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Opportunities for biomass valorisation through sorption-enhanced gasification: assessing environmental and economic aspects on biochar production

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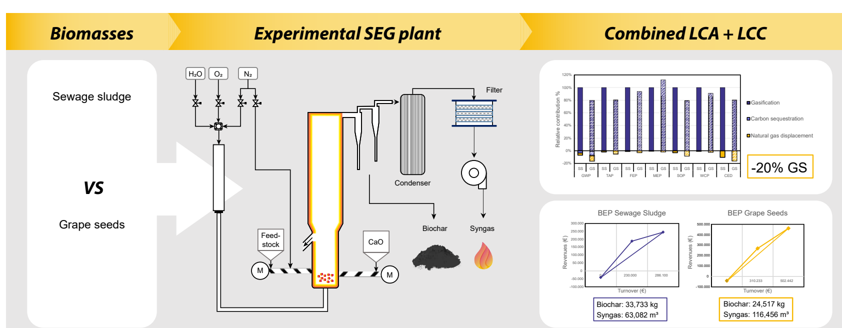
HIGHLIGHTS

- Life cycle assessment and costing of biochar in a pilot sorption-enhanced gasifier.
- Sewage sludge (SS) and grape seeds (GS) are evaluated as feedstocks.
- 1 kg of biochar emits 17.8 and 11.0 kg of CO_2 for SS and GS, respectively.
- Unit profits for biochar production are 0.82 and 0.94 €/kg for each feedstock.
- The sewage sludge system is more sensitive to fluctuation in electricity prices.

GRAPHICAL ABSTRACT



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ABSTRACT

Biochar has garnered significant attention for its potential to enhance soil quality and mitigate climate change. Despite its promise, comprehensive studies evaluating the feasibility of biochar systems remain limited. This research addresses this gap by analysing biochar production via sorption-enhanced gasification (SEG) using sewage sludge and grape seeds as feedstocks. A life cycle assessment evaluates the environmental impacts of producing 1 kg of biochar, while a life cycle costing examines the economic viability of SEG technology. Results show that grape seeds-based biochar yields lower environmental impacts compared to sewage sludge, with GHG emissions of 11.0 and 17.8 kg CO_2, respectively. The economic analysis also supports agricultural waste as a more favourable feedstock, obtaining a higher profit of 0.94 €/kg compared to 0.82 €/kg. This study underscores biochar's potential as a sustainable solution for waste management and soil amendment, while highlighting the need for further optimisation to improve its economic viability.

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1. Introduction

Biochar is a carbon-rich material that has gained popularity in recent years due to its potential environmental benefits (Allohverdi et al., 2021; Oliveira et al., 2017). While its recent applications have received much attention, the scientific study of biochar dates back a few decades. Early work by Glaser et al. (2002) explored its ability to improve highly weathered tropical soils by enhancing nutrient availability and water retention. Antal and Grønli (2003) later offered a detailed technical review of charcoal production processes, laying the foundation for modern biochar technologies. Lehmann (2007) helped bring biochar into the climate change conversation by highlighting its capacity to serve as a long-term carbon sink. Together, these studies shaped the initial scientific framework that continues to support current biochar applications.

Biochar is produced through the thermochemical conversion of biomass, which results in the carbonisation of organic materials. By sequestering and storing carbon for extended periods, biochar serves as a stable form of carbon storage, playing a crucial role in mitigating climate change (Li & Tasnady, 2023; Luo et al., 2023). This capability has significant implications for carbon credit markets, as biochar production is a form of carbon farming, offering new opportunities for sustainable agriculture and carbon trading (Dumortier et al., 2020). In addition to its role in climate change mitigation, biochar offers a range of applications, such as improving soil health by enhancing nutrient retention, increasing soil microbial activity, and improving water retention, as well as other industrial uses, including its function as a filler agent in bio-composite materials, air filtration, or energy storage (Bolan et al., 2021; Khan et al., 2021; Román et al., 2018).

As biochar is obtained through the valorisation of organic waste, it also represents an effective circular economy strategy for enhancing the value of these by-products. Various organic residues of agroforestry and urban origin have been previously studied for their feasibility for biochar production, investigating key factors such as their physicochemical properties, carbon content and heating values (López-Cano et al., 2018; Yang et al., 2017). Among the diverse biomasses suitable for biochar production are agricultural waste and sewage sludge (Srinivasan et al., 2015). In Spain, grape production is one of the leading agricultural activities, as it is the country with the largest vineyard surface in the world, covering 955 kha in 2022 (International Organisation of Vine and Wine, 2023). Different by-products from grape production, such as skins and seeds, are suitable feedstocks for biochar production. On the other hand, sewage sludge, which is obtained from wastewater treatment, is currently used as a fertiliser in agriculture, as encouraged by the Sewage Sludge Directive (Directive 86/278/EEC, 1986). However, the direct use of sewage sludge poses a risk of soil contamination due to the presence of hazardous substances such as viruses and heavy metals (Namdari et al., 2024; Singh et al., 2020). By converting sewage sludge into biochar, these potential contaminants are eliminated, producing a safer material for soil improvement (Singh et al., 2020).

