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Atmospheric carbon removal *via* industrial biochar systems: A techno-economic-environmental study

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ABSTRACT

It is critical to develop carbon removal projects that are both effective and financially viable. Herein, we investigated the carbon removal potential of an industrial biochar system in Spain. This study is the first to assess the techno-economic-environmental impact of large-scale olive tree pruning residue pyrolysis for atmospheric carbon removal, using an integrated assessment framework that is based on current market dynamics. Production optimization using response surface methodology (RSM) was carried out, aiming to maximize yield, production throughput and stable carbon content while prioritizing stability. It was determined that optimized biochar production was attained at 650 °C and 15 min residence time. Furthermore, a biochar plant with a biomass processing capacity of 6.5 tonnes-per-hour was designed for further analysis. A thermodynamic model was developed using Advanced System for Process Engineering (ASPEN Plus) software, and the process was determined to be self-sufficient with the availability of surplus energy. Moreover, a life cycle assessment (cradle-to-grave) revealed that approximately 2.68 tCO_2e are permanently removed from the atmosphere per tonne of biochar produced, after accounting for the carbon footprint of the entire process. This corresponds to a carbon removal capacity of 3.26 tCO_2e per hour and the removal of approximately 24,450 tCO_2e annually. The economic assessment revealed that the project is profitable; however, profitability is sensitive to pricing of the carbon removal service and biochar. A project internal rate of return (IRR) of 22.35% is achieved at a price combination of EUR 110/tonne CO_2e removal and EUR 350/tonne biochar, and a feedstock cost of 45 EUR/tonne (delivered with 20% moisture content), where service and product pricing are both within the lower bound of market pricing. If the project was exclusively designed to offer a carbon removal service, a minimum price of EUR 206/tonne CO_2e removal is required to achieve project profitability, based on the same feedstock cost. The findings of this study demonstrate the viability of immediately deploying large-scale biochar-based carbon removal via pyrolytic conversion of olive tree pruning residues to address the climate crisis.

1. Introduction

The present global efforts to tackle climate change stipulate an objective of limiting global temperature rise to 2 °C by the end of the century while pursuing measures to keep it below 1.5 °C (Fawzy et al., 2020). However, there is growing evidence that existing emission reduction efforts, as well as future emission reduction commitments announced globally are not sufficient to meet the targets set by the Paris agreement in 2015(Lawrence et al., 2018; Nieto et al., 2018). The integration of carbon removal efforts along with emission reduction is critical to curb global temperatures over the coming decades(Fawzy et al., 2020).

Given the current state of climate emergency, it is critical to develop carbon removal projects that are both effective and financially viable. Biochar has been highlighted as a promising technology that facilitates the capture, utilization, and storage of atmospheric carbon (Fawzy et al., 2021; Woolf et al., 2010). Presently, carbon removal services through biochar are available via voluntary sophisticated marketplaces that demand rigorous certification, lending confidence to the services

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List of abbreviations

ANOVA	Analysis of variance
ASPEN Plus	Advanced System for Process Engineering
$CaCO_3$	Calcium carbonate
CCD	Central composite design
CORC	CO_2 removal certificate
DCF	Discounted cash flow
DoE	Design of experiments
DPBP	Discounted payback period
EBC	European biochar certificate
FTIR	Fourier transform infrared spectroscopy
IRR	Internal rate of return
LCA	Life cycle analysis
NPV	Net present value
OTPR	Olive tree pruning residues
PAHs	Polycyclic aromatic hydrocarbons
RSM	Response surface methodology
SEM	Scanning Electron Microscopy
XPS	X-ray photoelectron spectroscopy
XRD	X-ray powdered diffraction

provided. To successfully design and establish biochar-based carbon removal systems, it is fundamental to create a product that meets environmental standards and application-specific requirements, achieve carbon stability and permanence, and, most importantly, attain economic feasibility. This is very specific to the feedstock selected and carbon reservoir targeted, and the local conditions of the project location.

Globally, it is estimated that around 33 million tonnes of olive tree pruning residues (OTPR) are generated annually, with a large concentration in the Mediterranean area (Cuevas et al., 2019; González Arias et al., 2020). Valorization routes for OTPR have been investigated thoroughly in the literature covering energy, bioconversion into edible mushrooms, composting, biorefining for ethanol, the production of cellulose nanofibers and the conversion into various intermediate chemicals (Abou Fayssal et al., 2020; Contreras et al., 2020; García Martín et al., 2020; González Arias et al., 2020; Manzanares et al., 2017; Martín-Lara et al., 2017; Rivas et al., 2021; Sánchez-Gutiérrez et al., 2020). However, the pyrolytic conversion of OTPR to produce biochar for the purpose of atmospheric carbon removal, is yet to be explored, and is an attractive approach that strongly supports the circular economy and offers various environmental and social advantages (Fawzy et al., 2021).

Various life cycle analysis (LCA) studies have been conducted for the pyrolytic production of biochar. Yang et al. investigated country-level potential of biochar carbon sequestration in China using a variety of highly available crops and concluded that over 0.92 tCO_2e could be removed by converting 1 tonne of agricultural residues into biochar (Yang et al., 2021). Lefebvre et al. investigated the pyrolytic conversion of sugarcane residues to biochar using an LCA and identified the potential of removing 36 million tCO_2e annually in the state of Sao Paulo, Brazil, if 100% of such residues are allocated to biochar production (Lefebvre et al., 2021). Furthermore, Munoz et al. studied the environmental effects of a biochar-soil system using biochar derived from agricultural and forestry residues and produced at 3 different temperatures (300, 400 and 500 °C). The authors concluded that the highest carbon sequestration potential was 2.74 tCO_2e per tonne of biochar produced when forestry residues were converted at 500 °C (Muñoz et al., 2017). A recent study by Zhu et al. extensively reviewed and contrasted numerous LCA studies of biochar production from a range of agricultural residues. The authors noted the difficulty in directly comparing results due to variations in functional units and system boundaries, but despite these challenges, the sequestration potential of biochar systems has been highlighted as remarkably promising (Zhu et al., 2022).

Furthermore, techno-economic studies have also been conducted on biochar production, presenting a wide range of results based on feedstocks, scale of technology deployed and location-specific costs. Most techno-economic studies focus on identifying biochar production costs or assess economic feasibility of biochar production without taking into account the carbon removal aspect that has recently emerged as a new market and a potential major revenue stream (Haeldermans et al., 2020; Nematian et al., 2021; Zhang et al., 2017). Since biochar has been widely acknowledged as a viable carbon removal technology, it is vital to incorporate the carbon removal potential of such systems into project assessments. As a result, production optimization to promote carbon removal and the deployment of an integrated techno-economic-environmental evaluation framework is critical moving forward.

In this study, atmospheric carbon removal via biochar production, based on OTPR, will be holistically investigated. Initially, biochar is produced at optimized conditions using a pilot-scale continuous pyrolysis unit, and the biochar is characterized. Based on the experimental results, a thermodynamic model for a commercial-scale biochar production plant is developed for further analysis. In addition, a life cycle assessment is conducted, and the carbon removal potential of the system is estimated utilizing a protocol used for the commercial issuance of carbon removal certificates. Moreover, an economic analysis is carried out to quantify carbon removal costs and evaluate the system's overall economic feasibility. It is important to note that economic feasibility is highly dependent on the specific conditions and costs associated with the location of the project, the feedstocks used, and the investment requirements of the technology deployed. To the best of the authors' knowledge, this study is the first to assess the techno-economic-environmental impact of large-scale OTPR pyrolysis for atmospheric carbon removal in Spain, using an integrated assessment framework that is based on current market dynamis.

2. Methods

A holistic approach is deployed to assess the carbon removal potential of an industrial biochar system. The methodology includes i) biochar production and optimization, ii) characterization, iii) plant design and process modelling, iv) life cycle assessment, v) carbon removal quantification, and vi) economic assessment.

2.1. Biochar production and optimization

2.1.1. Material preparation

Olive tree pruning residues (OTPR) were procured from an agricultural waste management facility, where the feedstock was delivered in chipped form with approximately 15-20 wt% moisture content, and an average particle size of 30 mm diameter and 150 mm length. The average dry bulk density of the delivered material was approximately 152 kg/m^3. The material mainly contained a woody fraction as well as leaves, and a small amount of dust and stones. The material was sieved to remove dust and stones and was left to dry naturally to a moisture content of approximately 6-8 wt%. Furthermore, a hammer mill was used to reduce the average particle size to less than 6 mm diameter, to allow for a more homogenous material for enhanced conversion efficiency as well as increase bulk density to increase throughput capacity. An average dry bulk density of 302 kg/m^3 was attained after size reduction.

