

Evaluating Sugarcane Bagasse-Based Biochar as an Economically Viable Catalyst for Agricultural and Environmental Advancement in Brazil through Scenario-Based Economic Modeling

Sebastian G. Nosenzo

PSR Energy Consulting and Analytics, Rio de Janeiro, Brazil

Email: sebastian.nosenzo@gmail.com

How to cite this paper: Nosenzo, S.G. (2024) Evaluating Sugarcane Bagasse-Based Biochar as an Economically Viable Catalyst for Agricultural and Environmental Advancement in Brazil through Scenario-Based Economic Modeling. *Journal of Power and Energy Engineering*, 12, 97-124.

<https://doi.org/10.4236/jpee.2024.1211007>

Received: October 16, 2024

Accepted: November 26, 2024

Published: November 29, 2024

Copyright © 2024 by author(s) and Scientific Research Publishing Inc.

This work is licensed under the Creative Commons Attribution International License (CC BY 4.0).

<http://creativecommons.org/licenses/by/4.0/>



Open Access

Abstract

The increasing global demand for sustainable agricultural practices and effective waste management has highlighted the potential of biochar as a multifaceted solution. This study evaluates the economic viability of sugarcane bagasse-based biochar in Brazil, focusing on its potential to enhance agricultural productivity and contribute to environmental sustainability. While existing literature predominantly explores the production, crop yield benefits, and carbon sequestration capabilities of biochar, there is a notable gap in comprehensive economic modeling and viability analysis for the region. This paper aims to fill this gap by employing a scenario-based economic modeling approach, incorporating relevant economic models. Findings include that biochar implementation can be economically viable for medium and large sugarcane farms (20,000 - 50,000 hectares) given the availability of funding, breaking even in about 7.5 years with an internal rate of return of 18% on average. For small farms, biochar can only be viable when applied biochar to the soil, which in all scenarios is found to be the more profitable practice by a large margin. Sensitivity analyses found that generally, biochar becomes economically feasible at biochar carbon credit prices above \$120 USD/tCO₂e, and at sugarcane bagasse availability percentages above 60%. While the economic models are well-grounded in existing literature, the production of biochar at the studied scales is not yet widespread, especially in Brazil and uncertainties can result. Reviewing the results, the land application scenario was found to be the most viable, and large farms saw the best results, highlighting the importance of scale in biochar operations. Small and medium farms with no land application

were concluded to have no or questionable viability. Overall, sugarcane bagasse-based biochar can be economically viable, under the right circumstances, for agricultural and environmental advancement in Brazil.

Keywords

Biochar, Economic Viability, Scenario-Based Modeling, Pyrolysis, Sugarcane Bagasse, Biomass, Carbon Credit, Soil Amendment, Crop Yield

1. Introduction

Among the wide array of increasingly relevant solutions to waste management and climate change, biochar emerges as one that can tackle multiple significant problems at once, and it comes with a host of co-benefits. Dubbed by the World Economic Forum as “carbon removal’s ‘jack of all trades’” [1], recent literature on the material suggests that biochar holds the key to the most important climate and agricultural solutions of today.

In Brazil, biochar’s potential is immense, due to the country’s large agricultural sector. While there are sizable bodies of research on biochar’s soil amendment and carbon sequestration capabilities, as well as the environmental effect of the material, studies on the economic feasibility of biochar production are fewer. There exist a number of economic analyses of biochar in locations around the world such as Canada, Australia, China, and the USA, but such research for Brazil does not exist in detail and depth. With the goal of evaluating sugarcane bagasse-based biochar as an economically viable catalyst for agricultural and environmental advancement in Brazil, this paper presents an economic analysis through scenario-based modeling.

1.1. Background

Biochar is one the three products of the thermochemical process pyrolysis, in which biomass materials are converted at high temperatures, and in the absence of an oxidizing agent, such as O_2 , into liquids (bio-oil), non-condensable gasses (biogas), and solids (biochar) [2]. The process works by breaking down the large structural biomass molecules of the feedstock [3], and is able to do so utilizing practically all biomass material, unprocessed or processed [4] [5].

Of particular interest, however, is the use of agricultural crop residues as the feedstock for pyrolysis. This is due to the fact that doing so would address the buildup of the crop residues left on a farm after harvest, reducing or eliminating residue disposal costs [6], or otherwise finding utility for the residues that would release 70% of its carbon content into the atmosphere within one year [7]-[9].

The search in recent times for alternatives to fossil fuels has resulted in a wide range of prospective technologies, and crop residues have been implemented in various biomass energy structures. However, pyrolysis stands out from these alternative biomass conversion processes in that on top of valorizing waste streams

[10], it brings many unique advantages such as different biomass sources application, reducing the competition between fuel and food by using unwanted material, and significant energetic optimization efficiencies [6] [11].

1.2. Biochar's Properties

The properties of biochar can be categorized into three types: soil enhancement, crop yield increase, and carbon sequestration. While soil enhancement and crop yield increase are closely correlated, the two factors present distinct benefits.

Biochar's properties as a soil amendment are in part what makes it such a highly appealing material to convert biomass into. The term "biochar" was developed to refer to the substance previously called "Terra Preta de Índio", a particularly fertile soil discovered near the ruins of a pre-Columbian civilization located in the Amazon basin, contrasting with the typically nutrient deficient soils of the Amazon Rainforest [8] [12]. This "Terra Preta" was used by the region's inhabitants to improve the local soil for agricultural purposes [13]. Research in the centuries following its discovery has unearthed an array of benefits that biochar poses when applied to soil, especially soils with existing deficiencies.

Biochar application has been found to increase microbial activity in the soil, as well as accelerate the mineralization of organic matter, nutrient cycling, and organic matter content, resulting in higher levels of nutrient uptake by a plant grown in that soil [14]-[20]. Furthermore, biochar can affect crop plant root morphology by promoting fine root proliferation, increasing specific root length, and decreasing both root diameter and root tissue density [21]. In addition to these properties, biochar improves soil pH and soil structure in terms of porosity (50% increase) and bulk density (40% decrease) depending on soil type [22] [23], improving aeration and water content up to over 100%, an aspect especially beneficial in arid regions [24]. For agricultural purposes, this results in less water use and reduced frequency of irrigation, tillage, and other crop management practices.