Various technologies are available for the thermochemical conversion of biomass into biochar, each with its own characteristics and advantages (Tripathi et al., 2016). These technologies include pyrolysis, gasification, torrefaction and hydrothermal carbonisation, which differ in operating temperature, reaction environment and product yield (Low & Yee, 2021; Safarian, 2023). Among these, gasification has been proven to effectively transform organic biomass into biochar while also producing synthesis gas (syngas) that can be used as fuel in bioenergy applications. Within gasification technologies, sorption-enhanced gasification (SEG) has emerged as a promising technology for biomass conversion (Fuchs et al., 2019; Karl & Pröll, 2018). This technology uses a CO_2 sorbent, typically calcined limestone, which reacts with the CO_2 produced during gasification reactions, thereby driving the process towards hydrogen production (Fuchs et al., 2019; Pfeifer et al., 2009). Moreover, the gasification process improves the quality of the biochar by increasing its carbon content (Tan et al., 2023). SEG also has the potential to provide a cost-effective method for CO_2 capture when the secondary combustion/calcination reactor is operated under oxyfuel conditions (Martínez & Romano, 2016). Overall, sorption-enhanced gasification represents an advancement in thermochemical conversion technologies that contributes to the production of high-value biochar while effectively managing organic waste.

Although biochar appears to offer environmental benefits, the extent of these advantages remains under discussion. The thermochemical processes used to convert biomass require significant energy, potentially diminishing the overall environmental performance (Osman et al., 2021). Additionally, the economic feasibility of SEG technology is still uncertain, although some studies support its cost-effectiveness in terms of hydrogen production (Santos & Hanak, 2022; Schweitzer et al., 2018). To assess the environmental and economic sustainability of biochar production through gasification, its quantifiable impacts need to be evaluated.

Life cycle assessment (LCA) and life cycle costing (LCC) are methodologies that enable a thorough analysis of the impacts associated with processes and products. Different studies have conducted LCAs of biochar production, and there is research focusing on the environmental benefits of biomass gasification (Azzi et al., 2019; Ramos & Ferreira, 2022; Singh et al., 2020). Furthermore, scholars have examined the economic viability of biochar and gasification technologies. Most studies employ techno-economic analysis, exploring scenarios that consider parameters such as investment (Ramos & Ferreira, 2022; Santos & Hanak, 2022) and production costs (Rajaee et al., 2024; Schweitzer et al., 2018; Tang et al., 2024). However, there is still a gap in studies that address the joint environmental and economic analysis of biomass gasification processing. This research aims to evaluate the environmental impacts of biochar production in a pilot-scale sorption-enhanced gasification plant through LCA and LCC analyses, representing the first attempt of this kind in the literature. Specifically, grape seeds and sewage sludge were selected as biomass feedstocks, as these have already been assessed under sorption-enhanced conditions in prior studies (Martínez et al., 2020; Moles et al., 2024). These wastes represent relevant, locally available by-products that require sustainable valorisation solutions. Their contrasting origins and compositions—lignocellulosic agricultural residues versus nutrient-rich municipal wastes—allow a comparative assessment of biochar production across diverse feedstock types.

To address the environmental and economic implications of harnessing sewage sludge and agricultural waste, this study explores several key aspects. It examines the gate-to-gate environmental impacts of producing biochar in a sorption-enhanced gasification plant that uses sewage sludge and grape seeds as feedstocks. Additionally, it evaluates the broader environmental impacts of a multifunctional gasification system that produces both biochar and syngas. The research also assesses the economic feasibility of investing in a sorption-enhanced gasification plant, particularly when using the mentioned feedstocks. Lastly, it investigates the economic sustainability of the plant depending on the type of raw material processed. As the yield of biochar production varies depending on the feedstock used, conducting a comparative study offers valuable insights. By comparing these feedstocks, this study aims to deliver a clearer understanding of the potential benefits and trade-offs associated with biochar production.

2. Methodology

2.1. LCA & LCC

Life cycle methodologies are comprehensive and systematic approaches that evaluate various sustainability aspects across the life cycle of a product or system. In this study, LCA and LCC analyses have been performed to assess the environmental impacts and economic viability of producing biochar through sorption-enhanced gasification, using sewage sludge and grape seeds as feedstocks. LCA is one of the most widely used methodologies for analysing environmental impacts, as it provides a robust framework outlined by the ISO 14040 and 14,044 standards (International Organization for Standardization., 2006a; International Organization for Standardization., 2006b). On the other hand, institutions and companies have been using LCC for decades to assess the economic impacts of projects (UNEP/SETAC, 2011). Like LCA, it represents a systematic method that offers a detailed overview of the principal financial factors surrounding the object of interest. Together, LCA and LCC allow for the quantification of the environmental and economic consequences of a subject matter in a straightforward and exhaustive manner.

2.2. Gasification pilot plant and scenarios

This research focuses on a TRL4 gasification plant located at the Institute (name of institution anonymised for blind review). The unit consists of a bubbling fluidised bed reactor with a nominal thermal input of 30 kW, and a dense bottom zone standing at 0.6 m. Two distinct scenarios were analysed to compare outcomes based on different feedstocks fed into the gasifier: sewage sludge and grape seeds. These feedstocks were selected due to their regional availability and their potential as feedstocks for hydrogen production. Published data on the gasification of sewage sludge and grape seeds gasification in this facility under SEG conditions have been used for the analyses (Martínez et al., 2020; Moles et al., 2024). By examining these two scenarios, the study aims to provide comprehensive insights into the efficiency, environmental impact, and feasibility of using diverse organic materials under SEG gasification conditions.