2.1.2. Biochar production

A continuous screw-based pyrolysis system was utilized for experimental purposes. The system is composed of a material silo, a screw-based feeding system, a second material silo (buffer), a pyrolysis reactor (diameter of 133 mm and length of 2260 mm) equipped with a shaftless screw, discharge tank, discharge cooling screw, biochar holding tank, condenser, as well as a gas filtration and combustion system. The reactor is equipped with 4 heating zones that are controlled separately using temperature controllers with a regulation precision of ±1 °C, and the discharge tank is also heated separately with temperature control. The pyrolysis system can be adjusted accordingly with a temperature range of 200–900 °C. The heated areas are well insulated using ceramic fibre. Furthermore, the feeding and discharge conveying systems and the reactor screw are controlled using frequency converters to adjust for material flow rate and residence time in the reactor, respectively. Separate experiments were conducted to estimate average residence time in the reactor based on various reactor motor frequencies. In addition, to prevent air from entering the system, the unit is equipped with 2 pneumatic knife gate valves at the lower end of the material silo and the discharge tank. A high temperature induced draft fan is situated towards the end of the process to regulate pressure as well as flush air out of the system prior to starting the operation. Moreover, the system is operated at a slight negative pressure. Fig. S1 presents a schematic of the continuous pyrolysis system utilized.

2.1.3. Optimization – response surface methodology (RSM)

The Design of Experiments (DoE) method (Design-Expert V.13 software, Statease Inc.) was used to evaluate the effect of critical process parameters on the pyrolysis of OTPR to produce biochar. Response surface methodology (RSM) analysis was employed to design experimental runs using the Central Composite Design (CCD) approach. RSM is a well-established statistical technique for predicting and optimizing response variables. The objective of the optimization work herein is to maximize system carbon removal potential, taking into account feedstock conversion efficiency, carbon stability and production throughput. Biochar yield (%), stable carbon content (%) and biochar throughput (kg/h) were selected as responses, and the process parameters were optimized to maximize these values.

Eqs. (1)–(3) explain the calculations used to assess biochar yield, biochar throughput, and stable carbon content, respectively. The pyrolysis temperature and residence time were chosen as the investigated parameters, with each being considered with low and high coded values of 500/750 °C and ~15/37 min (corresponding to reactor motor frequency of 25/10 Hz), respectively. Furthermore, the maximum and minimum values (-alpha and + alpha) determined by the software were 448/802 °C and ~13.2/54.1 min (corresponding to reactor motor frequency of 28.1/6.9 Hz), respectively. A total of 13 runs were suggested by the software, including 5 centre point replicates. Each experiment was based on the conversion of ~7 kg of OTPR biomass with an average moisture content of 6-8%. The results are then evaluated using analysis of variance (ANOVA) to identify and construct relationships between the control parameters and the response variables for subsequent predictions and optimization. Model selection was based on software recommendations, where further model reduction was carried out based on term significance. For optimization, stable carbon content was set to an importance level of 5, as compared to biochar yield and throughput which were set to a level of 3.

2.1.3.1. Biochar yield calculation.

$$\text{Biochar yield (\%dry basis)} = \frac{\text{Biochar weight} \times (100 - \text{Moisture}_{\text{biochar}})\%}{\text{Raw biomass weight} \times (100 - \text{Moisture}_{\text{raw biomass}})\%} \quad \text{(Eq. 1)}$$

2.1.3.2. Biochar throughput calculation

$$\text{Biochar throughput} = \text{Biochar weight} \times (100 - \text{Moisture}_{\text{biochar}})\% \times \frac{60}{\text{Experiment time in minutes}} \quad \text{(Eq. 2)}$$

2.1.3.3. Stable carbon content calculation

$$\text{Stable carbon content } (\%_{\text{dry basis}}) = C_{\text{org } \%\text{dry basis}} \times F_p^{\text{TH,Ts}} \quad \text{(Eq. 3)}$$

where C_{org} % is the organic carbon content on a dry basis and $F_p^{TH,Ts}$ is the permanence factor of biochar organic carbon over a given time horizon TH and a specified soil temperature Ts. The permanence factor is computed according to Puro.earth methodology, where $F_p^{TH,}$ is a function of the H/C_{org} molar ratio and follows the relationship provided in Eq. (4)(Puro.earth, 2022).

$$F_p^{\text{TH,Ts}} = c + m \times \frac{H}{C_{org}} \quad \text{(Eq. 4)}$$

For this analysis a global mean soil temperature of 14.9 °C is used, where c = 1.04 and m = −0.64. These regression coefficients estimate carbon stability for a time horizon of 100 years. The H/C_{org} molar ratio is computed using Eq. (5).

$$\frac{H}{C_{org}}(molar) = \frac{m_H(\%)}{m_C(\%)} \times \frac{M_C\ (g\ mol^{-1})}{M_H\ (g\ mol^{-1})} = \frac{m_H(\%)}{m_C(\%)} \times \frac{12}{1.0} \quad \text{(Eq. 5)}$$

Given the low inorganic carbon content of low-ash biochar, it was assumed that the organic carbon content (C_{org} %) of the OTPR biochar was equivalent to the total carbon content (C%) obtained by ultimate analysis.

2.2. Biochar characterization techniques

The biochar produced under optimized conditions was analyzed by Eurofins laboratories, which is a laboratory accredited by the European Biochar Certificate (EBC) foundation. A complete EBC analysis was carried out to investigate the overall quality of the biochar and to ensure that EBC requirements are met. This includes an ultimate analysis (CHNSO), identifying the organic carbon content, and computing the H/C and O/C molar ratios that represent stability. Furthermore, pH, conductivity, water holding capacity, surface area, ash content, bulk density, moisture content, nutrient content, trace metals and polycyclic aromatic hydrocarbons were included in the analysis. Table S1 in the supplementary material presents the methods/standards used for the analyses. Furthermore, XRD, FTIR, XPS and SEM analyses were conducted, and details of the equipment used can be found in the supplementary material.

2.3. Biochar plant design and modelling

Based on the optimized production parameters, a hypothetical biochar plant is designed with a biomass throughput capacity of 6500 kg/h. A technology provider was consulted for process flow design and to ensure that the entire plant was adequately sized. The process is based on material being delivered with 20% moisture content and an average dry bulk density of 152 kg/m^3. The process includes pre-cleaning, size reduction to a particle size of 6 mm (which increases the average dry bulk density to approximately 302 kg/m^3), drying, pyrolysis, and

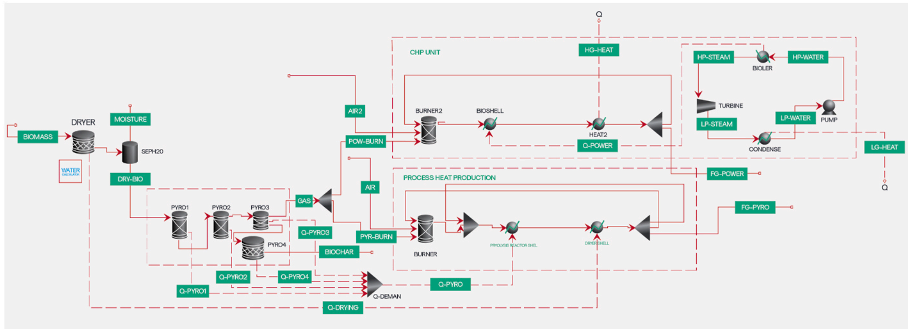

Fig. 1. Reaction process chart representing drying, pyrolysis and combustion, including separation blocks used at various stages of the process as well as the steam-based power production unit.

packaging and is equipped with a control and automation system as well as the necessary conveyors for the entire process. The line is equipped with a rotary dryer, and the pyrolysis reactor is an indirectly heated rotary kiln. The packaging station is designed for packaging jumbo bags. The maximum electric power demand is 441.5 kW_{el} for the complete production line. The plant is equipped with a steam rankine cycle power production unit to cover electrical requirements. In relation to the steady-state operation, the system is conceptually designed to utilize pyrolytic gases to sustain the process. External energy is used during reactor start-up. A process model for the biochar plant is constructed to assess if the process is self-sustaining in terms of energy. In this context, APSEN Plus v11 is deployed to develop a thermodynamic model to simulate the steady-state operation of the hypothetical biochar plant. The analysis provides the overall energy requirements of the process and highlights if the process is a net energy importer or exporter. Details of the process model are presented in the supplementary material. Fig. 1 presents the reaction process chart developed to simulate the biochar production process.

2.4. Life cycle assessment

In this study, a life cycle assessment (LCA) was conducted to analyze the environmental load of the production and use of biochar derived from olive tree pruning residues, specifically global warming potential for a time horizon of 100 years. The LCA was conducted using SimaPro v9 and Ecoinvent database and followed ISO 14040:2006 and ISO 14044:2006 standards.

2.4.1. Goal and scope

Life cycle assessment had a cradle-to-grave attributional approach. The assessment was performed excluding infrastructure processes, and then an additional 20% global warming potential was added to account for infrastructure processes, following findings from Jungbluth et al. (2008). This is because, for most of the data points, such as pyrolysis plant or rankine cycle installation, infrastructure processes are not readily available in the literature. Moreover, an additional 10% buffer was added to account for any measurement errors. Therefore, a total of 30% was added to the calculated results. The functional unit was considered as 1 tonne of biochar (dry basis) produced. Fig. S2 presents the LCA model used in this study.

