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Cost–Benefit Analysis of Biochar Production: The Case Study of an Abandoned Rural Site, Borgo di Perolla, in Tuscany, Italy

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Abstract

The transition towards circular economy is now a key strategy to address the environmental issues we are facing. Within this framework, biochar, a carbon-rich material derived from residual agricultural pyrolysis, can represent a sustainable and circular solution. This paper aims at evaluating the possibility of implementing a local biochar-production system as part of an economic and social strategy of the redevelopment of an abandoned rural site, Borgo di Perolla, in Tuscany, Italy. A cost–benefits analysis (CBA) was conducted to evaluate the economic feasibility of three different scenarios of production and strategies: Scenario 1 considers revenues solely from the production and sale of biochar and wood vinegar; Scenario 2 additionally includes potential income from the sale of voluntary carbon credits; and Scenario 3 incorporates biochar credits within the European Union Emission Trading System (EU ETS). For each scenario, three indicators were calculated: Net-Present Value (NPV), Internal Rate of Return (IRR), and Breakeven point (BEP). The most evident result that emerged is that the sale of biochar and its by-products alone is not sufficient to ensure the project's economic sustainability, mainly due to high production costs. Only through carbon-credit-trading markets biochar becomes not only an environmentally strategic tool but also an economically rewarding one. In this sense, market infrastructures, such as the ETS, are essential for the dissemination of circular models, like biochar, that generate both environmental and economic benefits. Previous studies on biochar have largely focused on its application and associated benefits, while cost–benefit analyses have primarily examined its economic feasibility through the commercialization of biochar as a soil amendment, particularly within the United States context. The present work contributes to this literature in three main ways. First, it provides a site-specific and replicable CBA framework applied to a real territorial regeneration project (Borgo di Perolla), grounded in primary data collected through field surveys, stakeholder interviews, and expert validation. Second, the study explicitly compares multiple market-access scenarios within the same analytical framework, ranging from biochar-only sales to voluntary carbon markets, allowing for a clear identification of the economic thresholds at which biochar becomes financially sustainable. Third, and most importantly, the main contribution of this work lies in the explicit modeling of biochar integration into the EU Emissions Trading System. This paper extends the analysis to a regulated carbon market scenario, assuming the recognition of biochar-based carbon removals within the EU ETS framework. From a methodological perspective, the study quantitatively assesses how ETS price dynamics affect the profitability, internal rate of return, and break-even point of a biochar project over a long-term horizon. From a policy perspective, the analysis anticipates recent regulatory developments, such as the EU Regulation 2024/3012, on establishing a Union certification framework for permanent

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carbon removals, carbon farming, and carbon storage in products, by showing how biochar could function as a fully market-integrated climate technology.

Keywords: biochar; circular economy; cost–benefit analysis; carbon credits; ETS; environmental sustainability

1. Introduction

In recent years, the transition toward a circular economy has become a central pillar of global strategies for sustainable development, especially with the new circular economy action plan [1]. Within this framework, the valorization of agricultural and forestry residues represents a crucial opportunity to reduce waste generation, improve resource efficiency, and mitigate climate change.

Among the various nature-based and circular solutions, biochar, a carbon-rich material obtained through the thermochemical conversion (pyrolysis) of biomass, has attracted increasing scientific and policy attention [2]. Biochar application to soil has been associated with improved soil fertility, enhanced water retention, and long-term carbon sequestration, offering potential benefits for both agricultural productivity and climate mitigation [3]. The present study aims to analyze the economic and environmental feasibility of implementing a local biochar-production system as part of the redevelopment project of Borgo di Perolla, in Tuscany, Italy, an abandoned area characterized by agricultural and forested land that produces significant amounts of residues and wood biomass. These materials were identified as potential feedstock for biochar production, offering an opportunity to implement a local circular system that combines waste valorization, carbon sequestration, and soil regeneration.

By applying a cost–benefit analysis (CBA) across multiple production and market scenarios, the research investigates whether biochar can become a sustainable driver of circular regeneration at the territorial level. The results indicate that while biochar alone is not yet economically self-sufficient, its integration into carbon credit mechanisms, like the Voluntary Carbon Market and the EU Emission Trading System (ETS), can transform it into both environmentally and economically viable solutions. The paper is structured as follows: in Section 2, a brief explanation of the study area and biochar is provided; Section 3 describes the methodology and materials used for the analysis; Section 4 presents all the results, and finally, the paper ends with Section 5 with some concluding remarks

2. Background and the Area of Study

2.1. Biochar

Biochar is a carbon-rich material produced by heating biomass, such as wood, leaves, or manure, in conditions of limited or no oxygen. Its main feature is its high carbon content. Biochar is a porous carbonaceous product derived from biomass pyrolysis and applied in ways that ensure long-term carbon storage or the substitution of fossil carbon in industrial processes [4].

Pyrolysis is a thermochemical conversion process that enables the production of biochar from various waste materials. As previously described, it involves the decomposition of organic matter through high-temperature heating, typically between 250 °C and 900 °C [4]. During pyrolysis, biomass undergoes decomposition, depolymerization, and condensation reactions.

As the temperature increases, the water contained in the biomass is converted into vapor, initiating a dehydration phase that reduces the moisture content and consequently the mass of the feedstock [5]. Subsequently, the biomass is transformed into biochar through the loss of its volatile components [5].

Pyrolysis generates three product streams in solid, liquid, and gaseous forms: biochar (solid), bio-oil or wood vinegar (liquid), and syngas (gas). Depending on the temperature, heating rate, and feedstock characteristics, pyrolysis can be classified into slow, fast, or intermediate regimes [6].

Biochar is applied across multiple sectors, including agriculture, construction, wastewater treatment, and livestock management, owing to its favorable physicochemical characteristics and associated environmental benefits.