As a result and in addition to these soil amendment properties of biochar, its implementation in agriculture results in relevantly increased crop yields [25]. Depending on soil and crop, increases with biochar implementation resulted in 10% to 30% crop yield, with 15% on average [14]. This metric describing a 15% increase in crop yield over traditional fertilizers is commonly found with biochar application with various crops such as corn, wheat, rice, and soybean [8] [26]-[28], with the combined use of biochar and fertilizer presenting even higher increases in some studies [29].

As evidenced in a study by Borges *et al.* conducted in Brazil, biochar implementation resulted in a 15% higher crop yield compared to traditional triple superphosphate fertilizers. Additionally, the study noted that biochar maintained a soil pH between 7 and 8, which enhanced phosphorus availability, further benefiting crop growth. This highlights biochar's ability not only to replace but, in some cases, surpass the effects of conventional fertilizers.

Importantly, studies found that biochar land application has a much greater

crop yield increase effect in tropical climates over temperate ones, with averages up to 25% increases in crop yield in tropical agriculture [30]. Brazil, being a country that experiences tropical and subtropical climates [31] fits this criteria and holds a further potential in its agriculture for biochar implementation.

The most relevant aspect of biochar is its carbon sequestration property. Through the process of pyrolysis, biochar retains the majority (60% - 80%) of the carbon content of the biomass feedstock [32], resulting in a stable solid, rich in carbon and capable of resisting chemical and microbial breakdown [29] [33]. When applied to the soil, which, as mentioned, comes with a multitude of soil enhancement and crop yield increase benefits, the material effectively sequesters the carbon, maintaining the carbon content in its stable form for hundreds to thousands of years [34]. This, when done according to the approved biochar carbon credit methodologies and verified by certification agencies, generates carbon credits for the removal of carbon, which can be a significant stream of revenue for the entity producing and applying biochar. The removal credits generated via biochar land application are frequently regarded as superior to alternative reduction credits in the global carbon market, commanding much higher prices. This is because removal efforts are often easier to justify and measure than reduction projects. According to recent forecasts, demand for the project type may expand 20 times over the next decade, and evidence suggests that the relevant market size is increasing steadily [35] [36]. In fact, recent purchases of biochar credits by corporate giants such as Microsoft and JP Morgan Chase points to the growing significance and confidence in the biochar credit market [35]. Currently, biochar carbon credits sales have prices that range between 100 and 200 \$USD per metric ton of CO₂ removed, with the average price being \$179/tCO₂e [1] [10].

It is important to consider, however, that biochar is a relatively new player on the global scene and these benefits might not see their full potential for years. For example, the worldwide biochar demand is still almost 500 times smaller than the fertilizer demand, even though biochar can produce better results [27]. On top of this, a combination of a lack of standardization and a lack of scale in the industry may be holding biochar back in terms of widespread use [10] [27] [37]. Overall and in time, though, with the global crop residue production increasing 33% in ten years, crop residue-based biochar production could be an effective tool to combat greenhouse gas emissions and invigorate agricultural industries simultaneously through the use of biochar [26] [29] [38].

1.3. Biochar in Sustainable Agriculture

The global shift toward sustainable agriculture is driven by the need to reconcile growing food demands with the imperative to minimize environmental degradation. Agriculture is a major contributor to greenhouse gas emissions, soil depletion, and biodiversity loss, making it essential to adopt practices that not only enhance productivity but also restore ecological balance. Biochar, with its unique combination of benefits, is considered a highly promising solution. By converting

agricultural waste into biochar, the dual objectives of reducing waste and enhancing the resilience of farming systems can be achieved, positioning biochar as a key player in sustainable agriculture.

In Brazil, where agriculture forms a substantial part of the economy, the potential for biochar application is significant. As one of the largest agricultural producers, the country faces unique challenges in balancing its agricultural expansion with environmental conservation. Monoculture practices, deforestation, and soil degradation are significant concerns, particularly in the production of crops like sugarcane. Biochar's ability to repurpose agricultural residues such as sugarcane bagasse offers a practical and scalable solution.

The integration of biochar into Brazil's agricultural systems could provide multiple co-benefits: reducing waste, improving soil health, and generating additional revenue through carbon credits.

1.4. Brazilian Sugarcane Production

While biochar production can be executed using any biomass or crop residue, sugarcane bagasse is an especially appealing choice for a feedstock due to its high content of organic compounds cellulose and hemicellulose vital to the pyrolysis process, its positive influences of the final biochar's soil amending properties, and, in countries where it is a main crop, its abundance.

With sugarcane as one of its main commodities, Brazil is the world's largest producer of the crop, producing over 700 million tons and 25% of the world production [6] [39]. In Brazil and in the main developing countries, sugarcane plays an important role in the energy and economic systems, producing the large-scale products sugar and ethanol [40].

In the context of biochar, the main part of sugarcane that is used for pyrolysis is the bagasse that remains after the sugarcane's use for sugar and ethanol production. On average 1 ton of sugarcane produces 280 kg of bagasse [2] [17] [41].

This sugarcane residue can be burned in boilers for power generation, but this is still underused by the vast amount available and much of the bagasse's potential remains largely untapped [6] [28] [38]. Moreover, it is established that burning crop residues greatly harms human health and the environment by releasing greenhouse gasses into the atmosphere [42]. Thus, the alternative of using the bagasse for biochar production is even more appealing for Brazil.

1.5. Sugarcane Bagasse-Based Biochar

Such use of sugarcane bagasse to make sugarcane bagasse-based biochar would involve the aforementioned process of pyrolysis. The process can yield differing results and products (liquids, gasses, and solids in varying amounts [43]) depending on a multitude of factors, of which the type of pyrolysis is a main aspect. Multiple studies have found that the so-called "slow pyrolysis" at 300°C - 500°C not only results in the highest amount of biochar (50.3%), but is also more cost effective [2] [44] [45]. Overall, comparisons of the pyrolysis biochar system with other

bioenergy production systems for carbon abatement found that the pyrolysis biochar system is 33 % more efficient than direct combustion, even if the soil amendment benefits of biochar are ignored [46].

