carbon sequestration, furthering climate change mitigation goals. These outcomes not only contest the traditional view of waste as an environmental burden but also emphasize its potential role in global warming mitigation. As the field looks ahead, the following areas warrant exploration: a more in-depth life cycle analysis of each method, probing the economic and societal implications alongside environmental aspects, and studying the potential for advancing technology in energy recovery and biochar production. There's also a need to examine how these strategies can seamlessly merge with existing infrastructure. In essence, this research paves the way for reframing waste management towards a more sustainable and climate-responsive trajectory, emphasizing the indispensable role of integrated, multi-disciplinary investigations in maximizing the opportunities this perspective brings.

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