Agriculture represents the most established field of biochar application. Biochar is primarily used to enhance agricultural productivity, mitigate environmental pollution, restore degraded soils, and sequester atmospheric carbon [3]. Its properties, such as high porosity and an alkaline pH, improve soil fertility, water retention, nutrient availability, and microbial habitat quality [7]. Biochar also absorbs pollutants and heavy metals, aiding soil remediation [8]. Overall, biochar improves soil fertility and quality by acting on its physical and chemical properties, thereby contributing to improvements in both the quality and quantity of agricultural production [8]. Biochar also offers an effective solution for reducing organic waste and related environmental problems by transforming waste biomass into a useful material. [8]

One of the most relevant properties of biochar is its ability to contribute to the reduction of greenhouse gas emissions. Biochar contributes significantly to carbon sequestration due to its chemically stable carbon fraction, which can persist in soils for centuries to millennia [9,10]. The pyrolysis process further prevents carbon from returning to the atmosphere, enabling long-term CO_2 removal of approximately 2–3 t CO_2 per ton of biochar [11]. This function makes it a key strategy in climate mitigation. The carbon sequestration process consists of two main phases [12]: carbon dioxide is absorbed by vegetation through photosynthesis; biochar is produced from organic biomass via pyrolysis, which increases its resistance, and is subsequently incorporated into the soil, preventing carbon from returning to the atmosphere as carbon dioxide.

The use of biochar in concrete production allows for a reduction in the amount of cement required, resulting in lower carbon emissions [13]. Biochar also has a strong CO_2-absorption capacity in cement-based applications, making it an environmentally friendly option for construction materials. Furthermore, biochar produced from wood waste, when integrated into concrete, enhances robustness and water resistance [14]. At the same time, as it is derived from organic waste and is therefore recyclable, biochar helps reduce waste and minimize the extraction of new resources, making the process more sustainable [13].

Biochar can then be used directly in wastewater treatment systems as an adsorbent material for contaminant removal, or it can be applied to soils to improve water quality [15]. Finally, several positive effects on animal health have been observed when animals follow diets including biochar, which can be considered a true dietary supplement [16]; in addition, biochar's characteristics help mitigate methane emissions produced by livestock.

Up to these points, the positive effects of biochar have been described. However, several critical issues surround this topic. In particular, biochar does not always have favorable effects on soil and its properties [17]. Moreover, despite its long-term stability, biochar undergoes chemical, physical, and biological changes over time, making it difficult to accurately predict all of its effects.

Some adverse effects associated with biochar arise from interactions with soil physicochemical properties, other chemicals present in the soil, or substances co-applied with biochar [17]. Biochar may contain pollutants and harmful substances such as heavy metals and polycyclic aromatic hydrocarbons, originating from the biomass itself or formed during pyrolysis [18]. For these reasons, to ensure safe and sustainable biochar use, it is essential to select uncontaminated biomass types and carefully control pyrolysis conditions, particularly the temperature, to reduce hazardous substance formation [18].

2.2. Borgo Perolla and the Redevelopment Project

Borgo di Perolla is located in the inland area of the municipality of Massa Marittima, in the province of Grosseto, within the Tuscan Maremma region. The study area covers approximately 1300 hectares, including an extensive forest complex of more than 1000 hectares, as well as agricultural plots comprising vineyards, olive groves, chestnut groves, and pastures. The site is characterized by high biodiversity, a landscape, and a notable cultural and architectural heritage, partly compromised by a prolonged period of neglect and abandonment.

Over recent decades, the entire estate has undergone substantial degradation, resulting in the progressive loss of ecological, productive, and landscape functions: the forest has not been properly managed, agricultural activities have been gradually abandoned, and many historical buildings have deteriorated. This situation has generated the need for an intervention aimed at environmental, agricultural, and structural restoration.

The main issues identified through the forest assessment and field inspections include the absence of sustainable forest management, leading to risks of biodiversity loss and the instability of local ecosystems; the deterioration of rural and historical infrastructure; the abandonment of traditional cultivations, with olive groves and vineyards showing low or no productivity; and the need to implement restoration measures grounded in environmental sustainability, integrating agroecological, forestry, and circular approaches. This evidence is derived from a confidential report prepared by experts involved in the site inspections.

In response to these challenges, the owners of Borgo di Perolla started a regeneration project conceived as an integrated sustainable development intervention, with the aim of enhancing the area from both environmental and socio-economic perspectives. Complementing this broader sustainability project, this paper investigates the economic feasibility of implementing a biochar-production system using branches and woody residues from the estate.

The aim is to define a circular economy strategy that ensures not only the efficient reuse of residual biomass but also access to the biochar market and the voluntary carbon credit market, while highlighting the environmental and climate benefits of the material.

In summary, the Borgo di Perolla initiative represents a coordinated set of environmental, agricultural, and cultural restoration measures that contribute to the ecological transition of marginal rural areas, fostering sustainable and long-lasting environmental, social, and economic development.

3. Materials and Methods

The research methodology is a cost–benefit analysis (CBA), as it represents a robust economic tool for assessing the feasibility of a project [19]. This methodology allows for the identification and estimation of all associated costs and benefits, comparing investment alternatives and evaluating their monetary value in present terms (NPV).

When multiple project alternatives are available, the CBA allows for the selection of the most profitable option in monetary terms, that is, the one where the final benefits exceed the costs, thus effectively addressing situations characterized by uncertainty and risk [19]. The CBA becomes an important tool for analyzing projects that also consider environmental effects, in addition to economic and social costs and benefits. In this case, it is referred to as an environmental CBA [19].

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The research therefore employed a cost–benefit analysis (CBA) to evaluate the economic and environmental feasibility of establishing a biochar-production system for a period of 20 years. The time horizon selected for the analysis is 20 years, as this period is considered appropriate as it captures the full life cycle of the project and its economic effects, while also accounting for environmental impacts and benefits that may materialize over the long term [20]. It is further assumed that production can begin in the first year, since the proposed production equipment does not require preliminary testing or trial phases, but only an adequate supply of biomass to be processed.

Data collection involved both primary and secondary sources to ensure analytical robustness. Primary data were obtained through direct fieldwork, including site visits, interviews, and discussions with agronomists, and sustainability experts involved in the project. Secondary data were gathered from scientific literature and policy reports, focusing on biochar-production technologies and carbon credit markets.

The site currently generates approximately 300 tons per year of residual biomass, which until now has been discarded. This quantity represents the baseline feedstock used in the analysis.