In the context of this study, which considers biochar in Brazilian sugarcane production, the liquid and gas products of pyrolysis, which would have to undergo refining, treatment, and transportation [2], incurring costs, are disregarded and assumed to be utilized by the producer as fuel to start the pyrolysis or for heating. Finally, questions remain as to biochar's economic sustainability. This study aims to provide a comprehensive evaluation of sugarcane bagasse-based biochar's economic viability in Brazil as a protagonist in the country's agricultural and environmental initiatives.

2. Methodology

To assess the economic viability of sugarcane bagasse-based biochar as a catalyst for agricultural and environmental advancement in Brazil, various economic models were implemented. These include a life cycle cost analysis, cost-revenue-based break even analysis, return on investment, cost-benefit analysis, net present value and internal rate of return, and sensitivity analyses, all forming a comprehensive Biochar Economic Viability Model.

2.1. Study Area, Scenarios, and Values

In order to evaluate sugarcane bagasse-based biochar as an economically viable catalyst for agricultural and environmental advancement in Brazil, and to analyze biochar economically within an area where its aforementioned significant potential exists, scenarios within the study area of Brazil were considered. Scenarios A—the direct sale of biochar (carbon credits) following production, and B—the land application of produced biochar followed by the sale of surplus biochar (carbon credits)—were chosen to reflect possible business structures adopted by a farm producing biochar. Each scenario (A, B) was considered for farms of 10,000 ha, 20,000 ha, and 50,000 ha in size, for a total of 6 distinct scenarios.

Table 1 and **Table 2** detail relevant values determined through a review of existing biochar-related literature and relevant values determined for this study, respectively. All chosen values or assumptions for this study were developed with the cooperation and insights from PSR Energy Consulting and Analytics in Rio de Janeiro, Brazil.

2.2. Life Cycle Cost Analysis

To calculate the life cycle costs for each studied scenario, the following model was used (Equations (1)-(3))

$$C_{total} = C_i + \sum_{y=0}^n C_y \quad (1)$$

$$C_i = C_{pd} + C_{tw} + C_{es} + C_{pv} \quad (2)$$

$$C_y = C_m + C_o + C_l + C_{cc} + C_{ta} \quad (3)$$

where C_{total} is total life cycle costs, C_i is initial investment costs, C_y is yearly costs, n is the total number of years C_{pd} is planning and design costs, C_{iw} is indirect and working capital costs, C_{es} is equipment and setup costs, C_{pv} is permit and carbon credit project validation costs, C_m is maintenance costs, C_o is operation costs, C_l is labor costs, C_{cc} is carbon credit certification costs, and C_{la} is land application costs, for which Scenario A has none.

Table 1. Values determined through a review of existing biochar-related literature.

Description	Value	Unit	Reference
Sugarcane yield	73.7	t·ha ⁻¹	[39]
Bagasse: sugarcane	28	%	[41]
Biochar: bagasse	50.3	%	[2]
Dry: bagasse ^[a]	60	%	[2]
Land app. rate	4.2	t/ha	[47]
Biochar yield inc.	15	%	[26]
Interest rate	9.00	%	[48]
Inflation rate	3.00	%	[49]
BRL to USD	0.18	\$/R\$	(July 2024)
Sugarcane m. p.	30.6	\$ t ⁻¹	[50]
Carbon credit m. p.	179	\$.tCO ₂ e ⁻¹	[1]
C.C. ^[b] issuance fee	0.30	\$.Credit ⁻¹	[51]
C.C. review fee	1.9	k	[51]
Fertilizer cost	34	\$.ha ⁻¹	[52]
Crop mgmt. cost	437	\$.ha ⁻¹	[52]
Land app. cost ^[c]	320	\$.ha ⁻¹	[52]

[a] Bagasse needs to be dried from 50% to 10%wt moisture for pyrolysis [b] Carbon Credit [c] Crop management cost, including tillage, irrigation, and other soil preparation.

Table 2. Values chosen for this study's economic modeling.

Description	Value	Unit
Analysis time frame	20	y
Farm size (small)	10,000	ha
Farm size (medium)	20,000	ha
Farm size (large)	50,000	ha
Planning/design cost % of init. investment	5	%
Permit cost % of init. investment	2	%
Maintenance cost % of FCI ^[a]	2	%
Industrial scale factor	0.7	x

[a] Based on Ramirez *et al.* [3] study.

To calculate the value of the variables, a reference study of three biofuel plants simulating an 84,000 t/y use of sugarcane bagasse in Queensland, Australia was used [3]. Values were then location-adjusted to be relevant for the study area of Brazil, using a ratio of the Price Level Index (PLI) of both locations for the equipment, setup, and operation costs [53], and a ratio of the minimum wage (2024) of both locations for the labor costs [54] [55]. Reference values from the Ramirez *et al.*, 2019 study are outlined in **Table 3**.

Table 3. Reference cost values in \$ USD millions from Ramirez *et al.* [3] study for life cycle cost analysis.

Description	Value	Unit
Total installed costs	38.42	\$M
Total indirect + working capital costs	13.63	\$M
Labor cost	1.17	\$M/y
Operation cost excl. feedstock	2.08	\$M/y

2.3. Cost-Revenue-Based Break Even Analysis

To conduct a cost-revenue-based break even analysis for each studied scenario, cumulative life cycle costs from the life cycle cost analysis were used, as well as life cycle revenues calculated using the following models (Equation (4)) and (Equation (5)) for Scenario A and Scenario B, respectively

$$R_{total} = R_b + R_{cc} \quad (4)$$

$$R_{total} = R_b + R_{cc} + R_s \quad (5)$$

where R_{total} is total life cycle revenues, R_b is revenues from biochar sales, R_{cc} is revenues from carbon credit sales, and R_s is revenues from increased sugarcane sales, for which Scenario A has none.

2.4. Return on Investment

To calculate the return on investment percentage per year for each studied scenario, the following model was used (Equation (6))

$$ROI = \frac{R_t - C_t}{C_i} \times 100 \quad (6)$$

where R_t is total revenues for year t , C_t is the total costs for year t (where C_t for the first year does not include the initial investment cost), and C_i is the cost of the initial investment.