2.4.2. Inventory analysis

In this study, we did not consider the planting process, and only the olive tree pruning size reduction, transportation and further processing were assessed. It was considered that since the olive tree pruning residues are a waste resource, they do not account for any environmental impacts. This is in line with other life cycle assessment studies based on the conversion of waste-based feedstocks (Aberilla et al., 2019; Al-Mawali et al., 2021; Al-Muhtaseb et al., 2021, 2022; Bacenetti, 2019; Schmidt Rivera et al., 2020; Tanzer et al., 2019). Furthermore, this is also in accordance with Puro's carbon removal quantification protocol (Puro.earth, 2022). The transportation distance of feedstock to the production unit, including the return journey, was conservatively estimated as 600 km. Following the transportation of wet feedstock, it was considered that the moisture removal of 20% would take place. Furthermore, it was assumed that the plant is equipped with a steam rankine cycle power production unit to cover electrical requirements. Concerning steady-state operation, the system is conceptually designed to utilize pyrolytic gases to sustain the process. External energy in the form of natural gas is used only during reactor start-up. Greenhouse gas emissions were accounted for transportation of a mobile shredding unit four times a year and diesel consumption for running to reduce feedstock size at 18.4 kWh/t of feedstock treated following Wargula et al. (Warguła et al., 2022).

Furthermore, greenhouse gas emissions for feeding crushed olive pruning to the pyrolysis plant by a wheel loader were modelled according to Jassim et al. (2019). Moreover, it was assumed that the pyrolysis plant would need the heat-up duty in the form of natural gas for a total of 120 min in a year for starting up the process. Process water was used in an amount of 250 kg for raising the moisture content of 1 tonne of produced biochar. Packaging used for packaging 1 tonne of biochar was modelled according to an LCA prepared by a commercial biochar producer (Carbofex.fi, 2022). Greenhouse emissions incurred due to using a forklift truck for handling biochar were parametrized according to Fuc et al., assuming an operating distance of 100 m (Fuc et al., 2016).

Similar to feedstock transportation, a distance of 600 km (including return journey) was accounted for biochar transportation to farms for application. Biochar application was considered as 2.5 t/ha in close range with a recent study in Norway (Tisserant et al., 2022). Greenhouse gas emissions due to fertilizing by broadcaster and tillage, harrowing by rotary harrow were calculated according to ISU (2016) (Table S3).

2.5. Carbon removal quantification

Puro.earth's protocol for calculating the net amount of carbon dioxide removed over a 100-year period is used in this study(Puro.earth, 2022). Eq. (6) is used to calculate the amount of CO_2 sequestered per tonne of biochar over a 100-year time horizon, taking into consideration the biochar's life cycle greenhouse gas emissions associated with its supply of feedstock, production and use. According to Puro.earth, each carbon removal certificate (CORC) represents 1 tonne of sequestered CO_2.

$$\text{CORCS} = E_{stored} - E_{biomass} - E_{production} - E_{use} \quad \text{(Eq. 6)}$$

where E_{stored} is the amount of CO_2 sequestered over a 100-year period per amount of biochar produced, $E_{biomass}$ represents the emissions arising from the production and supply of the feedstock to the production facility, $E_{production}$ are the emissions arising from the conversion of the biomass into biochar, and E_{use} represents the emissions arising from

Table 1
Presents the design of experiments, operational factors and the experimental results of the response parameters.

Std	Run	Factor 1	Factor 2	Response 1	Response 2	Response 3
		A:Temperature	B: Reactor Frequency	Biochar yield	Biochar throughput	Stable carbon content
		°C	Hz	%	kg/h	%
10	1	625	17.5	23.75	1.60	72.09
5	2	448	17.5	29.17	1.97	59.82
13	3	625	17.5	23.89	1.61	74.65
11	4	625	17.5	23.96	1.62	74.22
2	5	750	10	20.26	0.77	77.59
1	6	500	10	25.73	1.01	68.00
12	7	625	17.5	23.52	1.59	75.62
7	8	625	6.9	22.55	0.52	78.29
3	9	500	25	26.78	2.72	62.08
9	10	625	17.5	23.44	1.58	74.51
8	11	625	28.1	24.07	2.67	74.07
6	12	802	17.5	20.20	1.37	81.52
4	13	750	25	21.04	2.04	80.43

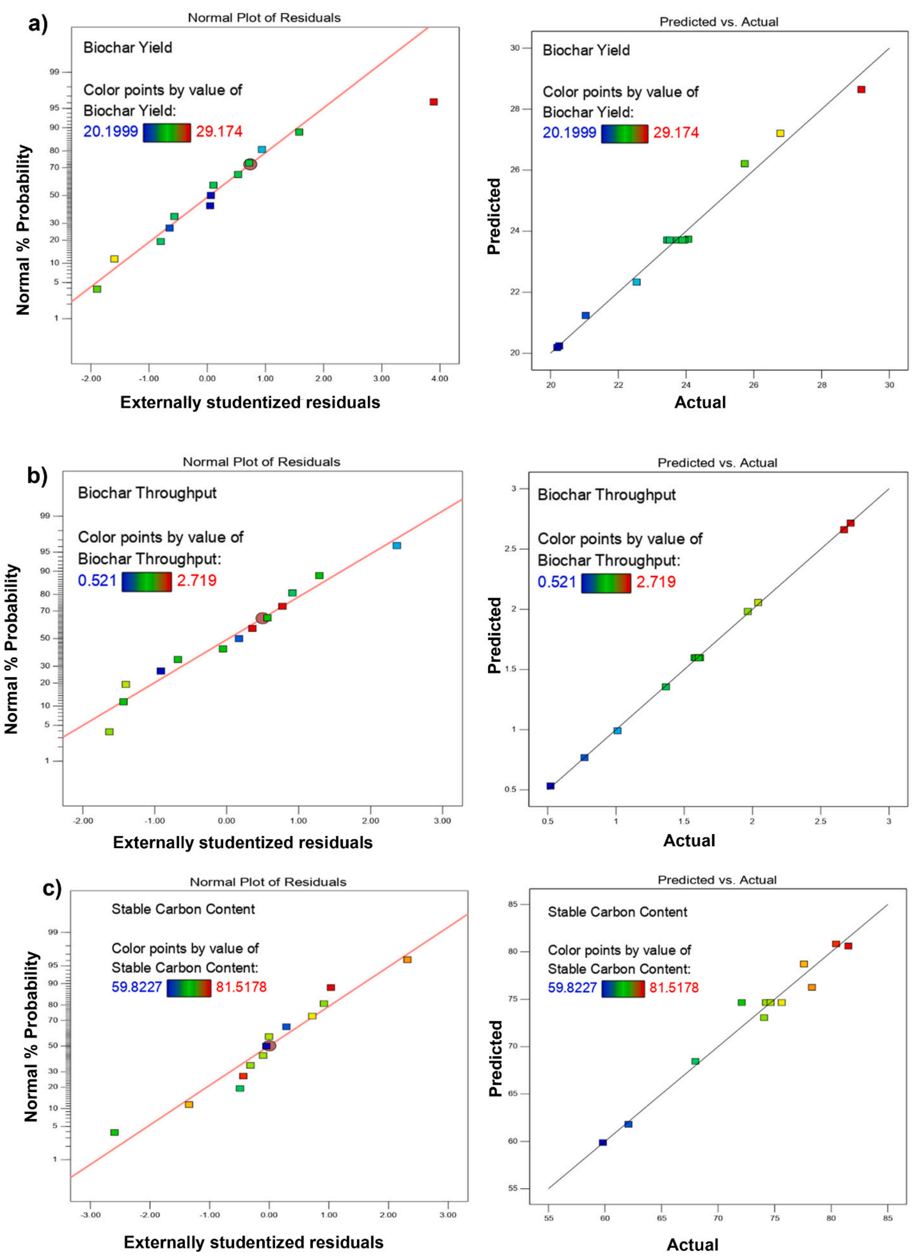

Fig. 2. Diagnostic plots for (a) biochar yield, (b) biochar throughput and (c) stable carbon yield.