Three main scenarios and one sensitivity analysis were designed to test the project's feasibility under different technical and market conditions. Scenario 1 included the production and sale of biochar and wood vinegar as the sole sources of revenue. Scenario 2 added potential revenues from the sale of voluntary carbon credits. Scenario 3 simulated the inclusion of biochar credits within the European Union Emission Trading System after the fifth year. Finally, Scenario 4 provides a brief in-depth analysis of the possible development of Scenario 3, considering, exclusively, the use of residual biomass, without resorting to resources from the logging plan. Each scenario incorporated two distinct assumptions regarding production capacity, considering either the operation of three production units or five production units, as this was the condition provided by the suppliers of the units.

Economic feasibility was assessed using three indicators, including the Net Present Value (NPV), the Internal Rate of Return (IRR), and the break-even point (BEP). For each scenario, 4 discount rates (3%, 6%, 10%, and 14%) were applied to improve the robustness of the analysis.

The first discount rate corresponds to that of the European Central Bank (ECB), which, in February 2025, was equal to 2.9% (for this paper, an approximation to 3% was used). The choice is justified by the fact that the ECB rate represents a stable and official benchmark widely used for economic and financial decisions at the European level. Moreover, since the project is developed in Italy, a Eurozone country, using the ECB discount rate ensures alignment with the relevant macroeconomic context. The second, third, and fourth discount rates, equal to 6%, 10%, and 14%, respectively, were selected from research that identifies these values within a range between 4% and 16%, with an average value of 10% [21]. The fourth and highest rate ($i = 14\%$) was chosen to test the point at which the project's value deteriorates, as this rate heavily discounts future cash flows and favors projects that are profitable in the short term. The adoption of four different discount rates aims to broaden the sensitivity analysis, strengthening the robustness and completeness of the study.

3.1. Indicators

In the presence of multiple scenarios and alternatives, the cost–benefit analysis allows for the selection of the most profitable option in monetary terms, namely the one in which final benefits exceed costs, addressing situations characterized by risk [19].

The methodology is based on the comparison of different cash flows, derived from the difference between the benefits and costs generated by the project under analysis. These monetary values are subsequently discounted using the selected discount rate, to identify the investment with the highest return and ensure a rational decision-making process. Important concepts to introduce how CBA practically works are capitalization and discounting.

The future value V is defined as the future value of resources invested today at a given interest rate i [19]. It is expressed as follows: $V = PV(1+i)$, where PV denotes the invested capital, meaning the present value. If the capital is invested for two years, the accumulated value becomes $\mathrm{V} = \mathrm{PV}(1+\mathrm{i})^2$; for three years, $\mathrm{V} = \mathrm{PV}(1+\mathrm{i})^3$, and so forth. In general, the accumulated value after t years is $V_t = PV(1+i)^t$ [22].

Capitalization therefore represents the return generated by the investment. When the interest rate is positive, the accumulated value increases with time [22].

Discounting is the inverse process of capitalization [23] and consists of determining the present value of future monetary resources. The present value of a sum received in one year is $PV = \frac{V}{(1+i)}$, while for two years it is $PV = \frac{V}{(1+i)^2}$. More generally, the present value of a monetary flow received after t years is $PV = \frac{V}{(1+i)^t}$, where $\frac{1}{(1+i)^t}$ is defined as the discount factor, and the interest rate i used in the calculation is referred to as the discount rate [22].

The net present value is calculated as follows:

Equation (1). NPV

$$\mathrm{NPV} = \sum_{t=0}^{n} \frac{N_t}{(1+i)^t} \tag{1}$$

where N_t is the net cash flow (difference between benefits and costs) at period t, n is the length of the reference period, t is the specific time period, and i is the discount rate used for discounting [19].

Therefore, the NPV TEST [19] is as follows:

- If NPV is positive (NPV > 0), the project is profitable and should be undertaken because it increases the current economic value; the expected future return on the project is greater than the opportunity cost of the capital invested.
- If NPV is negative (NPV < 0), the project should not be undertaken because it does not add value but rather destroys it; the expected future return on the project is lower than the opportunity cost of the capital invested.
- If NPV is equal to 0 (NPV = 0), there is no net economic benefit, making the decision to undertake the project, or not, indifferent.

Between two or more alternatives with positive NPVs, the one with the highest NPV will be chosen as it generates the greatest value. Therefore, the higher the NPV, the more attractive the project is.

The second comparison criterion chosen is the Internal Rate of Return (IRR). It as a method used to evaluate an investment, indicating the discount rate at which the net cash flow yields an NPV of zero [24]. The IRR represents the equivalent interest rate required to balance the project's NPV, that is, the expected return of the investment necessary to generate the same value as the project [24].

Equation (2). IRR

$$\mathrm{IRR} : NPV = \sum_{t=0}^{n} \frac{N_t}{(1+i)^t} = 0 \tag{2}$$

In this analysis, NPV and IRR are used complementarily (), so that

- If IRR is greater than the discount rate (IRR > i), the project is economically viable [24]. Here, i represents the opportunity cost of capital, i.e., the potential return from alternative investments. In this case, the project's return in present value terms exceeds that of other opportunities, corresponding to NPV > 0.

- If IRR is less than the discount rate (IRR < i), the project would have a negative NPV (NPV < 0) and is therefore economically unviable [24]. This means that the project is less profitable than other investment options.

Finally, the third measure is the break-even point (BEP), which represents the payback period of the investment. The BEP corresponds to the number of years required for the project to recover its initial investment. Practically, it is the point in time when positive cash flows equal negative cash flows, offsetting the initial investment costs [25]. With reference to the net present value, the BEP identifies the year in which the cumulative discounted cash flows turn from negative to positive. In other words, it marks the moment when the project starts generating actual economic value, and every subsequent cash flow contributes to producing a surplus over the invested capital [25]. In this analysis, a graphical method was used to determine the break-even point, employing a line diagram that compares the evolution of net costs and benefits for each period and for the selected discount rate.