2.5. Cost-Benefit Analysis

To compare the costs and benefits for each studied scenario, total life cycle costs from the life cycle cost analysis were used. In addition, to calculate the benefits, the following model was used (Equations (7)-(8))

$$B_{total} = R_{total} + S_{total} \quad (7)$$

$$S_{total} = S_f + S_o \quad (8)$$

where B_{total} is total benefits, R_{total} is total life cycle revenues from the cost-revenue-based break even analysis, S_{total} is total savings, applicable to Scenario B only, as these savings are results of biochar land application, S_f is fertilizer savings, and S_o is operational savings.

To then conduct the cost-benefit analysis, the following model was used (Equation (9))

$$BCD = B_{total} - C_{total} \quad (9)$$

where BCD is benefit-cost difference, B_{total} is total benefits, and C_{total} is total costs.

2.6. Net Present Value and Internal Rate of Return

To calculate the net present value, or the present value of cash flows over the analysis time frame, the following model was used (Equation (10))

$$NPV = \sum_{t=0}^n \frac{CF_t}{(1+r)^t} \quad (10)$$

where NPV is net present value, n is the total number of years, CF_t is total cash flow for year t , t is the year, and r is the discount rate, which is used to translate future cash flows into present value by considering factors such as expected inflation and the ability to earn interest [56]. It is equal to the Brazilian nominal interest rate which accounts for both interest and inflation, and was determined using current forecasts for the years following 2024 [48] [57] [58].

To calculate the internal rate of return, or the annual rate of growth that an investment is expected to generate, the following model was used (Equation (11))

$$0 = \sum_{t=0}^n \frac{CF_t}{(1+IRR)^t} \quad (11)$$

where IRR is internal rate of return, n is the total number of years, CF_t is total cash flow for year t , and t is the year.

2.7. Sensitivity Analysis

The variables of 1) carbon credit market price and 2) available bagasse were identified as relevant variables to the results of the economic viability analysis of sugarcane bagasse-based biochar.

For the variable of carbon credit market price, current metrics suggest that biochar carbon credits are worth between \$100 and \$200 per ton of CO₂ emissions reduced/sequestered, with an average market price of \$179/tCO₂e [1] [10]. However, these prices are a reflection of a relatively new market [59], and at the scale of carbon credits in this study, this price may not be expected to hold. Therefore, a sensitivity analysis with their market price ranging from \$50 to \$200 per ton of CO₂e was chosen.

For the variable of bagasse availability, current sugarcane farms in Brazil are commonly using a percentage of their produced sugarcane bagasse for bioelectricity or heat in sugar and ethanol production processes [2]. The leftover bagasse (ex.

70% if the farm utilizes 30% for bioelectricity, a common practice), is what is available to be converted into biochar through pyrolysis without affecting current costs. Since the use of bagasse for bioelectricity varies from farm to farm depending on production, equipment, and bioelectricity usage, the percentage of bagasse available can also vary. Therefore, a sensitivity analysis with the percentage of available bagasse ranging from 50% to 90% was chosen.

As such, sensitivity analyses were conducted for both of these variables, analyzing the net present value of all studied scenarios with the variables ranging from 50 to 200 (\$/tCO₂e) for carbon credit market price and 50 to 90 (%) for bagasse availability.

2.8. Selection and Implementation of Models

The economic models employed in this study were selected to provide a comprehensive assessment of biochar's financial viability in Brazil, where both agricultural and carbon markets present unique challenges and opportunities. A life cycle cost analysis (LCCA) and net present value (NPV) were chosen to capture the full scope of investment and operational costs over the long term, particularly suited for high upfront capital projects like biochar production. To complement these, the internal rate of return (IRR) and cost-benefit analysis (CBA) models were applied to provide a clearer picture of profitability under different farm sizes and operational strategies. These models are well-suited for projects with high initial capital and long-term revenue streams, as they capture the full scope of investment, operating costs, and potential returns over time.

Given the nascent nature of the biochar and carbon credit markets, scenario-based modeling with these tools were necessary for a detailed examination of different operational scales and conditions.

To ensure scientific rigor and reproducibility, this study implemented these models using inputs derived from peer-reviewed sources, industry consultations, and localized agricultural data. Key parameters—such as bagasse conversion rates, carbon credit pricing, and operational costs—were adapted to reflect the specific conditions of the Brazilian sugarcane industry.

A series of sensitivity analyses on the most uncertain factors like carbon credit market prices and bagasse availability allowed for an exploration of the effects of market fluctuations on profitability and ensured that the results were adaptable to future shifts in both agricultural and environmental policy.

By integrating these established models and adapting them to Brazil's specific agricultural context, the study ensures a rigorous, replicable approach, making this analysis both scientifically grounded and highly relevant for evaluating biochar's feasibility in various agricultural settings.

3. Results

3.1. Life Cycle Cost Analysis

The life cycle costs of all six studied scenarios are detailed in **Figure 1**.

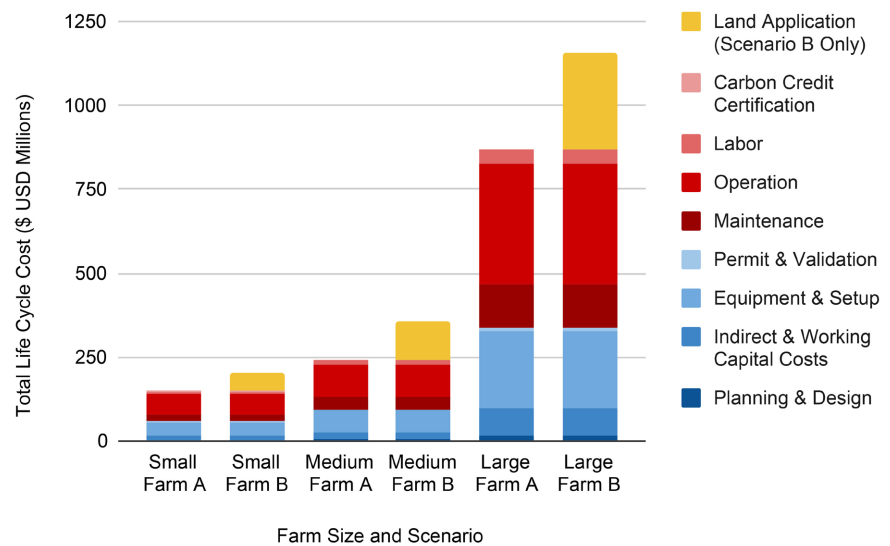


Figure 1. Life cycle cost components in \$ USD millions over 20 years for studied scenarios.