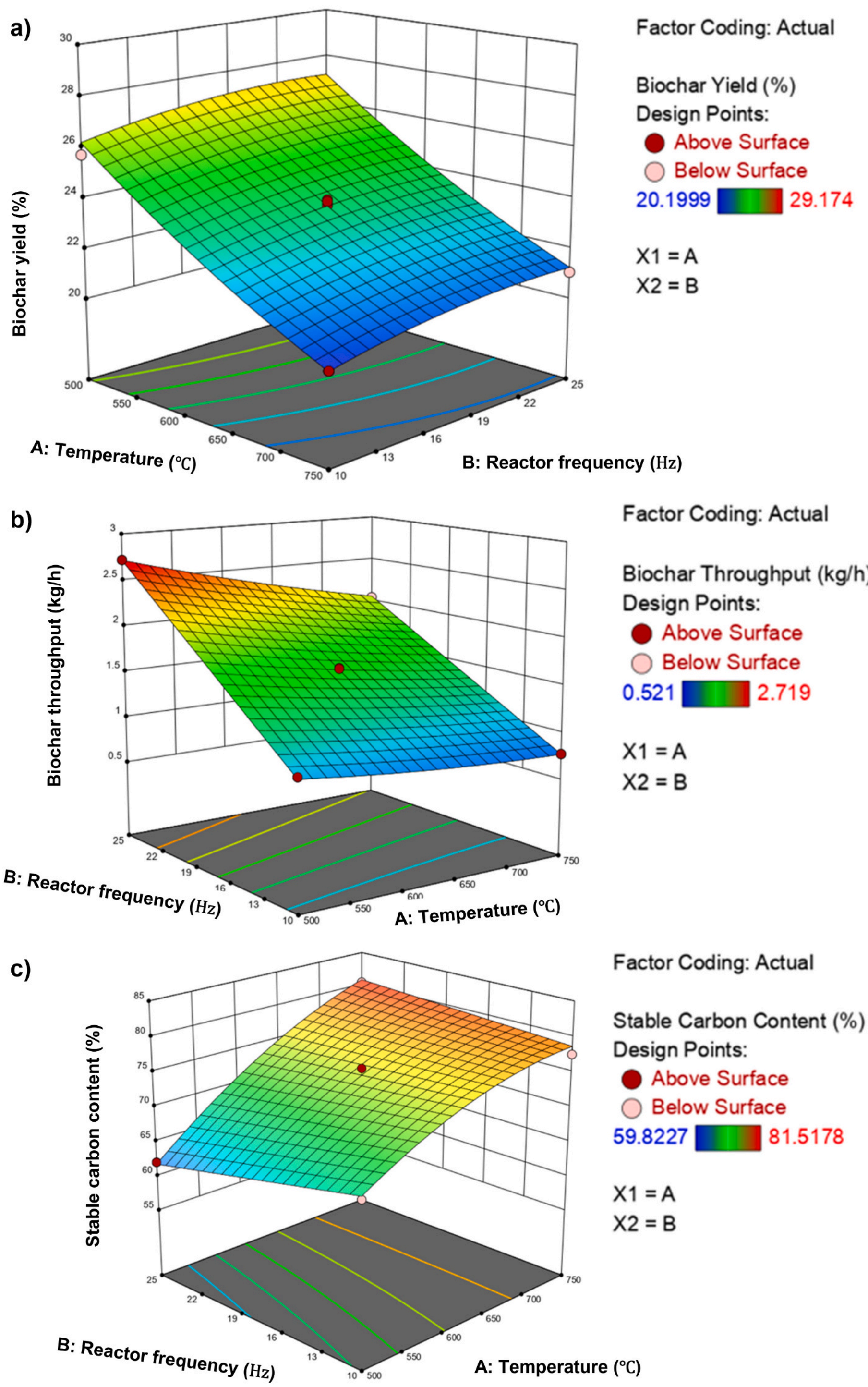

Fig. 3. Relationship between operating conditions and (a) biochar yield, (b) biochar throughput and (c) stable carbon content.

the transportation and final use of the biochar. In this study, carbon removal quantification is based on 1 tonne of biochar produced. Eq. (7) is used to compute E_{stored}, while values for $E_{biomass}$, $E_{production}$ and E_{use} are derived from the life cycle analysis results.

$$E_{stored} = Q_{biochar} \times C_{biocharorg}C_{biochar} \times F_p^{TH,T_s} \times \frac{44}{12} \quad \text{(Eq. 7)}$$

where $Q_{biochar}$ is the amount of biochar produced, $C_{biocharorg}C_{biochar}$ is the organic carbon content in the biochar, $F_p^{TH,Ts}$ is the permanence factor of the organic carbon fraction in the biochar over a specified time horizon and soil temperature. Eq. (4) is used to compute F_p^{TH}, based on a time horizon of 100 years and an annual mean soil temperature of 14.9 °C.

2.6. Economic modelling

The economic model was developed using Invest for Excel ® V4.0 (Datapartner, Finland), a software solution designed for capital budgeting, financial modelling and valuations. The model is based on the discounted cash flow (DCF) method, where the analysis includes computing the net present value (NPV) of the project, the internal rate of return (IRR) as well as the discounted payback period (DPBP), which are determined by discounting a stream of future cashflows at an appropriate rate that typically denotes the cost of capital. Eqs. (8)–(10) are employed to compute the NPV, IRR and DPBP, respectively(Datapartner, 2022). Additionally, the minimum selling price per tonne of CO_2 removed is determined under a variety of scenarios by computing the carbon removal price at which the project yields an NPV = 0. Moreover, the minimum selling price per tonne of biochar is also determined under a variety of feedstock and carbon removal service pricing. Finally, carbon removal costs (NPV = 0) are determined assuming the project is designed to exclusively offer a carbon removal service, without considering the sale of the physical product.

The NPV computed in the analysis is static since it assumes constant values for all variables involved. However, variables such as biochar and carbon removal certificate prices, operating expenses, as well as capital expenditure cannot be considered to remain constant, as they change in practice. A Monte Carlo analysis is used to determine the influence of these varying factors on the NPV and to compute a probability for the project to achieve a positive NPV. A preliminary sensitivity analysis for all variables included in the calculation of the cash flows is carried out to determine the main variables that highly influence the project's profitability. These variables are then selected for the Monte Carlo simulation. Details of the economic model assumptions are presented in the supplementary material.

$$NPV = \sum_{t=0}^{N} FCF_t \times (1+r)^{-t} \quad \text{(Eq. 8)}$$

where FCF (t) = free cash flow in period t, t = period, r = discount rate per period, N = number of periods, and for residual values t = N.

$$0 = NPV = \sum_{t=0}^{N} FCF_t \times (1+IRR)^{-t} \quad \text{(Eq. 9)}$$

where FCF (t) = free cash flow in period t, t = period, IRR = internal rate of return (per period), and N = number of periods.

$$Payback\ time\ (years) = \frac{The\ number\ of\ periods\ (t) for\ which\ NPV = 0}{\frac{12}{Duration\ of\ period\ in\ months}} \quad \text{(Eq. 10)}$$

3. Results and discussion

3.1. Biochar production and optimization

Table 1 presents the results obtained through the experimental work carried out. It can be noted that a range of 20.2–29.17% was achieved for biochar yield, while biochar throughput ranged from 0.52 to 2.67 kg/h. Furthermore, the stable carbon content attained in the various experiments ranged from 59.82 to 81.52%. The biochar yield results are in agreement with the range reported in the literature of ~21–36% between 400 and 800 °C for OTPR pyrolysis(Abenavoli et al., 2016; Sánchez-García et al., 2019; Zabaniotou et al., 2014).

The results from the experimental runs were then statistically analyzed using ANOVA. Tables S4, S5 and S6 in the supplementary material present the ANOVA analysis results for biochar yield, biochar throughput and stable carbon content, respectively. As noted, a reduced quadratic model was constructed for each of these response variables, based on significant terms, where all models developed were statistically significant (p-value < 0.0001). Furthermore, the lack of fit test was non-significant for all models with a p-value of 0.0935, 0.4318 and 0.4075 for yield, throughput and stable carbon content, respectively, which is highly desired. Regarding feedstock conversion efficiency, the temperature was determined to be the parameter with the highest impact on yield, as shown by the F-value of 525.36, which is significantly higher than all other terms. The model exhibited a high adjusted R^2 value of 0.9786 and a predicted R^2 value of 0.9405. In relation to biochar

Table 2
European biochar certificate analysis results.