3.2. Costs

Biomass pre-processing and mobile pyrolysis units are evaluated for biochar and wood-vinegar production using 3- and 5-unit configurations. Each option entails different biomass requirements, opportunity costs, and labor needs. Fixed expenditures include scientific consulting, operational support, and project management. Capital expenditure (CAPEX) refers to the initial investments required to establish the biochar-production facility, including the pyrolysis equipment, biomass handling infrastructure, and installation costs. CAPEX is treated as an upfront investment at $t = 0$. Operating expenditure (OPEX) includes all recurring costs during the project lifetime, such as labor, maintenance, utilities, biomass collection and transportation, and the disposal of residual materials. These are considered in each period t when calculating net cash flows. Table 1 outlines all first-year costs for each scenario.

Table 1. Summary table of first-year costs for each scenario.

	Scenario 1		Scenario 2		Scenario 3	
Amount of Equipment	**3**	**5**	**3**	**5**	**3**	**5**
Fixed costs						
Infrastructure	3000.00€	3000.00€	3000.00€	3000.00€	3000.00€	3000.00€
Scientific consultancy	16,300.00€	16,300.00€	17,900.00€	17,900.00€	17,900.00€	17,900.00€
Operational consultancy	14,000.00€	15,000.00€	14,000.00€	15,000.00€	14,000.00€	15,000.00€
Project management	10,000.00€	10,000.00€	10,000.00€	10,000.00€	10,000.00€	10,000.00€
Variable costs						
Equipment	150,000.00€	200,000.00€	150,000.00€	200,000.00€	150,000.00€	200,000.00€
Operational staff	20,359.60€	30,539.40€	20,359.60€	30,539.40€	20,359.60€	30,539.40€
Opportunity cost	2331.00€	6885.00€	2331.00€	6885.00€	2331.00€	6885.00€
CO_2 broker cost	0.00€	0.00€	450.85€	751.41€	450.85€	751.41€

The pre-processing of the biomass fed into the machinery, which involves the removal of approximately 20% of the humidity that is required for the combustion process, is achieved through simple stacking of the biomass in a dry, sun-exposed area, with basic covering in case of rain. The estimated cost for constructing this structure is €3000. The acquisition of these mobile units is flexible and can occur in groups of three or five units, depending on the company's operational needs. Accordingly, the estimated investment costs differ: the purchase of three units is estimated at €150,000, while five units require an investment of approximately €200,000. The machines operate in daily "cycles," where one working day corresponds to one biochar-production cycle. Each cycle includes the biomass supply, loading into the unit, biochar production through pyrolysis, and extraction of the final product. Each cycle requires 0.6 tons (600 kg) of biomass, with an additional 10% allocated to initiate the combustion process. A biochar yield of 22% is assumed, meaning that each production cycle produces approximately 0.1452 tons (145.2 kg) of biochar from the total biomass input. Consequently, the total biomass demand and biochar output vary according to the number of units in operation. In parallel with biochar production, the same machinery generates an additional by-product, wood vinegar (or wood distillate), while the capture of the biogas produced during the pyrolysis is not possible. For each production cycle, the output of wood vinegar is estimated at 10 hectoliters.

For the purposes of this analysis, a total of 230 working days per year is assumed, corresponding to 230 production cycles.

In the analysis, also, an opportunity of cost arises from allocating part of the biomass derived from the estate's forest-management plan to biochar production instead of selling it as timber. This is because the residual biomass already available on the estate is not sufficient to supply the mobile pyrolysis units for a total of 230 production cycles. As a result, a potential revenue of €15 per tonne of timber is forgone. All quantitative data on biomass availability, timber prices, and operational assumptions are derived from confidential company and suppliers' documentation, technical reports prepared by the researchers involved in the site assessments, and direct meetings with the estate management.

3.3. Benefits

The benefit assessment considers revenues from biochar, wood vinegar, and biochar-derived carbon credits. Owing to substantial market volatility and limited transparency, price estimates were based on published studies, expert consultations, and supplier comparisons. For the CBA, conservative mean values were adopted.

Beginning with biochar, its market price exhibits substantial variability and is currently difficult to define with precision [26]. In some cases, it may reach values ranging between €1000 and €1500 per ton [27]. This variability is largely attributable to the fact that biochar markets are not yet fully consolidated and remain characterized by considerable uncertainty with respect to their future development. A robust assessment of the profitability of biochar-related markets would require an updated and publicly accessible database of sale prices [21]. However, unlike other commodities, such information is not currently publicly available [21]. A further factor contributing to price fluctuations is the diversity of the product's physicochemical characteristics and the wide range of uses and potential markets [21].

For the purposes of the present analysis, based on the data previously collected and discussed with biochar representatives, it was possible to identify a realistic selling price ranging between €200/t (minimum value) and €500/t (maximum value). Accordingly, a mean value of €300/t was adopted for the cost–benefit analysis (CBA) across all scenarios.

A similar issue concerns wood distillate (or wood vinegar). Despite its growing popularity and the numerous potential applications across various sectors, a substantial research gap persists. There is a lack of quantitative analyses capable of providing a comprehensive overview of wood vinegar [28]. The price selected for the CBA (across all scenarios) is €180, chosen within a broader range of €100 (minimum value) to €200 (maximum, but variable value) based on comparisons of major Italian suppliers and producers of wood distillate.

Scenarios 2 and 3 incorporate additional benefits from participation in the voluntary carbon market and ETS, where certified biochar is assumed to sequester 1.5 t CO_2-eq per ton applied. Over the past four years, prices of biochar-derived carbon credits (BCRs: Biochar Carbon Removal is a negative emissions technology that converts biomass into biochar, and it is one of the most scalable and technically advanced solutions that implement Carbon Dioxide Removal (CDR). BCR can be tracked, certified, and accounted for utilizing certification systems that are based on evidence and product measurement [29]. Biochar has since become an important technology for providing credits within the voluntary carbon market, a market that allows companies and individuals to voluntarily offset their carbon footprint [30])) have experienced significant growth, with a compound annual growth rate (CAGR: Annual growth rate) of 29.2% [31]. Although future price trends cannot be predicted with certainty, market dynamics indicate sustained upward pressure. The global demand for CO_2-removal solutions via biochar is accelerating rapidly, while supply remains limited. This imbalance is expected to intensify in the medium term as an increasing number of companies strive to meet net-zero commitments. In 2024, prices for biochar carbon credits ranged from $113 to $310 per ton of CO_2 (i.e., per credit), with a weighted average price of $165 [31]. Also, the value of one ton of CO_2 equivalent from biochar was estimated at $131 in 2023 and $212 in 2022 [32] with a price range between $42 and $250 per ton, with higher values primarily associated with the co-benefits of biochar, including support for local community development, biodiversity conservation, job creation, and other positive impacts [32].