2.3. Goal and scope

The purpose of this study is to analyse and compare the environmental and economic impacts of pilot-scale gasification of sewage sludge and grape seeds. The system boundaries were defined to include all relevant processes associated with the system under study. The stages considered include those within the pilot-scale plant, from the arrival of the prepared feedstocks to the production of biochar and syngas, resulting in a gate-to-gate life cycle approach. The functional unit selected was 1 kg of biochar produced in the gasifier.

The two primary outputs of gasification, biochar and syngas, make it a multifunctional process that results in two valuable products with distinct applications. There are two main approaches for dealing with multi-product systems in life cycle methods: the attributional and consequential methods (Ekvall et al., 2016; Schaubroeck et al., 2021). In this research, a hybrid approach was employed. Initially, only the impacts related to biochar production were considered. Economic allocation was used to address the impact allocation problem, based on the price of coproducts. Later, a system expansion was carried out to compare the impacts of the whole system. Furthermore, environmental and economic credits stemming from the production of biochar and syngas were accounted for. As biochar can fix carbon in soils, the CO_2 sequestered from the atmosphere was estimated. Conversely, syngas was assumed to displace natural gas production, thereby resulting in a reduction of the associated impacts.

2.4. Life cycle inventory

As previously mentioned, the biochar production scenarios were based on two published works performed at the pilot plant (Martínez et al., 2020; Moles et al., 2024), which served as references for the inventory data. Additional primary data was collected directly by the plant personnel and researchers at the Institute. For the environmental analysis, the Ecoinvent v3.8 database was used for background data. Table 1 presents the main data for analysing the production of 1 kg of biochar for each feedstock.

Biochar used as soil amendment sequesters carbon, reducing atmospheric CO_2 levels. The amount of carbon stored depends on the carbon content in the biochar which is linked to the type of original biomass and conversion process used. It is estimated that biochar from gasification processed above 700 °C can retain 89 % of its carbon content for over 100 years (IPCC, 2019). The carbon sequestration potential of biochar was calculated using the IPCC method (Eq. (1) for estimating the change in mineral soil organic carbon stocks from biochar amendments (IPCC, 2019):

$$\Delta BC_{Mineral} = \sum_{p=1}^{n} \left(BC_{TOT_p} \times F_{C_p} \times F_{perm_p} \right) \quad (1)$$

where BC_{TOT} is the amount of biochar mass incorporated into the soil, F_C is the organic carbon content in the biochar, and $F_{perm,p}$ is the fraction of biochar remaining in mineral form after 100 years.

To account for the displacement of natural gas in the system expansion, the low heating value (LHV) of the syngas was calculated. The LHV, a measure of the energy capacity of a fuel, helps estimate the quantity of displaced natural gas on the basis of energy equivalence. The calculation followed Tamošiūnas et al. (Tamošiūnas et al., 2023), as shown in Eq. (2):

$$LHV_{syngas} = \sum \left(LHV_i \times Y_{i,syngas} \right) \quad (2)$$

where $Y_{i,\ syngas}$ is the volumetric concentration of syngas components and LHV_i is the calorific value of each *i-component* in MJ/Nm^3.

2.5. Life cycle impact assessment

The environmental analysis was conducted using the SimaPro v. 9.4.0.3 software. The selected methods included the ReCiPe 2016 Midpoint v1.08 and Cumulative Exergy Demand v1.07. The ReCiPe Midpoint method features 18 impact categories addressing diverse environmental concerns (Huijbregts et al., 2016). For this study, six categories were selected: global warming (GWP), terrestrial acidification (TAP), freshwater eutrophication (FEP), marine eutrophication (MEP), scarcity of mineral resources (SOP) and water consumption (WCP). The cumulative exergy demand categories were aggregated into a single indicator to capture the total energy required in both scenarios. These categories were chosen because they are among the most widely used in bioenergy LCA studies (Hijazi et al., 2016; Zhu et al., 2022) and to address the impacts of key inputs, such as CaO for bed material and water consumption.

2.6. Life cycle costing analysis

To assess the economic feasibility of biochar production via the gasification of sewage sludge and grape seeds, an LCC analysis was performed. The economic framework adopted was based on the full-costing approach as described by Uzawa (Uzawa, 1964). Details of the cost items and the corresponding data sources are provided in Table 1. Initially, the production costs associated with the two primary outputs of the gasification system, namely biochar and syngas, were calculated. These costs were subsequently allocated between the products using the same economic allocation method adopted in the LCA. To maintain consistency between the analyses, the selling prices for biochar and syngas were held identical to those in the LCA. In contrast to the LCA, the production capacity of the plant was maximised to simulate a plausible industrial-scale development scenario (European Biochar Industry, 2024). The unit production costs were derived based on the respective yields of biochar and syngas produced from each feedstock (Ahmed et al., 2016).

The profitability of the production process, constrained within the established system boundaries, was assessed by comparing the estimated costs with the sales prices. Furthermore, the variation in profitability between the different feedstocks was analysed using the break-even point (BEP) framework (Kampf et al., 2016; Nematian et al.,

Table 1
LCA and LCC index data to produce 1 kg of biochar from sewage sludge (SS) and grape seeds (GS).