Parameter	Unit	As received	Dry basis
Biochar properties			
Bulk density	kg/m^3	–	177
Specific surface (BET)	m^2/g	–	341.53
Water holding capacity (WHC) < 2 mm	%	–	145.8
Moisture	% (w/w)	1.7	–
Ash content (550 °C)	% (w/w)	10.4	10.6
Total carbon	% (w/w)	83.9	85.4
Carbon (organic)	% (w/w)	83.4	84.9
Hydrogen	% (w/w)	1.2	1.3
Total nitrogen	% (w/w)	0.84	0.86
Sulphur (S), total	% (w/w)	0.08	0.08
Oxygen	% (w/w)	4.5	4.5
Total inorganic carbon (TIC)	% (w/w)	0.5	0.5
carbonate-CO_2	% (w/w)	1.7	1.7
H/C ratio (molar)		0.17	0.18
H/Corg ratio (molar)		0.18	0.18
O/C ratio (molar)		0.04	0.04
pH in $CaCl_2$		9.8	–
salt content	g/kg	16.7	–
salt content	g/l	2.96	–
Conductivity at 1,2 t pressure	mS/cm	–	75
Conductivity at 2 t pressure	mS/cm		97
Conductivity at 3 t pressure	mS/cm		120
Conductivity at 4 t pressure	mS/cm		130
Conductivity at 5 t pressure	mS/cm		150
Trace metals			
Arsenic (As)	mg/kg	–	<0.8
Lead (Pb)	mg/kg	–	<2
Cadmium (Cd)	mg/kg	–	<0.2
Copper (Cu)	mg/kg	–	28
Nickel (Ni)	mg/kg	–	3
Mercury (Hg)	mg/kg	–	<0.07
Zinc (Zn)	mg/kg	–	22
Chromium (Cr)	mg/kg	–	6
Boron (B)	mg/kg	–	29
Manganese (Mn)	mg/kg	–	35

(continued on next page)

Table 2 (*continued*)

Parameter	Unit	As received	Dry basis
Silver (Ag)	mg/kg	–	<5
Nutritional elements			
Calcium as CaO	% (w/w)	–	25.3
Iron as Fe_2O_3	% (w/w)	–	0.9
Potassium as K_2O	% (w/w)	–	20.5
Magnesium as MgO	% (w/w)	–	3.4
Sodium as Na_2O	% (w/w)	–	6.1
Phosphorus as P_2O_5	% (w/w)	–	10.9
Sulphur as SO_3	% (w/w)	–	1.6
Silicon as SiO_2	% (w/w)	–	5.5
Macronutrients			
Total nitrogen	g/kg	8.4	8.6
Phosphorus as P_2O_5	g/kg	–	11.6
Potassium as K_2O	g/kg	–	21.7
Calcium as CaO	g/kg	–	26.8
Magnesium as MgO	g/kg	–	3.5
Sodium as Na_2O	g/kg	–	6.5
Sulphur as SO_3	g/kg	–	1.7
Iron (Fe)	g/kg	–	0.7
Silicon (Si)	g/kg	–	2.7
Organic contaminants			
Naphthalene	mg/kg	–	1.1
Acenaphthylene	mg/kg	–	0.2
Acenaphthene	mg/kg	–	<0.1
Fluorene	mg/kg	–	<0.1
Phenanthrene	mg/kg	–	0.6
Anthracene	mg/kg	–	0.1
Fluoranthene	mg/kg	–	0.3
Pyrene	mg/kg	–	0.2
Benz(a)anthracene	mg/kg	–	<0.1
Chrysene	mg/kg	–	<0.1
Benzo(b)fluoranthene	mg/kg	–	<0.1
Benzo(k)fluoranthene	mg/kg	–	<0.1
Benzo(a)pyrene	mg/kg	–	<0.1
Indeno(1,2,3-cd)pyrene	mg/kg	–	<0.1
Dibenz(a,h)anthracene	mg/kg	–	<0.1
Benzo(g,h,i)perylene	mg/kg	–	<0.1
Total 8 EFSA-EPA excl. LOQ	mg/kg	–	Not calculatable as all results are less than level of quantification
Total 16 EPA-PAH excl. LOQ	mg/kg	–	2.5
Benzo(e)pyrene	mg/kg	–	<0.1
Benzo-(j)-fluoranthene	mg/kg	–	<0.1

throughput, residence time, as represented by reactor frequency, exhibited the highest impact on this variable, followed by temperature, as demonstrated by the F-values of 16466 and 1419.6, respectively. Once again, the model presented a high adjusted R^2 value of 0.9993 and a predicted R^2 value of 0.9984. Regarding stable carbon content, the temperature had the highest impact on carbon stability, with the highest F-value of 222.71. Residence time didn't have a significant impact, as demonstrated by its low F-value of 5.31 and significance (p-value = 0.0502). Moreover, the fit statistics show a predicted R^2 value of 0.9226, which is in reasonable agreement with the adjusted R^2 value of 0.9545.

Fig. 2a-c and 3(a-c) present the diagnostic plots and 3D model graphs for yield, throughput and stable carbon content, respectively. As noted, the diagnostic plots for the three variables show well-distributed residuals and consistent predicted vs actual results, indicating that the three models adequately represent the relationship between the processing parameters and the response variables and are reliable for generating predictions. Fig. 3a demonstrates the impact of the interrelationship between temperature and residence time on biochar yield. As shown, temperature negatively impacts yield, where the highest yields are observed at a temperature of 500 °C. Residence time also has an impact on yield, however not as significant as temperature, where longer residence times (corresponding to lower reactor frequencies) negatively impact yield. The results indicate that the highest yield can be achieved at a temperature of 500 °C and a reactor frequency of 25 Hz (corresponding to ~ 15 min residence time). Furthermore, Fig. 3b presents the impact of temperature and residence time on biochar throughput. As noted, the highest throughput is attained at the lowest temperature of 500 °C and the highest frequency of 25 Hz (corresponding to ~ 15 min residence time). Finally, Fig. 3c indicates a positive relationship between pyrolysis temperature and stable carbon content, where the highest values are attained at 750 °C. Overall, the results demonstrate that the three models constructed are reliable for generating predictions to be utilized for statistical optimization.

Optimization was carried out using the Design-Expert V.13 (Statease, Inc.) optimization function. Importance levels were selected for each of the response variables, where stable carbon content was prioritized and was set to a level 5, and yield, as well as throughput, were set to a level 3. The optimum processing parameters were determined mathematically using the variable weightings selected. Table S7 in the supplementary material presents six solutions that were identified by the software to achieve the highest desirability. A temperature range of 633–650 °C and a reactor frequency of 25 Hz (corresponding to ~ 15 min residence time) were provided by the software to attain maximum values for stable carbon content, biochar yield and throughput while prioritizing carbon stability. At such operating conditions, a yield of 23.3–23.7%, approximately 2.3 kg/h throughput and stable carbon content of 74.1–75.3% can be achieved. In validating the results obtained, solution 6 (649.997 °C and 25 Hz) was selected, representing optimum conditions. The highest temperature was selected to further maximize stable carbon content. Fig. S3 depicts the processing conditions and the predictions of the 3 response variables for the solution selected. Furthermore, an experimental run under optimized conditions was carried out. The results attained under optimized conditions are 23.38%, 2.3 kg/h, and 78.9% for biochar yield, throughput and stable carbon content, respectively. The results for yield and throughput are very close to the predicted mean, while the result for stable carbon content is closer to the upper bound of the prediction interval, as shown in Table S8.

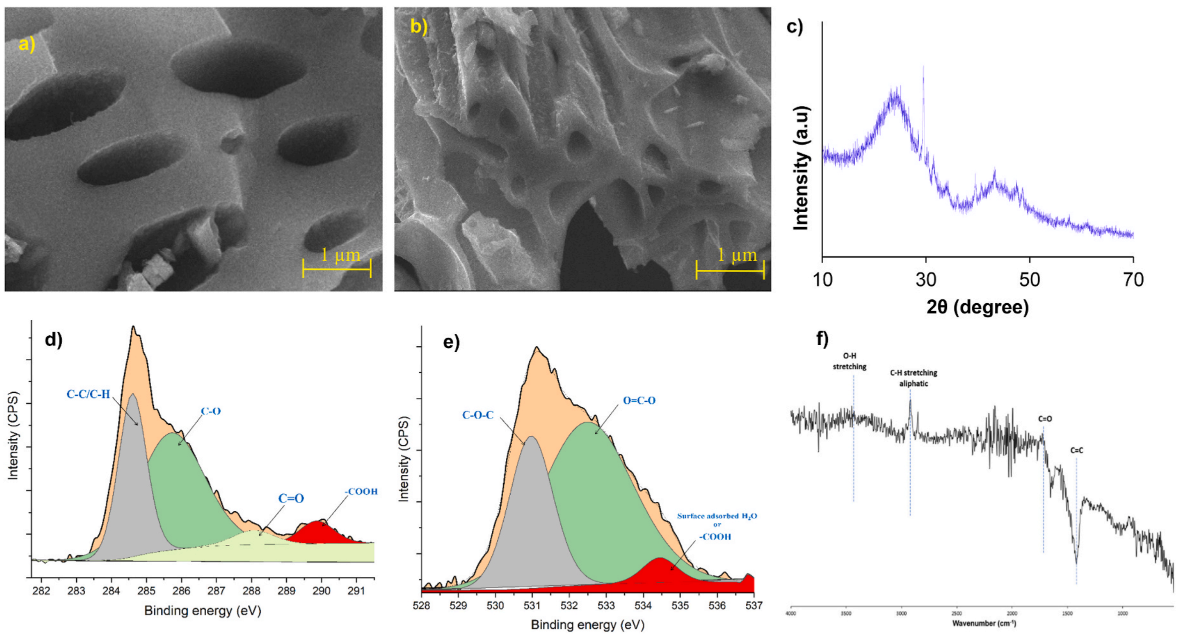

Fig. 4. (a, b) are SEM images, (c) XRD, (d) XPS C*1s*, (e) XPS O*1s* and (f) is the FTIR spectrum of the optimized biochar produced at 650 °C.