Considering this data, a mean price reflecting current values within the voluntary carbon market was selected for the feasibility analysis. Thus, one carbon credit generated from biochar is assigned to a value of €150.

Table 2 reports the reference prices used in the CBA.

Table 2. Summary table of average prices used in the CBA.

Average Prices	€
Average selling price of 1 t of Biochar	300€
Average selling price of 1 hl of Wood vinegar	180€
Average price of 1 CO_2 credit (=1 t di CO_2 sequestered) (BCR)	150€

3.4. Scenario 3 Data

Scenarios 1 and 2 consist of direct applications of a CBA using the data previously described. Scenario 3, however, requires formulating a CBA that incorporates a potential increase in the value of biochar-derived carbon credits, assuming that such credits become eligible within the mandatory Emissions Trading System (ETS).

Integrating these carbon credits into the ETS would represent a major opportunity for producers of this form of carbon removal, and this possibility is currently under discussion.

Inclusion in the ETS could further raise their price. If biochar credits were accepted within the emissions trading system, demand would increase because companies would be required to offset their emissions, leading to a substantial rise in credit prices (which would also be influenced by the price and availability of other allowances). Moreover, if biochar was integrated into the EU ETS, it could help stabilize carbon prices and prevent excessively rapid increases. Given its low cost, biochar could also help contain allowance-price inflation and maintain greater market stability. Additionally, biochar credits may be particularly valued within the ETS, as they ensure long-term carbon sequestration in soils [33].

ETS allowances are currently traded at variable prices between €60 and €80 per ton of CO_2. In 2024, the average recorded price was approximately €64.74 [34]. ETS allowance prices may reach €149 per ton by 2030, indicating a potential increase of more than 130% in five years [35].

Considering these projections and assuming that biochar credits (BCR) are incorporated into the ETS, a conservative estimate was adopted for Scenario 3: an 80% increase in carbon-credit value by the fifth year (2030), corresponding to the assumed date of entry into the EU ETS. Thus, if the voluntary-market value of biochar carbon credits is €150/t, their price would rise to €270/t from the fifth year onward.

To strengthen the analysis, the same scenario was also developed using the average ETS allowance price for the period 2021–2025. This average price, calculated using daily ETS price data [36], is approximately €70/t. For completeness, the scenario was further examined in the appendix using the minimum (€33/t) and maximum (€98/t) ETS prices recorded in the 2021–2025 period. The effects of these price variations are discussed in the following chapter.

If a hypothetical CBA were developed considering only waste resources, the data would change. From the fifth year onward, biochar production would have to be limited to the 300 tons of waste biomass available on the estate, avoiding the use of timber from the harvesting plan, as previously assumed. Based on this decision and given the reduced biomass availability, the pyrolysis cycles would need to be decreased, making it reasonable to operate only three mobile units. The analysis would therefore assume the purchase and use of only three pyrolysis machines.

However, as previously noted, biomass to sustain a full annual production cycle for three units (230 cycles) would require an additional 155 tons of residues beyond the 300 tons available. Consequently, starting from the fifth year, working cycles would need to be reduced to 151, matching only the available waste biomass, resulting in an opportunity cost of €0 (due to the absence of foregone timber sales). With fewer cycles and working days, labor costs would decrease to €13,366.52 per year. However, reduced machine utilization and lower biomass inputs would also result in the reduced production of biochar, wood vinegar, and carbon credits (Scenario 4).

4. Results

4.1. Main NPV, IRR, and BEP Results

The analysis of NPVs (Table 3) across the scenarios reveals significant differences. Scenario s3-5 emerges as the most economically favorable, with a positive NPV even at the highest discount rate (i = 14%), reaching approximately 280,000 €, and nearly 902,000 € at i = 3%. Scenario s3-3 confirms this trend, yielding positive NPVs under all assumptions and demonstrating economically sustainable outcomes, although slightly lower than those with five machines.

Table 3. Summary table of the NPV for each scenario in the CBA.

	NPV			
Scenario	**3%**	**6%**	**10%**	**14%**
s1-3	−165,991.05€	−168,594.39€	−170,705.61€	−171,991.34€
s1-5	−21,553.42€	−65,599.08€	−102,859.33€	−126,979.01€
s2-3	175,871.52€	100,181.33€	36,103.98€	−5425.60€
s2-5	552,516.24€	385,891.24€	244,688.15€	153,055.18€
s3-3	385,377.23€	253,200.35€	142,108.12€	70,834.76€
s3-5	901,692.44€	640,922.94€	421,361.72€	280,155.78€
s4-3	176,154.45€	100,333.06€	36,123.56€	−5509.19€

Scenarios s2-5, s2-3, and s4-3 show good profitability at lower discount rates, but the NPV declines with increasing discount rates, turning slightly negative at i = 14%. Conversely, scenarios s1-3 and s1-5 consistently show negative NPVs, indicating economic unsustainability. These scenarios, based solely on biochar and wood distillate sales, are therefore not financially viable.

IRRs (Table 4) are positive in all scenarios except s1-3, which also exhibits a negative NPV, confirming its economic infeasibility. Higher IRRs are observed in scenarios where biochar is integrated into the voluntary carbon market and ETS (s2-3, s2-5, s3-3, s3-5, and s4-3). These results highlight the potential of carbon-market instruments to make high-environmental-impact technologies economically attractive, despite requiring substantial initial investments. Access to emissions reduction financing thus represents a critical factor for unlocking solutions such as biochar, capable of generating significant economic returns while contributing to mitigation goals.

Table 4. Summary table of IRR for each scenario in the CBA.