LCA inventory			LCC cost items			
Inputs/outputs	**SS**	**GS**	*Variable*	*Description*	**SS**	**GS**
Products						
Biochar [kg]	1	1	**Products**	The main products obtained in the gasification process. Prices of biochar and syngas are volatile and depend on regional data. Tentative prices have been considered contrasting various sources. *Source: Primary data*		
Syngas [m^3]	1.95	4.75				
Inputs						
Land [m^3]	0.00071	0.00052	**Quotes [€]**	It includes the pilot plant and the land area on which it lies.It considers the annual depreciation of the pilot plant (assuming a 15-year average life) , machinery, maintenance, insurance and unforeseen events. It also considers dismantling costs offset by steel sale revenues. *Source: Primary data* *Steel price: (EURecycle 2024)*	0.0786	0.0583
Steel [kg]	0.0404	0.0558				
Feedstock [kg]	3.9	5	**Raw materials [€]**	Common raw materials include water, N2, CaO. Specific feedstocks (sludge and grape seeds) are regionally available and cost-free. *Source: Primary data*	0.0858	0.0637
Water [kg]	2.20	6.72				
N_2 [m^3]	1.13	2.48				
CaO [kg]	1.36	0.92				
Electricity [kWh]	71.4	51.7	**Energy cost [€]**	Energy costs include electricity required for 5 resistors to operate the plant. *Source: Primary data, Energy cost: (Ministerio de Industria y Turismo, 2024)*	0.112	0.0833
Outputs						
Ash [kg]	0.0001	0.03	**Waste management [€]**	Costs include management for wastewater, ash and tar produced during gasification. *Source: Primary data for production* *Management costs: (Boletín Oficial de Aragón (BOA), 2024)*	0.00397	0.0285
Tar [kg]	0.023	0.14				
Wastewater [kg]	1.98	6.05				
			Labor cost [€]	Cover the gross cost of the technical personnel managing the plant. *Source: Primary data for employed hours* *Hourly cost: (Ministerio de trabajo y economía social, 2022)*	0.114	0.0846
			Interest on land capital, machinery and organizational costs [€]	Includes interest for land capital, machinery and tools and coordination activity costs. *Source: Primary data* *Rate of interest: (Blanc et al., 2019; Baima et al., 2024)*	0.0186	0.0138

2021). The BEP is defined as the juncture at which revenue equals costs, indicating the number of units that must be sold to cover costs before generating profits. It helps determine the most profitable biochar production process between sewage sludge and grape seeds biomass. In this context, the sales volume was identified as a critical threshold, beyond which an increase in quantity generates revenue, while a decrease results in economic losses. This value was subsequently utilised to calculate the amount of biochar and syngas production required to secure revenue for each feedstock. The calculation of the BEP encompasses fixed costs, which are common to both feedstocks, alongside variable costs specific to each. Fixed costs comprised expenditure on quotes, labour, and interests, whereas variable costs included expenses for raw materials, energy, and waste management (Table 1).

In conjunction with the preceding analysis, a scenario analysis was conducted to address the volatility of electricity prices – a key factor in the gasification system (Ma et al., 2022; Macedo et al., 2022). To explore the economic implications, a 40 % reduction and a 60 % increase in prices were considered, relative to the baseline. This range of fluctuation was determined by observing trends in the energy market over recent years (Balcilar et al., 2019). To assess the response of costs to this fluctuation, the elasticity of profit (Accastello et al., 2018) with respect to variations in electricity prices was calculated. A high elasticity implies that a 1 % increase in energy prices causes more than 1 % decrease in profit, meaning profitability of biochar is highly sensitive to energy costs. Conversely, profit is considered inelastic when a 1 % change in energy prices leads to a less than 1 % change in profit, suggesting that the economic performance of the system is stable despite energy price volatility. Given that changes in energy prices are a key factor influencing the economic viability of the system, the elasticity analysis provides insights into which production model is more resilient to such variations.

3. Results

3.1. Life cycle assessment

The environmental performance results for the production of biochar from sewage sludge and grape seeds are detailed in Table 2. The environmental impact values are generally higher for biochar produced from sewage sludge across all impact categories evaluated. For example, the global warming potential (GWP) associated with producing 1 kg of biochar from sewage sludge is 20.6 kg of CO_2 equivalent, compared to 11 for grape seeds. The majority of impacts of both production systems can be attributed to the significant energy consumption in the process, which accounts for 70 % or more of the environmental impacts across all categories, with the exception of marine eutrophication in the grape seeds scenario. The higher energy intensity of the sewage sludge biochar production process results in greater impacts. Furthermore, the increased yield of syngas production from grape seeds contributes more to the impacts than the biochar. The high energy requirements also limit

Table 2
Environmental impacts of 1 kg of biochar obtained from the gasification of sewage sludge (SS) and grape seeds (GS) by impact category.