The initial investment for both scenarios of the small farm amounted to \$57.5 million USD, with yearly costs over 20 years around \$91 million USD for Scenario A and \$148 million USD for Scenario B. For the initial investment, the highest amount lies in the equipment and setup of the pyrolysis plant, totaling \$39.5 million USD. Out of the yearly costs, the highest costs are operation, followed by maintenance and labor for Scenario A, at \$61 million USD, \$23 million USD, and \$7 million USD, respectively over 20 years accounting for inflation, and operation followed by land application and maintenance for Scenario B, at \$61 million USD, \$57 million USD, and \$23 million USD, respectively over 20 years accounting for inflation.

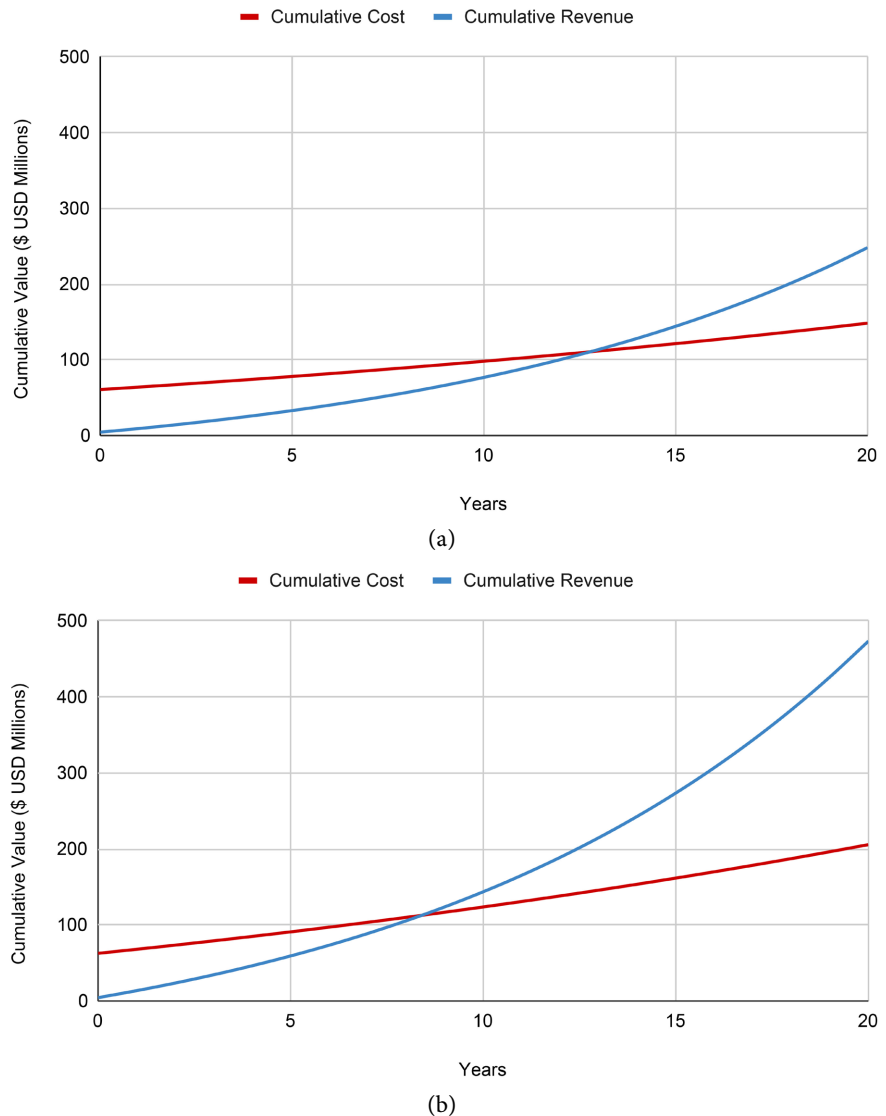
For both scenarios of the medium farm, the initial investment amounted to \$93 million USD, with yearly costs over 20 years around \$148 million USD for Scenario A and \$263 million USD for Scenario B. The equipment and setup of the pyrolysis plant account for the largest portion of the initial investment, coming in at \$64 million. Once again, out of the yearly costs, the highest costs are operation, followed by maintenance and labor for Scenario A, at \$99 million USD, \$37 million USD, and \$11 million USD, respectively over 20 years accounting for inflation, but for Scenario B, the highest cost was land application, followed by operation and maintenance, at \$115 million USD, \$99 million USD, and \$37 million USD, respectively over 20 years accounting for inflation.

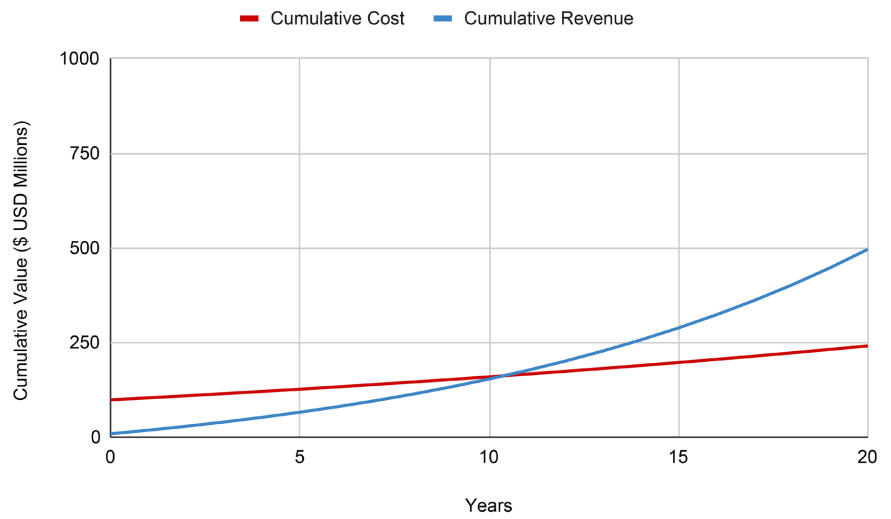
For the large farm, the initial investment in both scenarios was \$177 million USD. Yearly costs over the 20 years were \$281 million USD for Scenario A and \$568 million USD for Scenario B. For the initial investment, the highest amount was the equipment and setup of the pyrolysis plant, totaling \$121 million USD. Over 20 years and accounting for inflation, total yearly costs are most expensive for operation, followed by maintenance and labor in Scenario A, coming in at \$189 million USD, \$70 million USD, and \$21 million USD, respectively, and land application followed by operation and maintenance for Scenario B, coming in at \$287 million USD, \$189 million USD, and \$70 million USD, respectively.