			IRR				
Scenario	**s1-3**	**s1-5**	**s2-3**	**s2-5**	**s3-3**	**s3-5**	**s4-3**
	−17%	2%	13%	28%	21%	35%	13%

Results in Figure 1 indicate that scenarios s2-5, s3-3, and s3-5 are the most efficient, reaching the breakeven point quickly with minimal sensitivity to interest rate increases. These findings support the notion that integrating biochar into carbon markets (voluntary or ETS) enhances both economic returns (NPV, IRR) and the speed and stability of investment recovery.

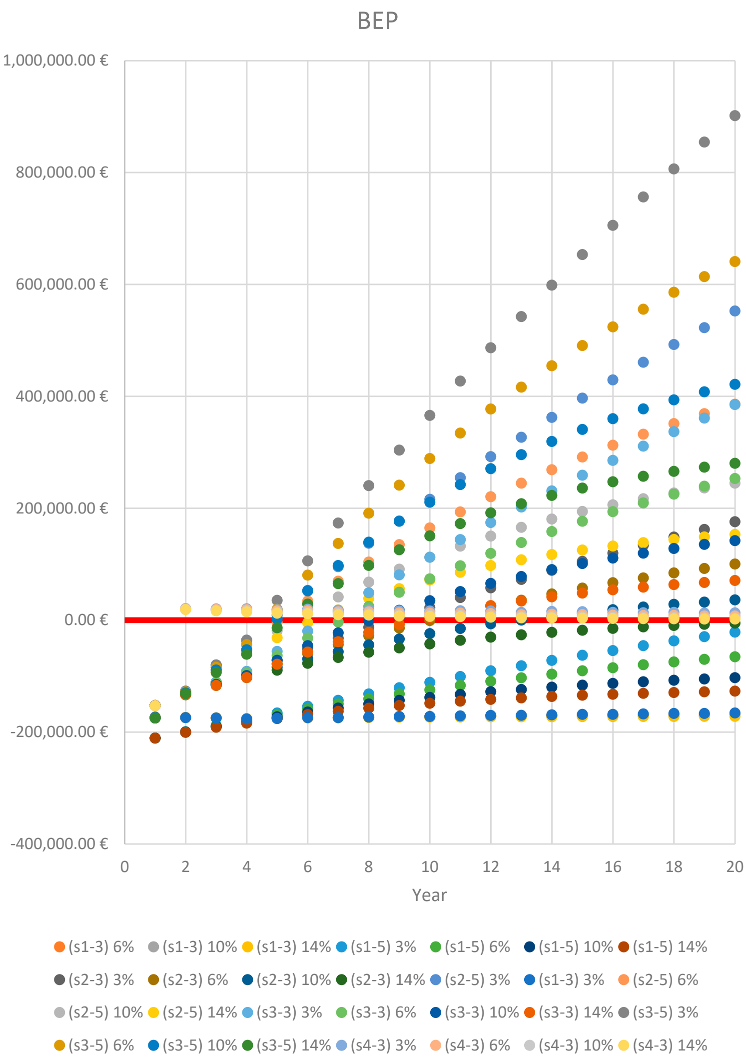

Figure 1. BEP for each scenario in the CBA.

Overall, Scenario 1 (biochar and wood distillate only) is not sufficient for economic sustainability, whereas access to voluntary carbon markets (Scenario 2) or integration into the EU ETS (Scenario 3) substantially improves profitability. Scenario s2-5 demonstrates the advantage of higher production capacity combined with market diversification, while Scenario 3 shows that increased carbon credit value within the ETS from the fifth year allows rapid BEP recovery and sustained positive returns.

Scenario 4, which considers biochar production exclusively from waste, also yields promising results, demonstrating that resource recycling and minimizing the environmental impact can support economic sustainability. Limiting production to waste reduces the physical output but significantly lowers operational costs, maintaining or even enhancing profitability through carbon credit valuation. This approach exemplifies circular economy principles, prioritizing input–output efficiency over maximum production, and fostering resilient, equitable, and environmentally harmonious long-term production models.

4.2. Sensitivity Analysis for Scenario 3

The project Scenario 3 was developed also considering the average ETS credit price over 2021–2025 (70 €/t) and assuming an 80% increase from the fifth year (126 €/t), and it shows similar results [Table 5]. The NPV is positive for both configurations (s3-3 and s3-5) across all discount rates, except for scenario s3-3 with three machines and discount rates of 10% and 14%, where the breakeven point is not reached.

Table 5. Summary table of the NPV for project evaluation price and average ETS price.

Price ETS Credit	**150.00€**		**70.00€**	
i/Scenario	s3-3	s3-5	s3-3	s3-5
3%	385,377.23€	901,692.44€	87,875.18€	405,855.68€
6%	253,200.35€	640,922.94€	25,418.52€	261,286.56€
10%	142,108.12€	421,361.72€	−27,017.74€	139,485.29€
14%	70,834.76€	280,155.78€	−60,612.20€	61,077.53€

Regarding the IRR [Table 6], scenario s3-3 presents a value of 8%, while scenario s3-5 reaches 19%. In both cases, the IRR exceeds the applied discount rates (with the exception of i = 10% and i = 14% in s3-3), confirming the economic feasibility of the project even when adopting an average ETS credit price.

Table 6. Summary table of IRR for project evaluation price and average ETS price.

Price ETS Credit	**150.00€**		**70.00€**	
Scenario	s3-3	s3-5	s3-3	s3-5
IRR	21%	35%	8%	19%

The breakeven point for scenario s3-3 is achieved in the thirteenth year with a discount rate of 3% and in the seventeenth year with a rate of 6%, indicating a slight delay compared to the same scenario calculated with a carbon credit price derived from biochar of 150 €. For scenario s3-5, the breakeven point occurs in the seventh year with i = 3%, in the eighth year with i = 6%, in the ninth year with i = 10%, and in the eleventh year with i = 14%.

With the minimum ETS price, positive results are obtained only for the s3-5 configuration, indicating that investment recovery is possible only when five machines are employed, and for discount rates of 3%, 6%, and 10%. Conversely, with the maximum ETS price, all NPVs are positive except for s3-3 with i = 14%. In all other cases, the IRR exceeds the discount rates applied.