3.2. Optimized biochar characterization

Table 2 presents the results of the EBC analysis package carried out by Eurofins laboratories, whereas Table S9 presents the extended results, highlighting the parameters, methodology used, EBC parameter thresholds (if any) and the actual results on an as-received and dry basis. The overall results indicate that the OTPR biochar is of high quality. The elemental composition of biochar reflects the carbon structure and degree of stability. Since nitrogen comprises a negligible proportion of biochar, carbon, hydrogen, and oxygen are the predominant constituents. Oxygen availability is strongly connected to surface functional groups that affect reactivity and promote degradation. Furthermore, the relationship between the concentration of hydrogen and carbon in biochar reveals the degree to which fused aromatic ring structures have been formed, which is an indicator of aromaticity (Leng and Huang, 2018; Leng et al., 2019). Essentially, the biochar exhibits a high carbon content of 85.4%, of which 84.9% is the organic fraction, with high stability as indicated by the H/C_{org} ratio of 0.18 and O/C ratio of 0.04. In comparison to the original feedstock (Table S2), the conversion facilitated an increase in carbon content from 47.83 to 85.4%, while a reduction in hydrogen and oxygen concentrations is observed, significantly improving biochar stability as indicated by the reduction of the H/C and O/C molar ratios from 1.66 to 0.68 to 0.18 and 0.04, respectively. The molar H/C and O/C ratios are the most widely used proxies for carbon stability described in the scientific literature and used by biochar certification authorities to regulate biochar stability. Biochar with lower values for both ratios is more resistant to thermal and biological decomposition(Fawzy et al., 2021). Biochar with H/C ratios lower than 0.2 are considered to be highly stable. Moreover, Spokas examined the durability of biochar in soils and concluded that biochar with a molar O/C ratio of less than 0.2 exhibited a half-life of at least 1000 years (Spokas, 2010). Therefore, it can be concluded that the optimized biochar is highly recalcitrant and can maintain permanence for at least 1000 years.

Furthermore, a decent specific surface area of ~341 m^2/g is noted, along with a water holding capacity of 146%. Additionally, the biochar has a pH of 9.8. The results indicate that EBC certification thresholds are met for all classes in terms of trace metals. For nutrient content, the biochar contains good calcium, potassium and phosphorus concentrations at 26.8, 21.7 and 11.6 g/kg, respectively. Moreover, in terms of organic contamination, the results of the polycyclic aromatic hydrocarbons (PAHs) analysis indicate a total of 2.5 mg/kg for the 16 EPA PAHs. Regarding the 8 EPA PAHs, no contamination was detected. The same applies to the requirements for benzo(e)pyrene and benzo-(j)-fluoranthene, where no contamination was detected. This meets threshold requirements for all certification classes and opens opportunities for using the biochar in multiple applications(Osman et al., 2022a). Further analysis is required if the product is to be used for animal feed. Abenavoli et al. investigated OTPR conversion using high-temperature pyrolysis and characterized the resulting biochar using the EBC analysis framework. In general, the results obtained through this work are consistent with the results reported by Abenavoli et al. however, slight differences, the carbon content of ~90% compared to 85.4% in this study, can be attributed to the pyrolysis unit design (fixed-bed) used by the authors where there is no control of pyrolysis temperature, which may have exceeded the 650 °C used in this study. Furthermore, the residence time may have been longer than the 15 min used herein. The authors did not specifically provide the temperature and residence time deployed in their analysis. However, the pyrolysis unit used is known to operate at a temperature range of 650–700 °C (Rockwood et al., 2020). Moreover, the slight differences related to elemental concentration of nutrients and trace metals can also be attributed to the inherent characteristics of the tree species as well as the cultivation practices related to the feedstocks used in both investigations. However, overall the results obtained in this work are consistent with the results of high-quality OTPR biochar reported in the literature in terms of physicochemical characteristics and low contamination, meeting EBC standards(Abenavoli et al., 2016).

Fig. 4 (a) and (b) show SEM micrographs of the optimized biochar, which revealed a porous structure. This implies that pyrolysis produces a carbonaceous structure, in which the primary porous structure of carbon is formed by the gaps between neighbouring crystallites. According to Scherrer's equation, the particle size was calculated to be 20.35 nm, confirming the formation of nano-biochar. The XRD diffractogram (Fig. 4c) shows the crystallographic plane (002) (JCPDS data 03–0289) at $2\theta = 22°$, while there is a shift to a higher diffraction angle implying a decreased interlayer spacing of the adjacent carbon stack layers. The sharp diffraction line at $2\theta = 29.4°$ is attributed to inorganic $CaCO_3$ within the biochar. The diffraction line at $2\theta = 45°$ (101 plane) corresponds to the amorphous carbonaceous structure in biochar. The XPS

Table 3
Global warming potential caused due to biochar production (1-tonne dry basis).

Process	Emissions ($kgCO_2e$)
Diesel, low-sulphur {Europe without Switzerland}| market for | APOS, S	4.696
Transport, freight, lorry >32 metric ton, euro6 {RER}| market for transport, freight, lorry >32 metric ton, EURO6 | APOS, U	0.003
Transport, freight, lorry >32 metric ton, euro6 {RER}| market for transport, freight, lorry >32 metric ton, EURO6 | APOS, U	72.201
Diesel, low-sulphur {Europe without Switzerland}| market for | APOS, S	0.987
Drinking water, water purification treatment, production mix, at plant, from groundwater {RER} S	0.144
Natural gas, high pressure {Europe without Switzerland}| market group for | APOS, S	0.085
Transport, freight, lorry >32 metric ton, euro6 {RER}| market for transport, freight, lorry >32 metric ton, EURO6 | APOS, S	40.555
Fertilizing, with spreader/broadcaster, 500 l (orchard)/FR U	2.778
Harrowing, with rotary harrow (standard equipment)/FR U	9.458
Polypropylene, granulate {RER}| production | Cut-off, U	12.946
Greenhouse gas emissions due to pyrolysis process and forklift	5.51

spectra of *C1s* and *O1s* from the optimized biochar are shown in Fig. 4d and (e), with the former exhibiting binding energy of 284.6 eV due to C–C and C–H bonding. Additionally, binding energies of 285.8 and 288.2 eV are noted, which are attributed to the carbonyl groups C–O and C═O, respectively. The carboxyl group is responsible for the peak at 290.01 eV (-COOH). The oxygen surface species in the optimized biochar exhibited a peak near 531 eV, which is attributed to C–O–C bonding or hydroxide formation. Furthermore, the analysis exhibits higher binding energy for O═C–C (at 532.6 eV) and a small peak at 534.5 eV, which is attributed to –COOH bonding or adsorbed water on the surface. The findings imply that the biochar's oxide species are abundant and could be used in various applications (Osman et al., 2020). Fig. 4f shows the FTIR of the optimized biochar herein. The absorption band at 3465 cm^{-1} is attributed to the OH stretching, which is possibly related to the remaining hydroxide on the surface of the biochar or water absorbed on the biochar. The aliphatic C–H stretching absorption band at 2918 cm^{-1} is due to the remaining cellulose. i.e., cellulose has not fully decomposed. The results are in agreement with previous work that demonstrated ~95% of cellulose decomposition at 650 °C within 15 min (Osman et al., 2022b). A small shoulder absorption band at 1745 cm^{-1} is attributed to C═O stretching, which includes carbonyl, ketones and carboxylic acids, while the C═C bond stretching band at 1605 cm^{-1} is derived from the lignin's aromatic rings along with the carbonized and aromatized materials within biochar (Chia et al., 2012). The absorption band at 1418 cm^{-1} is ascribed to –COOH stretching.

3.3. Biochar plant design and modelling

The hypothetical plant processes 6500 kg/h of wet feedstock (20% moisture content), which requires ~ 850 kW_{th} for drying the feedstock to a 5% moisture level. Furthermore, ~4076 kW_{th} is required for the pyrolytic conversion process. To cover the thermal energy requirements for drying and pyrolysis, it was determined that 31.26% of the pyrolysis gases generated from the process are required for combustion at ~1000 °C. The remaining fraction (68.74%) is directed toward power and heat production. Combustion of the remaining fraction yields ~10836 kW_{th}. It was determined that the steam power plant (450 kW_{el}) requires ~ 2524 kW_{th} to generate sufficient electrical power to sustain the operation, based on the operating conditions specified. Overall, the process was determined to be self-sustaining, with surplus energy of ~8312 kW_{th} available in the form of high-grade heat (~1000 °C) that can be used for other thermal purposes or to generate additional electric power. In the case of utilizing all the available heat for power generation, approximately ~1932 kW_{el} can be potentially generated, where 450 kW_{el} (to cover plant electrical requirements) are deducted, achieving net power generation of ~1482 kW_{el}.