Impact category	Unit	Biochar SS	Biochar GS
GWP	kg CO_2 eq	1.78E + 01	1.10E + 01
TAP	kg SO_2 eq	5.70E-02	3.24E-02
FEP	kg P eq	3.58E-03	2.36E-03
MEP	kg N eq	5.82E-04	4.60E-04
SOP	kg Cu eq	4.44E-02	2.49E-02
WCP	m^3	1.65E-01	1.06E-01
CED	MJ	554.0	314.3

Note: Impact category labels: GWP: global warming potential; TAP: terrestrial acidification potential; FEP: freshwater eutrophication potential; MEP: marine eutrophication potential; SOP: surplus mineral and metal ore depletion potential; WCP: water consumption potential.

the potential benefits of gasification in terms of carbon abatement and fossil fuel displacement.

As noted above, the results indicate superior environmental performance for biochar derived from grape seeds across all impact categories. In most categories, the impacts associated with grape seeds biochar are approximately 30 % lower than those of sewage sludge biochar, with the exception of marine eutrophication, where the grape seeds scenario exhibits a higher impact due to increased tar production when grape seeds are employed as feedstock.

The LCA results for the expanded boundaries of the gasification systems are illustrated in Table 3. The expansion of boundaries allows the inclusion of impacts associated with syngas production, which increases the impact values of the gasification process by approximately 23 % in the sewage sludge scenario and 67 % in the grape seeds scenario. As previously noted, the higher yield of syngas from grape seeds prompts an increased impact allocated to this coproduct. Therefore, when considering both biochar and syngas, the environmental impacts of gasification become more comparable between the sewage sludge and grape seeds systems. Notably, the elevated syngas production from grape seeds results in greater displacement benefits that offset more of the impacts. In addition, the carbon sequestration provided by the biochar helps to mitigatie carbon emissions within the GWP indicator.

Consistent with the previous findings, most of the impacts are observed to be higher in the sewage sludge scenario, with a decrease of 15–20 % in the grape seeds case. The exception is noted in the marine eutrophication category, where the grape seeds scenario surpasses the sewage sludge scenario by 10 %. The substantial impacts of the gasification process diminish the environmental benefits of carbon sequestration provided by the biochar and the natural gas displacement achieved through syngas production.

3.2. Life cycle costing

The production costs associated with the biochar and syngas production, detailed for each of the two feedstocks, are presented in Table 1.

The composition of the production costs for both scenarios is remarkably similar. Labour, raw materials, and energy costs represent the three main contributors to the total production expense. Since the two feedstocks employed are classified as waste materials within a circular economy framework, no direct costs were attributed to their use; however, costs for water, nitrogen (N_2) and calcium oxide (CaO) were included in this cost item.

Although the percentage contribution of the costs is almost equivalent, the composition of the raw materials differs between sewage sludge and grape seeds. Specifically, the quantity of CaO utilised in the sewage sludge scenario (28,080 kg) exceeds that in the grape seeds scenario (27,000 kg). Conversely, the amount of N_2 required in the grape seeds scenario is more than three times higher than that used for treating sewage sludge (10,368 m^3 versus 3,326 m^3 respectively). Considering the respective prices of 0.09 €/m^3 for N_2 and 0.60 €/kg for CaO, the total expenditure incurred remains consistent, despite differing quantities.

The incidence of waste management costs is 7.6 % higher in the grape seeds system, attributable to the greater volume of ash and tar produced during the processing of grape seeds compared to sewage sludge. The second most significant cost component is electricity. For this production factor, we sought to examine how the cost incidence might vary with fluctuations in the market price of energy. The base tariff data was established at 0.10272 €/kWh (Ministerio de Industria y Turismo, 2024). A range of variation between −40 % and +60 % was assumed. Within this range, it was observed that the incidence of energy costs in relation to total costs varied between 18.3 % and 37.4 % for sewage sludge and 16.7 % and 34.9 % for grape seeds. Energy costs proved to be critical for the whole production system. When considering the baseline price of electricity, this cost was the second largest; however, fluctuations in the price on the Spanish market could elevate it to the main expense, surpassing labour and raw material costs.

Particular attention must also be directed towards the depreciation costs of machinery: an industrial plant must be managed efficiently to ensure optimum productivity, and thus an effective return on the initial investment. The cost of machinery depreciation is approximately 18 %, making it the fourth largest cost component in percentage terms.

The profitability of the production process was assessed by the ratio of total costs and revenues to unit outputs: 1 kg for biochar and 1 m^3 for syngas, as detailed in Table 4.

The data presented in Table 4 reveals similar profitability trends for the two feedstocks used and their respective outputs, biochar and syngas. In both cases, biochar yields higher profits compared to syngas. The profitability of biochar produced from grape seeds processing is comparable to that of sewage sludge. Despite the fact that both feedstock systems share identical infrastructure and production processes, a marked disparity arises when comparing the revenues generated by biochar and syngas. The difference in profit outcomes is largely attributable to the significantly higher yield of grape seeds compared to sewage sludge. While the variation in unit profit between the two feedstocks remains relatively modest, when considering the annual profit generated – and assuming the same fixed costs – the utilisation of

Table 4
Calculation of unit profit for biochar and syngas from sewage sludge (SS) and grape seeds (GS) for a one-year period.