The timing of breakeven varies considerably. Under the maximum ETS price, the breakeven is reached quickly for all discount rates, whereas under the minimum price with the s3-3 configuration, it is never achieved. This highlights how investment profitability is strongly influenced by external factors, particularly ETS credit prices, which in turn are linked to international market trends, geopolitical conflicts, technological innovations, and public policies. Therefore, investment risk increases due to uncertainties in these external factors, which are not captured by quantitative cost–benefit analysis alone.

Further details of the analysis using minimum and maximum ETS prices are provided in Appendix A.

4.3. Replicability of the Analysis

For the model to be replicable in comparable agricultural contexts, a sufficiently large land area is required to ensure a stable annual supply of biomass capable of sustaining 230 production cycles per year. In this regard, Table 7 presents the NPV per hectare for each scenario, including variations based on ETS credit prices. Borgo di Perolla encompasses 35 hectares for biochar biomass production.

Table 7. NPV/hectare for each scenario.

	NPV/Hectare			
Scenario	**3%**	**6%**	**10%**	**14%**
s1-3	−4742.60€	−4816.98€	−4877.30€	−4914.04€
s1-5	−615.81€	−1874.26€	−2938.84€	−3627.97€
s2-3	5024.90€	2862.32€	1031.54€	−155.02€
s2-5	15,786.18€	11,025.46€	6991.09€	4373.01€
s3-3	11,010.78€	7234.30€	4060.23€	2023.85€
s3-5	25,762.64€	18,312.08€	12,038.91€	8004.45€
s3-3 (average price)	2510.72€	726.24€	−771.94€	−1731.78€
s3-5 (average price)	11,595.88€	7465.33€	3985.29€	1745.07€
s3-3 (maximum price)	5465.79€	2989.49€	909.23€	−424.57€
s3-5 (maximum price)	16,520.99€	11,237.41€	6787.23€	3923.75€
s3-3 (minimum price)	−1390.63€	−2261.87€	−2991.67€	−3457.86€
s3-5 (minimum price)	5093.63€	2485.14€	285.74€	−1131.73€
s4-3	4541.75€	2507.87€	783.55€	−336.21€

These results further indicate that entering both voluntary carbon markets and the ETS is crucial to achieving investment profitability. In particular, scenarios s1-3 and s1-5 consistently show negative values, suggesting the economic unsustainability of the investment. In contrast, scenarios s2-5 and s3-5 exhibit the highest NPV per hectare, maintaining positive returns even at higher discount rates, which highlights these as economically more robust scenarios. This demonstrates that, in terms of per-hectare profitability, market instruments, such as voluntary markets and ETS, combined with increased production capacity (five machines) make this high-impact environmental technology economically attractive, allowing for substantial profit generation.

Scenario s3-3 is particularly sensitive to ETS credit prices. With the maximum price, the NPV per hectare remains positive up to a 10% discount rate, whereas with the minimum price, it becomes negative in all cases. Even with the maximum price, the NPV per hectare turns negative at discount rates of 10% and 14%.

This implies that at an ETS price of 33 € (minimum price), the revenues generated are insufficient to cover investment costs, resulting in economic losses per hectare. Furthermore, as the discount rate increases, the negative values worsen, indicating a diminished capacity of the investment to generate value over time. A similar situation arises when using an

ETS price of 70 € (average price) with discount rates of 10% and 14%, which remain high and profitable only over the long term.

These per-hectare NPV results demonstrate that, even when biochar is recognized within the ETS system, the market does not always ensure the economic sustainability of the initiative. Therefore, it is essential to carefully evaluate and continuously monitor ETS market price fluctuations along with other external factors that may influence it.

5. Discussion and Concluding Remarks

This study assessed the economic feasibility and sustainability of a biochar production system using residual biomass from Borgo di Perolla through a cost–benefit analysis across multiple scenarios. The results indicate that project profitability is highly dependent on the integration of market mechanisms. Scenario 1, based solely on biochar and wood distillate sales, proved economically unviable. In contrast, Scenario 2, which incorporates voluntary carbon market credits, and Scenario 3, which includes ETS participation from the fifth year, demonstrated significant profitability, particularly under configurations with higher production capacity.

Biochar can represent a new and attractive market opportunity for start-ups in the agricultural sector, combining biomass treatment with the production of a value-added product that can contribute to the global green transition in several ways, including carbon sequestration and soil amendment.

Beyond its environmental benefits, the development of a biochar market may also generate a range of social benefits through the creation of a dedicated biochar supply chain, including increased rural employment, rural development, and improved social conditions associated with environmental restoration.

However, the feasibility of creating a new global biochar market crucially depends on the economic viability of biochar production at the micro level and on the ability of local implementation projects, such as the case analyzed in this study, to operate profitably.

Nevertheless, the realization of these potential environmental and social benefits ultimately depends on how effectively this innovative and promising market is supported during its early stages of development, in order to avoid failure and the risk of falling into the “valley of death” that characterizes many innovations that are not diffused because of insufficient institutional support.

The analysis highlights that market-based instruments, such as voluntary carbon markets and the EU ETS, are essential enablers for making high-impact environmental technologies economically attractive. These mechanisms not only generate financial returns but also facilitate broader environmental benefits, including soil improvement, sustainable waste management, and carbon sequestration. Without such instruments, innovative low-impact solutions risk remaining marginal or inaccessible despite their systemic advantages.

According to the results of the cost–benefit analysis, biochar only becomes an economically viable tool through carbon credit markets. In this sense, market infrastructures such as the ETS are fundamental for the dissemination of circular models that generate positive environmental and economic effects. It should also be noted that these types of technologies are still in the early stages of diffusion, often in start-up or experimental contexts, where installation, management, and maintenance costs are still high.

The research therefore emphasizes that public policies and market mechanisms aimed at offsetting environmental externalities are not secondary tools but enable conditions for the implementation of high-impact solutions. Without such support, key technologies for sustainable development, such as biochar, risk remaining marginal despite their potential, resulting in the waste of a concrete opportunity to combine economic development and environmental protection.