Furthermore, it is critical to highlight that the modelling results are based on mass yields of ~29% biochar and 71% pyrolysis gas. However, the experimental work determined mass yields of ~23.4 and 76.6% for the solid and gaseous fractions, respectively. The difference in biochar yield between the experimental and simulated results of ~5.6% is consistent with those reported in the literature (Liu et al., 2022). Attaining a lower solid yield experimentally and consequently, a higher gaseous fraction indicates that the process can actually produce more gas for combustion, increasing the amount of potential surplus energy after accounting for drying, pyrolysis, and electric power generation. This signifies that the results obtained from the modelling exercise are conservative and can be utilized for further analysis.

3.4. Life cycle assessment

3.4.1. Environmental impact assessment: global warming potential

Global warming potential for a horizon of 100 years was observed as 149 kg CO_2 equivalent for the production of 1 tonne of biochar utilizing CML-IA baseline v3.06 method. It was noted that the highest global

PROFITABILITY ANALYSIS					
Project description	Spain PyCCS Project				EUR
Nominal value of all investments		5,900,000	Discounted investments		5,900,000
Required rate of return		15.00 %			
Calculation term		16.0	years		1/2023 - 12/2038
Calculation point		1/2023	(In the beginning of period)		
Present value of business cash flows	Nominal	PV	Notes		
± PV of operative cash flow		8,667,169			
+ PV of residual value	2,200,816	235,190			
Present value of business cash flows		**8,902,358**			
- Present value of reinvestments	0	0			
Total Present Value (PV)		**8,902,358**			
Investment proposal	Nominal	PV			
- Proposed investments in assets	-5,900,000	-5,900,000			
+ Investment subventions	0	0			
Investment proposal	-5,900,000	-5,900,000			
Net Present Value (NPV)		**3,002,358**	>= 0	->	profitable
NPV as a monthly annuity		39,381			
Internal Rate of Return (IRR)		22.35%	>= 15 %	->	profitable
Payback time, years		8.0	Based on discounted FCF		
Simple Payback, years		4.7	Based on FCF		
Calculation is made by	Samer Fawzy				5/5/2022

Fig. 5. Base case profitability analysis.

Table 4
Influence of price combinations on project net present value (NPV) and internal rate of return (IRR).

CO2 Removal price / tonne (EUR)	Net present value (NPV) Biochar price/tonne (EUR)				Internal rate of return (IRR) Biochar price/tonne (EUR)			
	0	**200**	**350**	**500**	**0**	**200**	**350**	**500**
70	-16,213,122	-6,743,726	-862,927	4,424,137	-	-	12.60%	25.30%
110	-11,050,729	-2,284,705	3,002,358	8,289,422	-	8.05%	22.35%	32.89%
150	-5,888,336	1,580,580	6,867,643	12,154,707	-	19.10%	30.40%	39.70%
190	-1,603,552	5,445,865	10,732,928	16,019,992	10.14%	27.75%	37.51%	45.97%
230	2,261,733	9,311,150	14,598,213	19,885,277	20.87%	35.21%	43.99%	51.81%

warming potential was caused due to transportation of feedstock and biochar. This is due to the long distances. The second highest impacts were due to packaging, followed by biochar application in the field. As a self-sustaining process, pyrolysis was determined to have negligible impacts in terms of global warming potential. Furthermore, accounting for infrastructure processes as 20% and a 10% buffer (total of 30%), additional global warming impacts leads to a total of **193.7 kg CO_2 equivalent** per tonne of biochar produced (dry basis) (Table 3).

3.5. Carbon removal quantification

According to the Eurofins analysis report, with an organic carbon content of 84.9% and a H/C_{org} molar ratio of 0.18, a total of **2.879 tCO_2e** is embodied per tonne of biochar (dry basis). After accounting for the emissions associated with the supply of feedstock to the production facility, the conversion process and the transportation and final use of the biochar, based on the results obtained through the LCA carried out, a total of **2.6853 tCO_2e** are removed from the atmosphere per tonne of biochar produced. This equates to ~2.68 CO_2 removal certificates (CORCs) being issued per tonne of biochar via the Puro platform. Based on the hypothetical biochar plant production capacity with ~23.4% biochar yield on a dry basis (according to experimental results), the developed system removes **3.26 tCO_2e per hour**, corresponding to approximately **24,450 tCO_2e** per year based on 7500 h of operation.

3.6. Economic modelling

3.6.1. Base case evaluation

Based on the model assumptions, financial projections were constructed for the entire duration of the project. Projections of the income statement, working capital, cash flow statement, and balance sheet, as well as the investment and depreciation schedule are presented in the supplementary materials (Table S10). The cash flow calculations used to compute the NPV, IRR and DPBP are derived from the financial projections. Fig. 5 presents the financial results achieved for the base case scenario. According to the results, a positive NPV of **3,002,358 EUR** is attained, with a **22.35%** IRR and a discounted payback period of **8 years**. The results confirm that under the assumptions made the project is profitable.

3.6.2. Influence of pricing decisions on project profitability

Table 4 explores the influence of carbon removal and biochar pricing on NPV and IRR, respectively. In terms of carbon removal pricing, a range of 70–230 EUR/tonne in increments of 40 EUR is employed, in conjunction with a range of 0–500 EUR/tonne for biochar pricing. The base feedstock cost used in this analysis is 45 EUR per tonne (20% moisture content - delivered). The reason behind applying a price of 0 EUR for biochar is to explore the financial feasibility of the project if it is based purely on carbon removal services, without accounting for the sale of the biochar.

As demonstrated by the results, profitability depends on the pricing of the physical product and the carbon removal service. The red areas denote price combinations that result in a negative NPV and an IRR value less than the cost of capital/discount rate. On the other hand, the green areas indicate price combinations that result in positive financial returns. The results may guide management in determining the impact of pricing on the project's success. Please note that the carbon removal price range included in the analysis is based on current market prices. These should be net prices, which exclude any fees or taxes levied by the marketplace provider. Additionally, the price range for biochar of 200–500 EUR/tonne is at the lower end of global market pricing. Furthermore, the results demonstrate that if the project is purely based on carbon removal services (i.e. no biochar sales), a price of approximately 230 EUR/tonne CO_2 removal is required to achieve acceptable financial returns. Furthermore, with biochar prices set at 500 EUR/tonne, the project is profitable under all carbon removal pricing scenarios.

3.6.3. Minimum selling prices

Table 5 presents the minimum selling price for the CO_2 removal certificate (CORC), which represents the long-term removal of 1 tonne of CO_2 from the atmosphere, based on various feedstock costs and biochar selling prices. The results indicate that if biochar is sold below international market prices at 100 EUR/tonne, a minimum price of 139–222 EUR/CORC will be required, based on feedstock costs of 30–70 EUR/tonne (20% moisture), to achieve the required rate of return, which in this case is 15%. If the biochar is sold at 200 EUR/tonne, which is the minimum market price for biochar indicated in the literature (Haeldermans et al., 2020), then a minimum selling price of ~102–185 EUR/CORC will be required. At a biochar selling price of 350 and 500

Table 5
Minimum selling price of CO_2 removal certificate (CORC) representing 1-tonne removal per CORC, based on various feedstock costs and biochar selling prices and minimum selling price of biochar per tonne, based on various feedstock costs and selling prices of CORCs.

Feedstock cost/tonne (EUR)	CORC Minimum Selling Price				Biochar Minimum Selling Price			
	Biochar price/tonne (EUR)				CO_2 Removal price/tonne (EUR)			
	100	200	350	500	70	110	150	190
30	139.03	102.56	47.84	–	289.25	179.59	69.93	–
40	159.76	123.28	68.57	13.85	346.07	236.41	126.75	17.09
45	170.12	133.64	78.93	24.22	374.48	264.82	155.16	45.49
50	180.48	144.01	89.29	34.58	402.89	293.23	183.57	73.90
60	201.21	164.73	110.02	55.30	459.71	350.05	240.39	130.72
70	221.93	185.46	130.74	76.03	516.53	406.87	297.20	187.54

Table 6
Carbon removal costs based on a project design that exclusively offers a carbon removal service. IRR refers to internal rate of return.

Feedstock cost/tonne (EUR)	Carbon removal costs/tonne CO_2e (EUR)			
	Target IRR (%)			
	10%	15%	20%	25%
30	158.37	175.51	195.33	217.68
40	179.17	196.23	215.98	238.26
45	189.57	206.59	226.30	248.55
50	199.98	216.96	236.63	258.84
60	220.78	237.68	257.28	279.42
70	241.59	258.41	277.93	300.00

EUR/tonne, a minimum selling price of ~48–131 and 0–76 EUR/CORC is needed, respectively.

Furthermore, Table 5 presents the minimum biochar selling prices required, based on various feedstock costs and CORC selling prices. As noted, at the lower end of CORC pricing of 70 EUR, a range of ~289–516 EUR/tonne biochar is needed, depending on the feedstock cost. Moreover, a range of ~180–407, 70–297, and 0–187 EUR/tonne are required at pricing of 110, 150 and 190 EUR/CORC, respectively. The upper and lower limits of those ranges represent the feedstock costs of 30 and 70 EUR, respectively.