Feedstock		**SS**		**GS**	
Co-product		*Biochar*	*Syngas*	*Biochar*	*Syngas*
Quantity produced	kg	200,000		269,767	
	m^3		374,000		1,281,395
Price	€/kg	1.15		1.15	
	€/m^3		0.15		0.15
Revenue	€	230,000	56,100	310,233	192,209
Unit cost	€/kg	0.33		0.21	
	€/m^3		0.04		0.03
Total production cost	€	66,476	16,214	55,329	34,280
Profit	€/kg	0.82		0.94	
	€/m^3		0.11		0.12
	Total	164,000	41,140	253,581	153,767

Table 3
Environmental impacts of the gasification systems by impact category. The results show the LCA of 1 kg of biochar and 1.87 m^3 of syngas, and 1 kg of biochar and 4.75 m^3 of syngas obtained from the gasification of sewage sludge (SS) and grape seeds (GS), respectively.

Impact category	**Unit**	**SS SYSTEM** Gasification	Char carbon sequestration	Natural gas displacement	**GS SYSTEM** Gasification	Char carbon sequestration	Natural gas displacement
GWP	kg CO_2 eq	2.02E + 01	−7.30E-01	−6.90E-01	1.62E + 01	−1.47E + 00	−1.87E + 00
TAP	kg SO_2 eq	6.47E-02		−1.26E-03	5.22E-02		−3.42E-03
FEP	kg P eq	4.06E-03		−4.60E-05	3.81E-03		−1.24E-04
MEP	kg N eq	6.62E-04		−4.55E-06	7.42E-04		−1.23E-05
SOP	kg Cu eq	5.05E-01		−1.58E-03	4.02E-02		−4.27E-03
WCP	m^3	1.87E-01		−1.66E-03	1.71E-01		−4.48E-03
CED	MJ	6.29E + 02		−3.74E + 01	5.07E + 02		−1.01E + 02

grape seeds becomes more economically advantageous.

The Break-Even Point analysis offers an understanding of the overall profitability of the plant under consideration. Fig. 1a and 1b illustrate the BEP for sewage sludge and grape seeds, respectively.

The BEP associated with the use of grape seeds is marginally lower than that of sewage sludge, suggesting that employing grape seeds as an input may offer investment advantages over sewage sludge. The BEP for grape seeds is achieved with the production of 24,517 kg of biochar and 116,456 m^3 of syngas, whereas the quantities associated with sewage sludge are 33,733 kg and 63,082 m^3, respectively. The use of agricultural waste appears to be favourable, as it attains cost/revenue equivalence with slightly lower quantities of biochar. In terms of feedstock yield, each BEP corresponds to 122,585 kg of grape seeds and 128,523 kg of sewage sludge, which further supports the slightly superior performance of agricultural waste gasification.

The impact of the energy costs was evaluated through scenario analysis, where the profit generated by biochar and syngas was determined separately for each feedstock type. The energy cost variations were established within a range of −40 % and +60 % relative to the reference value. For the use of sewage sludge, the profit of biochar fluctuates between 0.76 and 0.85 €/kg, while that of syngas varies between 0.10 and 0.11 €/m^3. Conversely, for the grape seeds feedstock, the biochar profit shifts between 0.92 and 0.97 €/kg, and the syngas profit ranges from 0.12 to 0.13 €/m^3. Consequently, the analysis reveals that the profit obtained from biochar shows less variability with changes in energy costs (Fig. 2a) in the case of agricultural waste compared to the sewage sludge (0.05 €/kg versus 0.08 €/kg). This indicates that sewage sludge waste is more susceptible to profit fluctuations due to energy prices. The ability of a production system to withstand and mitigate the variability stemming from cost changes is critical for its economic resilience.

The profit sensitivity to changes in the energy price is quantified by elasticity (Fig. 2b). For sewage sludge, the absolute elasticity of biochar profit with respect to the €/kWh price ranges from 0.06 to 0.19, whereas for grape seeds this value spans between 0.03 and 0.09. While this does not indicate differing trends between the two elasticity curves, it does confirm that biochar production from sewage sludge is more volatile in relation to energy cost trends. As the elasticity values fall below 1, the relationship between biochar profit and energy price is considered to be inelastic; specifically, the profit changes by less than one unit for each unit change in energy price.

4. Discussion

As biochar continues to gain recognition as a promising material for sustainable applications, its environmental performance and economic viability have become focal points in research (Masud et al., 2023). Despite the growing interest in this area, a discernible gap persists in the literature regarding the viability of biochar and comparative analyses of different technologies and feedstocks (Khan et al., 2021; Kochanek et al., 2022). Biochar remains a relatively novel material in industrial applications, and its commercial production is being investigated through emerging technologies. Production facilities vary widely in scale, from small units to larger, centralised operations; however, most of the existing literature focuses primarily on laboratory-scale case studies (Youngsang et al., 2021). The production technologies are at different stages of development, with most currently falling within Technology Readiness Levels (TRL) 3 to 7, suggesting that further validation, demonstration, and scaling are still required before full industrial implementation (Sesko et al., 2015). This study provides valuable insights into the environmental and economic impacts of biomass gasification within a pilot-scale plant setting.