Overall, operation and equipment pose the largest costs, with land application costs being among the most expensive for all farms in Scenario B. Planning & design, permit, and carbon credit certification costs are negligible in all scenarios, accounting for less than 10% of total costs combined. Comparing scenarios directly, scenarios for the medium farm cost about 2 times the corresponding small farm scenarios, and large farm scenarios cost twice their corresponding medium farm scenarios, and four times their corresponding small farm scenarios. In general, Scenario B costs around one and a half times Scenario A. Finally, all scenarios would require a significant initial investment as well as significant yearly costs. The economic feasibility of such scenarios depends on available investment capital as well as the resulting revenue and savings.

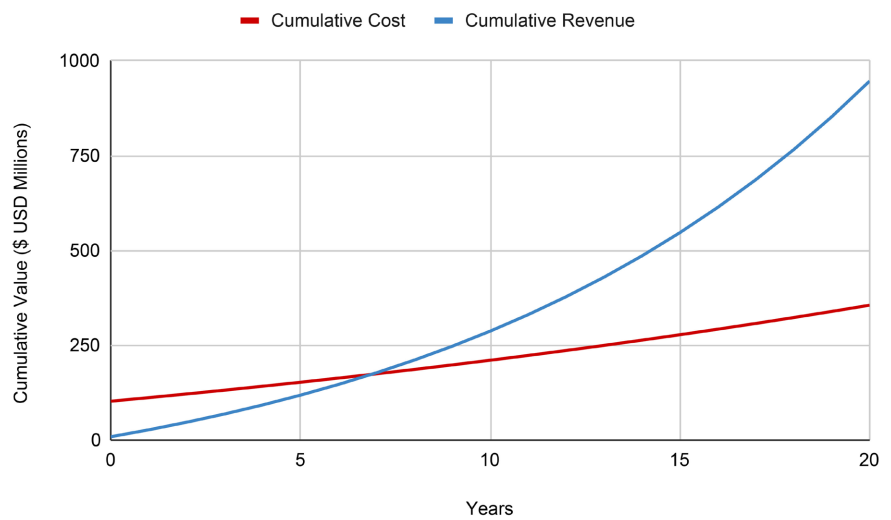
3.2. Cost-Revenue-Based Break Even Analysis

Figure 2 details the break even for the studied scenarios based on cumulative costs and revenues, while **Table 4** details the respective break even values in years.

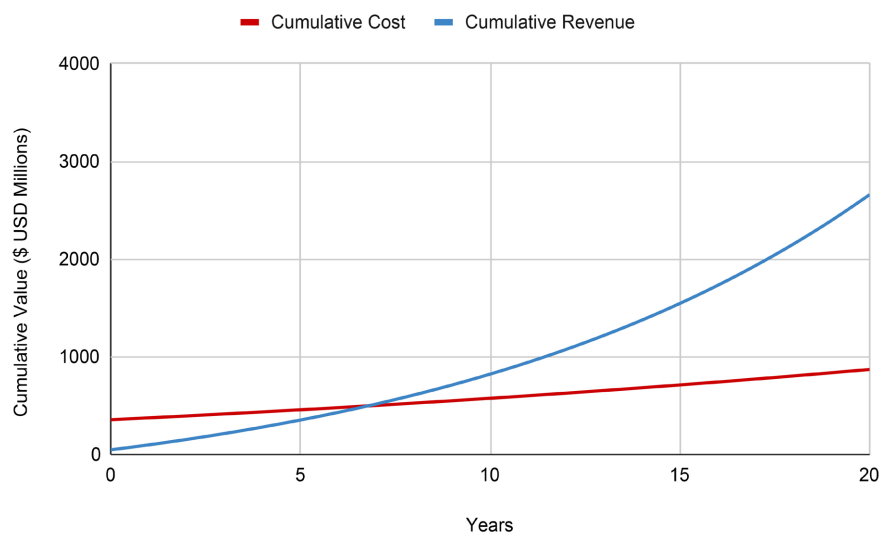




(c)



(d)



(e)

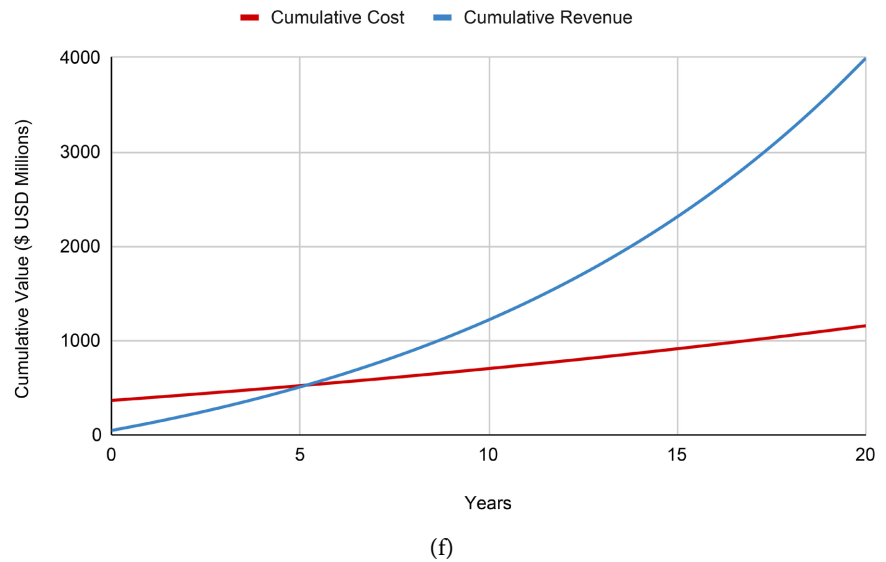


Figure 2. Life cycle break-even analysis based on cumulative costs and revenues in \$ USD millions over 20 years for a 10,000 ha farm in Scenario A (a), 10,000 ha farm in Scenario B (b), 20,000 ha farm in Scenario A (c), 20,000 ha farm in Scenario B (d), 50,000 ha farm in Scenario A (e), and 50,000 ha farm in Scenario B (f).