In this regard, the European Union is currently discussing the inclusion of permanent carbon-removal credits, such as biochar carbon removal within the ETS. With Regulation on Carbon Removal Certification Framework (CRCF), adopted in 2024 [37], the EU has begun developing a voluntary Union certification framework for permanent carbon removals, aimed at encouraging the uptake of these technologies.

Robustness analysis revealed that investment feasibility is sensitive to external factors, particularly fluctuations in ETS carbon credit prices and macroeconomic and geopolitical conditions, which introduce inherent risk. This underscores the need for ongoing monitoring of market dynamics. These results of this analysis further indicate that entering both voluntary carbon markets and the ETS is crucial to achieving investment profitability. In particular, scenarios with lower production capacity or relying solely on biochar and wood vinegar sales consistently show negative NPVs, highlighting the economic unsustainability of the investment under such conditions. In contrast, scenarios combining higher production capacity with access to market instruments, voluntary carbon credits, and ETS demonstrate the highest per-hectare NPVs, maintaining positive returns even at higher discount rates. This indicates that while market participation is important, alone it does not guarantee economic viability; the careful evaluation of credit prices and other external factors remains essential to ensure the long-term profitability of the project.

Future research should aim to quantify social and environmental benefits through multicriteria analyses and explore operational improvements to have a broader evaluation based on all the potential benefits and costs of the mass deployment of biochar as a key technology for the global green transition. Policy support remains crucial: economic incentives, tax relief, and the formal recognition of biochar as a certified removal technology under the ETS are key to promoting adoption. Equally important is the engagement of local stakeholders, including farmers and public authorities, to facilitate and ensure long-term sustainability. However, as previously explained, there are possible negative aspects and concerns regarding the global implementation of biochar that go beyond investment profitability. Interactions with soil physico-chemical properties, co-applied substances, or other chemicals present in the soil may cause unintended effects on soil health and crop productivity. Biochar can also contain pollutants such as heavy metals or polycyclic aromatic hydrocarbons, either from the biomass feedstock or formed during pyrolysis. To minimize these risks, the careful selection of uncontaminated biomass and strict control of pyrolysis conditions, particularly temperature, are essential.

Overall, this study demonstrates that integrating biochar production with carbon market mechanisms can provide a viable pathway toward economically and environmentally sustainable land management, while also offering a model for circular and resilient agricultural systems. In this context, the findings reaffirm the importance of promoting the application and use of biochar. As highlighted by the IPCC in its 2003 Good Practice Guidance for Land Use, Land-Use Change and Forestry (LULUCF) report, agriculture represents a key sector for climate change mitigation and adaptation, particularly through practices that enhance carbon sequestration in soils.

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Abbreviations

The following abbreviations are used in this manuscript:

CBA	Cost-benefit analysis
NPV	Net present value
IRR	Internal rate of return
BEP	Breakeven point
s1-3	Scenario 1 with three pieces of equipment
s1-5	Scenario 1 with five pieces of equipment
s2-3	Scenario 2 with three pieces of equipment
s2-5	Scenario 2 with five pieces of equipment
s3-3	Scenario 3 with three pieces of equipment
s3-5	Scenario 3 with five pieces of equipment
s4-3	Scenario 4 with three pieces of equipment
ETS	Emission Trading System
BCR	Biochar carbon removal

Appendix A

To strengthen the robustness of Scenario 3, an additional evaluation was conducted using the minimum and maximum EU ETS carbon credit prices recorded over the 2021–2025 period. These analyses complement the previous evaluations based on the average ETS price and the estimated voluntary market carbon credit price for biochar.

The minimum and maximum prices were calculated using daily estimates [36] for 2021–2025, resulting in a minimum price of €33/t and a maximum of €98/t.

For scenario s3-3, assuming the minimum ETS price, the project proves entirely economically unviable. The analysis indicates absolute infeasibility at all considered discount rates. All NPVs are negative, and the internal rate of the return IRR is 0%, indicating that the initial investment cannot be recovered. Consequently, the break-even point is never reached for any discount rate.

Conversely, scenario s3-5 remains positive even under the minimum ETS price. The project is economically viable for discount rates of 3%, 6%, and 10%, with NPVs significantly positive, particularly €178,277.06 at i = 3%. The only exception is the 14% discount rate, chosen to test project feasibility limits. The IRR is 11%, exceeding all discount rates except i = 14%. The break-even point occurs in year 11 for i = 3%, year 13 for i = 6%, and year 18 for i = 10%. While the break-even is not achieved for i = 14%, the IRR suggests that payback could be attained in subsequent years if the project duration were extended.

These results highlight that, under EU ETS participation, prioritizing biochar production using five machines (s3-5) is essential to ensure recovery of the initial investment. Table A1 reports the NPVs for each discount rate under the minimum ETS price of €33/t.

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Table A1. NPV for s3-3 and s3-5 with the minimum ETS price.

i/Scenario	s3-3	s3-5
3%	−48,671.99€	178,277.06€
6%	−79,165.48€	86,979.89€
10%	−104,708.42€	10,000.81€
14%	−121,025.11€	−39,610.67€

Using the maximum ETS price of €98/t, the project is economically sustainable under both production configurations. For scenario s3-3, NPVs are positive for discount rates of 3%, 6%, and 10%, with the highest NPV of €191,302.55 at i = 3%. The IRR is 13%, suggesting that investment recovery is possible even at i = 14% if the project duration is extended. Break-even occurs in year 10 for i = 3%, year 11 for i = 6%, and year 15 for i = 10%.

Scenario s3-5 exhibits even more favorable outcomes under the maximum price. NPVs are positive for all discount rates, with the highest at €578,234.62 for i = 3%. The IRR of 25% greatly exceeds all chosen discount rates. The break-even point is reached in year 6 for i = 3%, year 7 for i = 6% and i = 10%, and year 8 for i = 14%. Table A2 summarizes the NPVs under the maximum ETS price.

Table A2. NPV for s3-3 and s3-5 with the maximum ETS price.

i/Scenario	s3-3	s3-5
3%	191,302.55€	578,234.62€
6%	104,632.10€	393,309.19€
10%	31,822.96€	237,553.13€
14%	−14,859.96€	137,331.25€

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