A key finding of this research is that the yield of biochar production, in terms of the combined resources required, is crucial for determining the viability of the process. For the feedstocks evaluated, the yield of biochar production from SEG processing of agricultural waste is reasonably higher than that derived from sewage sludge. This observation is consistent with the findings of Ahmed et al., 2016, which discusses the variability in efficiencies across different input matrices. Overall, the LCA results support the use of grape seeds as a more environmentally friendly option compared to sewage sludge for biochar production. The comparison of allocated and expanded production systems reveals that the grape seeds feedstock consistently outperforms sewage sludge, with the exception of the marine eutrophication impact category. Nevertheless, thermal treatment of sewage sludge has been demonstrated to offer environmental advantages over its direct application (Rydgård et al., 2024). The economic analyses confirm the advantages of employing agricultural waste as feedstock for biochar production, compared to sewage sludge. Furthermore, the elasticity value (Accastello et al., 2018) also confirms that the utilisation of grape seeds reduces the vulnerability of the plant's profitability in response to fluctuations in production factors, specifically energy costs.

In terms of environmental performance, this research reveals that the substantial impacts associated with a SEG pilot plant diminish the displacement effects typically attributed to biochar and syngas production. The estimated carbon emissions for producing 1 kg of biochar amount to 17.8 and 11.0 kg CO_2 eq from sewage sludge and grape seeds, respectively. Previous studies have shown varying results regarding biochar production through biomass gasification. Analyses often show negative GWP values for biochar production via gasification (Kim and Kim, 2014; Marzeddu et al., 2021). This discrepancy is primarily due to the absence of electricity input required to achieve gasification temperatures, which is significant in the system studied. Biochar production systems exhibit considerable variability, which is influenced by the production methods and feedstocks used. In addition, Life Cycle Thinking methods are highly susceptible to the established system boundaries, leading to divergent outcomes. The calculation of energy benefits remains a prevalent approach in studies analysing thermal

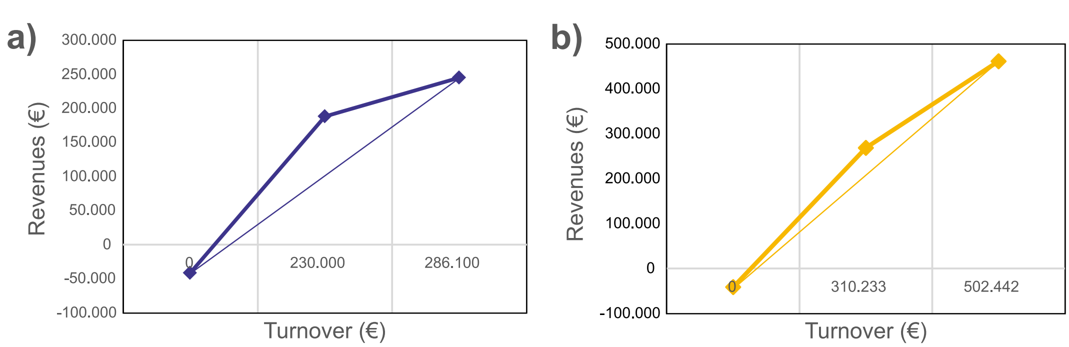

Fig. 1. Break-Even Point generated by biochar using sewage sludge (a) and grape seeds (b). On the x-axis revenues are represented: remaining at zero for zero production, for biochar solely and for the total of biochar and syngas produced. On the y-axis the difference between gross margin and fixed costs is displayed in relation to zero production, biochar alone, and for both biochar and syngas.

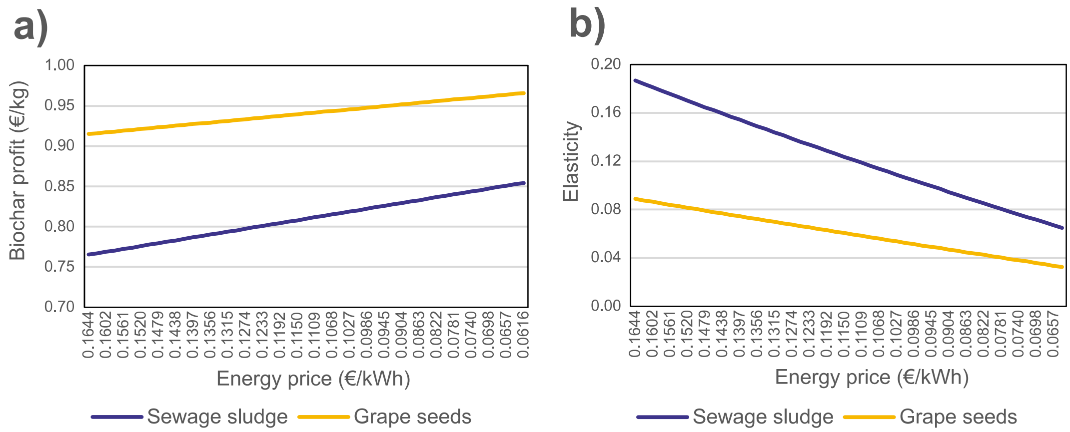

Fig. 2. Trends in profit (a) and elasticity (b) of biochar and syngas produced from sewage sludge and grape seeds in relation to energy price variations.

treatment of biomass (Hamedani et al., 2019; Marzeddu et al., 2021). This approach includes energy substitution from fuel production and thermal energy production, the latter of which was excluded from this research. Likewise, incorporating the environmental benefits associated with the carbon stock of biochar is a consistent practice in this area of research. Overall, previous research has demonstrated the potential for carbon removals through biochar production, although results vary depending on the specific systems and production methods employed. Additional findings from earlier studies are provided in the supplementary materials. The reported values for carbon removals are consistent with the calculations presented in this paper, ranging from 0.98 to 2.2 CO_2 per kg of biochar produced (Hamedani et al., 2019; Marzeddu et al., 2021). In their study, Hammond et al. (2011) estimated higher values for carbon abatement, ranging from 2.1 to 3.9 kg of CO_2 sequestered per kg of biochar, depending on the feedstock and scale of production. It is noteworthy that carbon abatement remains a controversial topic of discussion in biochar production systems. While some academics support the environmental advantages of this application (You & Wang, 2019), others dispute its effectiveness (Matuštík et al., 2021).