Table 4. Break-even year values for studied scenarios.

Farm Size	Scenario	Years
Small (10,000 ha)	A (Biochar Sale)	12.77
Small (10,000 ha)	B (With Land Application)	8.44
Medium (20,000 ha)	A (Biochar Sale)	10.46
Medium (20,000 ha)	B (With Land Application)	6.85
Large (50,000 ha)	A (Biochar Sale)	7.78
Large (50,000 ha)	B (With Land Application)	5.15

The revenue to cost ratio over 20 for each scenario (increasing farm size, Scenario A then B), the revenue to cost ratio was 1.7, 2.3, 2.1, 2.7, 2.7, and 3.2, respectively, with large farm scenarios being the most profitable overall. All investments took less than 13 years to break even, and the large farm in Scenario B broke even in 5.15 years.

3.3. Return on Investment

Figure 3 details the return on investment percentages for the studied scenarios, and **Table 5** details the respective total return on investment percentages.

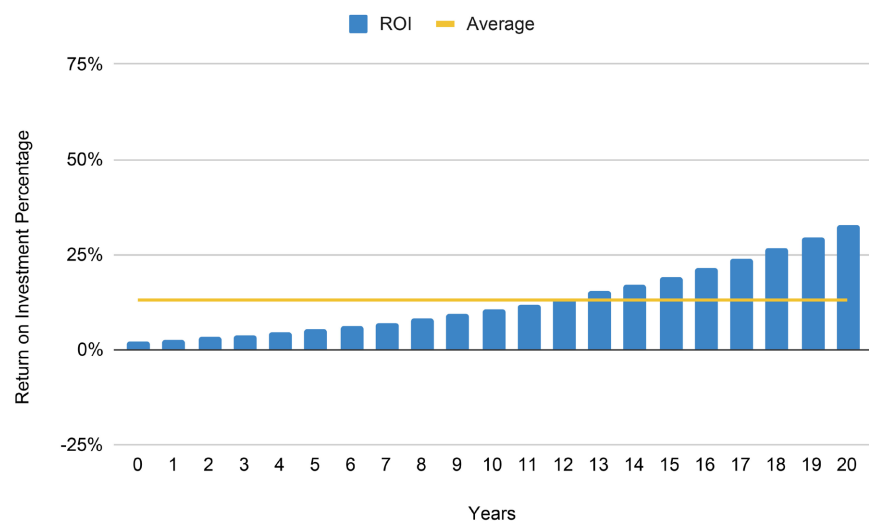
For each scenario (increasing farm size, Scenario A then B), the return on investment percentages ranged from 2% to 33%, -1% to 66%, 4% to 43%, 0% to 83%, 7% to 59%, and 1% to 113% over the 20 years, respectively.

The average return on investment per year for each scenario or each scenario

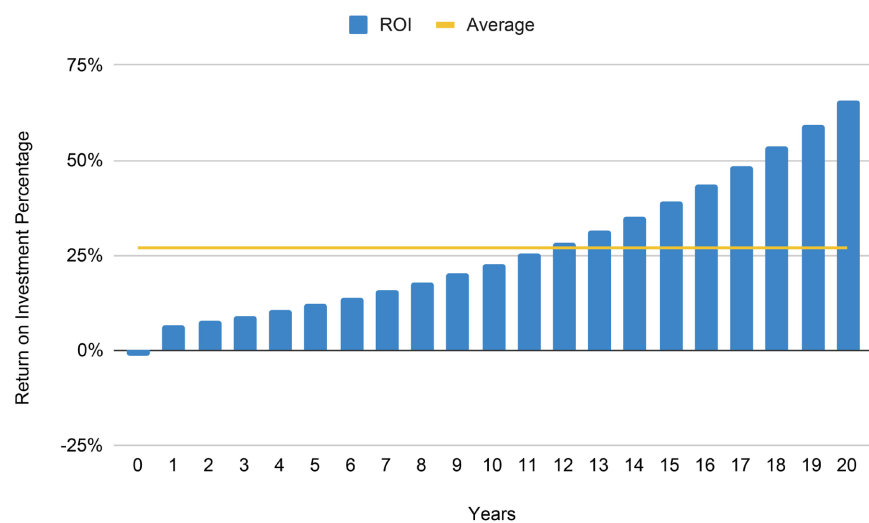
(increasing farm size, Scenario A then B) was 13%, 27%, 18%, 35%, 26%, and 48%, respectively. Scenario B farms did significantly better than their Scenario A counterparts in terms of return on investment for all farm sizes.

Table 5. Total return on investment percentage over 20 years for studied scenarios.