In relation to the base case scenario, at a feedstock cost of 45 EUR/tonne and biochar selling price of 350 EUR/tonne, a minimum selling price of 78.93 EUR/CORC will be required to break even. Furthermore,

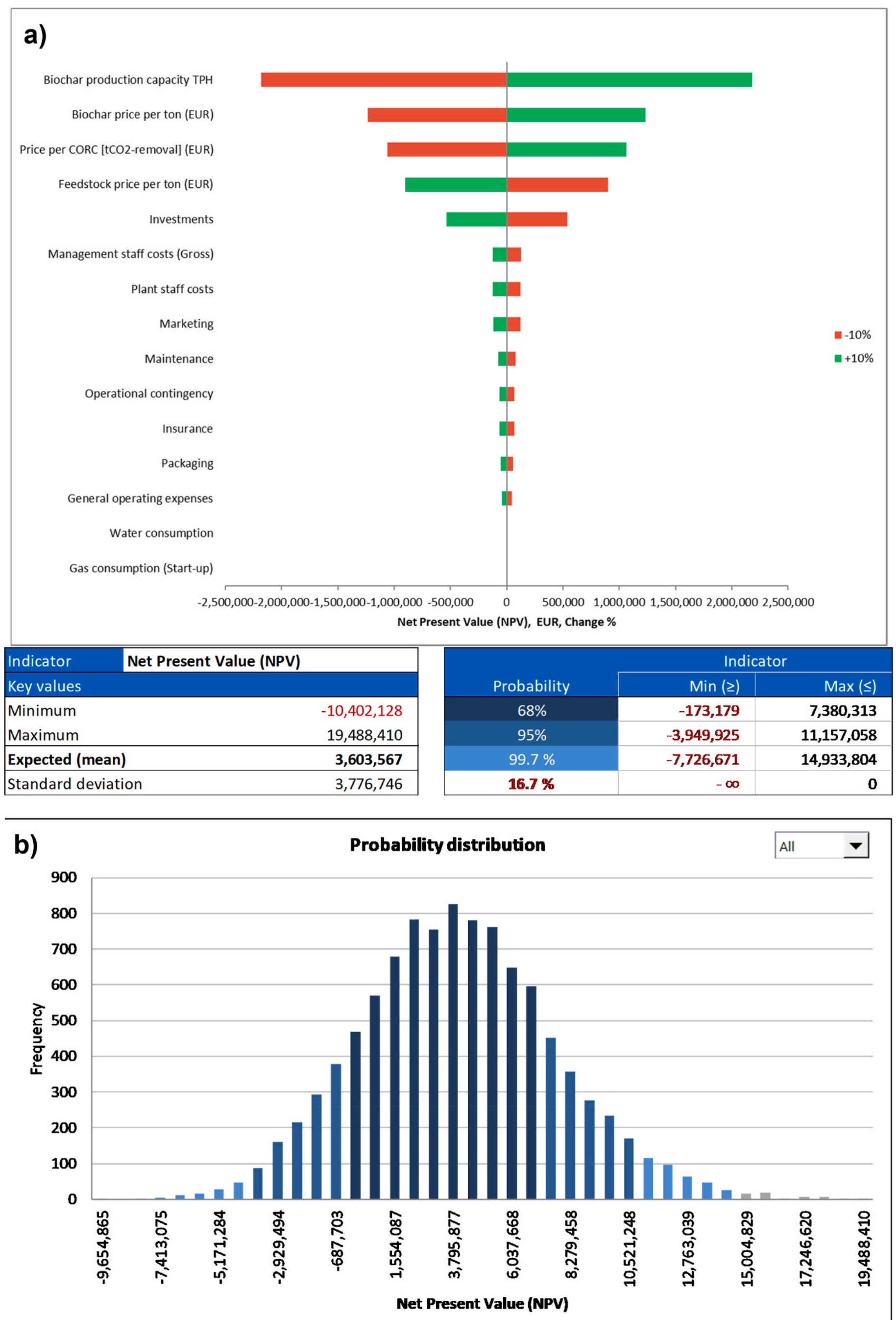

Fig. 6. **(a)** Tornado chart showing the influence of all variables on net present value (NPV). **(b)** Monte Carlo simulation incorporating the main variables that influence NPV.

at the same cost of feedstock, if the carbon removal service is offered at 110 EUR/CORC, the minimum selling price required for biochar is 264.82 EUR/tonne.

3.6.4. Carbon removal costs based on service-oriented model

Table 6 presents the results for the carbon removal costs computed, which can also be considered as minimum CORC selling prices, if the project is designed to exclusively offer a carbon removal service, without considering the sale of the physical product (i.e. biochar selling price is 0 EUR/tonne). This information can be directly compared to other carbon removal technologies. The carbon removal costs presented are based on various feedstock prices of 30–70 EUR/tonne and a range of expected rates of return of 10–25%. The results indicate a cost of **206.59 EUR/tonne CO_2e removal**, based on a feedstock cost of 45 EUR/tonne (20% moisture - delivered), to achieve the required rate of return of 15% for the base case scenario. A range of 175–258 EUR/tonne CO_2e removal would be attained based on feedstock prices of 30–70 EUR/tonne, respectively. Furthermore, a range of 158–242, 195–278, and 217–300 EUR/tonne CO_2e removal are achieved under required rates of return of 10, 20, and 25%, respectively. The lower and upper limits of the ranges provided represent feedstock costs of 30 and 70 EUR/tonne, respectively.

3.6.5. Risk analysis

Based on preliminary sensitivity analysis (Fig. 6a), it was determined that biochar yield, biochar selling price, CORC selling price, feedstock price and investment costs are the main variables that highly influence the profitability of the project, and that uncertainty can highly impact the NPV compared to the remaining variables. These variables were selected for the Monte Carlo simulation. For biochar yield, an expected value of 1.216 TPH was selected with a $\pm$ 5% for maximum and minimum, respectively which is based on the experimental work carried out. Regarding biochar pricing, a base case of 350 EUR/tonne was selected, with 200 and 500 EUR/tonne for minimum and maximum values, respectively. A base case for CORC selling price was set at 110 EUR, representing the lower end of the market pricing spectrum, with a minimum of 70 EUR and a maximum of 230 EUR. In relation to feedstock pricing, a base case of 45 EUR/tonne (20% moisture – delivered) was selected with a minimum and maximum of 30 and 70 EUR/tonne. Finally, investment costs were set at 5,900,000 EUR with $\pm$ 20% for minimum and maximum values. Fig. 6b presents the results of the Monte Carlo simulation. The results indicate **-10,402,128 EUR**, **19,488,410 EUR** and **3,603,567 EUR** for minimum, maximum and expected NPV values, respectively. As demonstrated, the expected value attained through the simulation is close to the NPV value achieved using the base case scenario of 3,002,358 EUR. Moreover, the results indicate a probability of **83.3%** that the project will achieve a positive NPV. It is generally assumed that projects achieving a probability higher than 80% are considered safe(Hacura et al., 2001).

4. Conclusion

In this work, the carbon removal potential of a biochar system based on olive tree pruning residues in Spain was investigated. It was determined that approximately 2.68 tCO_2e are permanently removed from the atmosphere per tonne of biochar produced (dry basis), after accounting for the carbon footprint of the entire process (cradle-to-grave), following the Puro.earth methodology. This corresponds to a carbon removal capacity of 3.26 tCO_2e per hour and the issuance of approximately 24,450 CO_2 carbon removal certificates (CORCs) annually, based on 7500 h of operation. The economic assessment revealed that the project is profitable at a CORC selling price of 110 EUR and biochar selling price of 350 EUR/tonne (dry basis), yielding a positive NPV of 3,002,358 EUR, IRR of 22.35% and a discounted payback period of 8 years. To maintain a very conservative assessment in this study, the sale of excess energy was not accounted for. However, this presents an opportunity to further enhance the potential value of the project as well as reduce the costs associated with the carbon removal service and biochar. In conclusion, the results obtained through this study indicate the feasibility of biochar-based carbon removal systems, however, the business model, type of feedstock, choice of technology, pricing decisions and ability to negotiate favourable terms and prices for feedstock supply are critical to the success of this approach. The findings of this study demonstrate the viability of immediately deploying large-scale biochar-based carbon removal via pyrolytic conversion of olive tree pruning residues to address the climate crisis.

Disclaimer

The views and opinions expressed in this paper do not necessarily reflect those of the European Commission or the Special EU Programmes Body (SEUPB)

CRediT authorship contribution statement

Samer Fawzy: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Ahmed I. Osman:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Neha Mehta:** Software, Formal analysis. **Donal Moran:** Formal analysis. **Ala'a H. Al-Muhtaseb:** Formal analysis. **David W. Rooney:** Supervision, Visualization, Writing – review & editing.

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.

Data availability

No data was used for the research described in the article.

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Appendix A. Supplementary data

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