The contemporary biochar economy is characterised by small-scale production and limited market demand (Nematian et al., 2021). However, the establishment of new biochar production facilities may be encouraged by bioeconomy trends that advocate the use of biomass residues as inputs for innovative production processes aimed at yielding valuable products (Huang 2017; Robb et al., 2020; Zhang et al., 2021). These local micro-economies often lack optimal economic efficiency from the management perspective (Nsamba et al., 2015). At the same time, large-scale investments often lead to less profitable outcomes (Maroušek 2014). Therefore, it is paramount to foster local economies, that are able to maximise production yields while utilising readily available waste from the surrounding regions as primary inputs (Maroušek 2014; Keske et al., 2020; Haeldermans et al., 2020; Bergman et al., 2022). The feedstocks studied in this research – sewage sludge and grape seeds – represent two types of waste materials suitable for use in an industrial gasification plant (Agrafioti et al., 2013; Martínez-Gómez et al., 2023). However, the global biochar scenario is evolving and there is currently no established market with proven cost-revenue for this product (Dickinson et al., 2015).

Moreover, the biochar market remains volatile, with prices subject to considerable annual fluctuation and regional fluctuations, further discouraging investment in the sector (Campion et al., 2023; You & Wang, 2019). The selling price of biochar considered in this paper is in line with estimates from Groot et al., 2018 (1600 \$/Mg, updated to 2024 as 1595.74 €/Mg) and Sahoo et al., 2019 (minimum price of biochar 1044 \$/Mg, updated to 2024 as 1070.44 €/Mg). Conversely, the syngas prices reported here are below those documented in the literature (Baena-Moreno et al., 2021) (1.15–1.56 €/Nm^3, updated to 2024: 1.34–1.82 €/Nm^3) while aligning with the data obtained by Intratec 2019 (0.24 \$/Nm^3 updated to 2024: 0.26 €/Nm^3).

The production cost estimates for biochar cited by Nematian et al. (2021) are 1.47 \$/kg (1.49 €/kg updated to 2024) – substantially above our findings – whilr Haeldermans et al. (2020) defined the production cost for biochar at 0.84 \$/kg (0.88 €/kg updated to 2024) similar to our results. Currently, as stated by Nematian et al. (2021), it is challenging to argue that a biochar plant employing waste materials can be profitable. Prospects suggest that the market for biochar will expand, reducing production costs and facilitating greater profitability. A pivotal element will drive the growth of this sector, as evidenced by our findings: the valorisation of waste products within a circular economy framework (Velenturf and Purnell, 2021), which aims to reduce the cost burden of raw materials (Homagain et al., 2016; Nematian et al., 2021).

The geographical location of prospective plants may influence the choice of utilising grape seeds or sewage sludge as feedstock. In Spain, a large proportion of land is devoted to agricultural activities, providing an abundance of agricultural waste suitable for biochar production. New facilities may be strategically established in rural areas with high availability of biomass waste. The planning of biomass treatment plants must also consider the optimisation of feedstock collection, alongside critical resources such as skilled trained personnel (Tang et al., 2024). This scenario encourages significant advances in biochar production from agricultural residues while limiting the growth of municipal and industrial waste use if processing facilities are located far from urban centres. Additionally, the efficient management of labour, one of the main cost components, should be a focal point (Dickinson et al., 2015). Transport and application costs associated with biochar were not considered in this study; however, they warrant consideration in comprehensive supply chain management due to their significant financial implications (Homagain et al., 2016; Sorensen and Lamb, 2018).

5. Conclusions

The production of biochar through gasification represents a promising opportunity for sustainable waste management. This study supports the use of grape seeds over sewage sludge for both environmental and economic considerations. Environmentally, the benefits of biochar and syngas do not fully offset the overall process impacts. Lower productivity during developmental stages negatively affects LCA results. While life cycle cost results are positive, profitability remains highly sensitive to fluctuations in energy prices. The biochar industry currently faces challenges related to scalability and market demand. Future research should focus on energy optimisation, alternative feedstocks, and the long-term benefits of biochar.

CRediT authorship contribution statement

Nuria Goldaraz-Salamero: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Lorenzo Baima:** Writing – original draft, Methodology, Investigation, Formal analysis, Data curation. **Samuel Moles:** Writing – review & editing, Methodology, Investigation. **Jorge Sierra-Pérez:** Writing – review & editing, Validation, Supervision, Methodology, Conceptualization. **Isabel Martínez:** Writing – review & editing, Validation. **Ramón Murillo:** Writing – review & editing, Validation. **Filippo Brun:** Writing – review & editing, Validation, Supervision. **Simone Blanc:** Writing – review & editing, Validation, Supervision, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.biortech.2025.132772.

Data availability

Data will be made available on request.

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