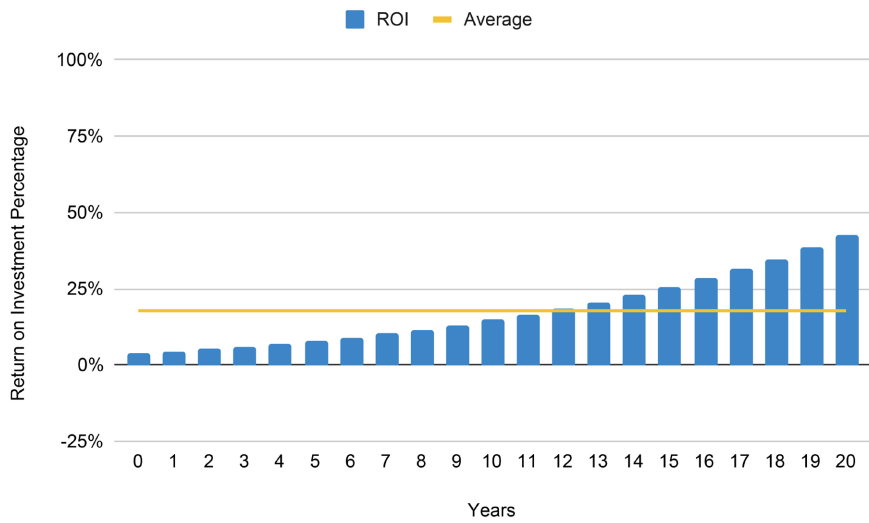
Farm Size	Scenario	ROI Percentage
Small (10,000 ha)	A (Biochar Sale)	274
Small (10,000 ha)	B (With Land Application)	566
Medium (20,000 ha)	A (Biochar Sale)	373
Medium (20,000 ha)	B (With Land Application)	733
Large (50,000 ha)	A (Biochar Sale)	542
Large (50,000 ha)	B (With Land Application)	1015



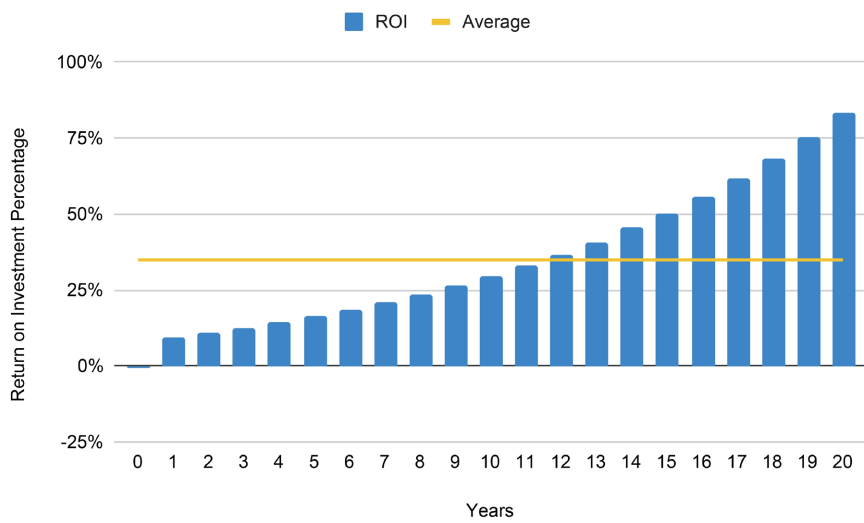
(a)



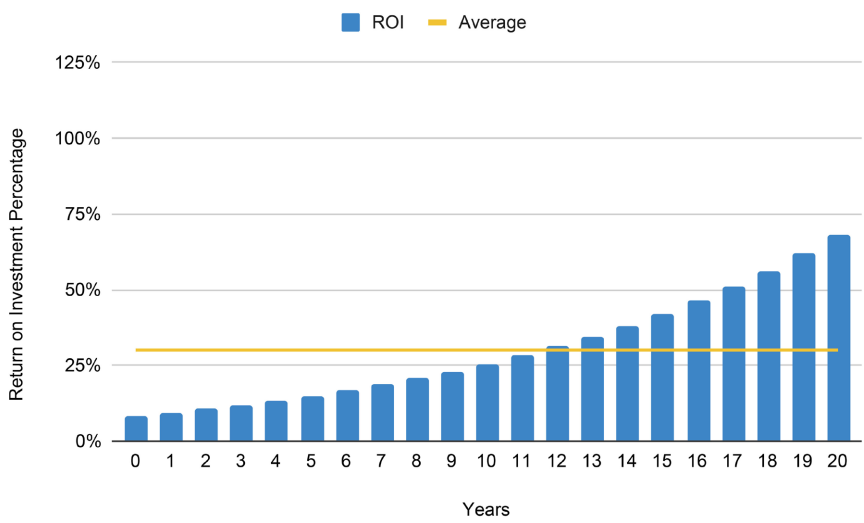
(b)



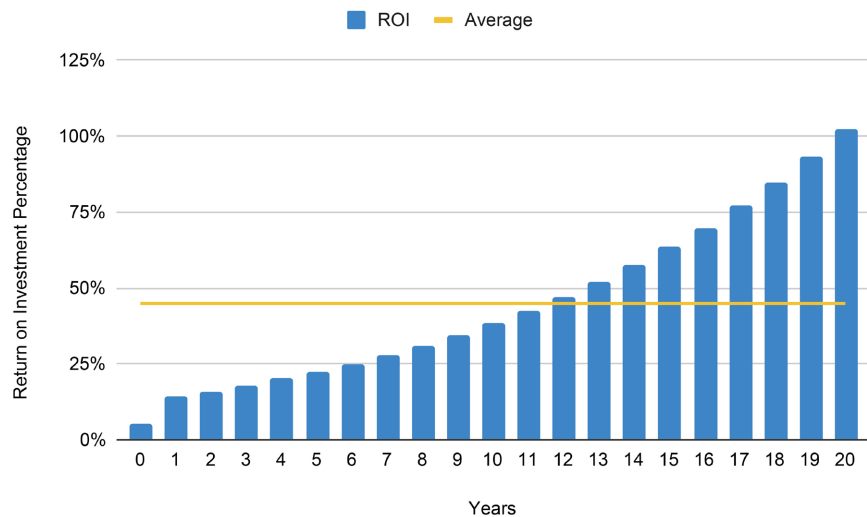
(c)



(d)



(e)



(f)

Figure 3. Return on investment percentages per year over 20 years for a 10,000 ha farm in Scenario A (a), 10,000 ha farm in Scenario B (b), 20,000 ha farm in Scenario A (c), 20,000 ha farm in Scenario B (d), 50,000 ha farm in Scenario A (e), and 50,000 ha farm in Scenario B (f).

3.4. Cost-Benefit Analysis

The cost benefit comparison for the studied scenarios is detailed in **Figure 4**.

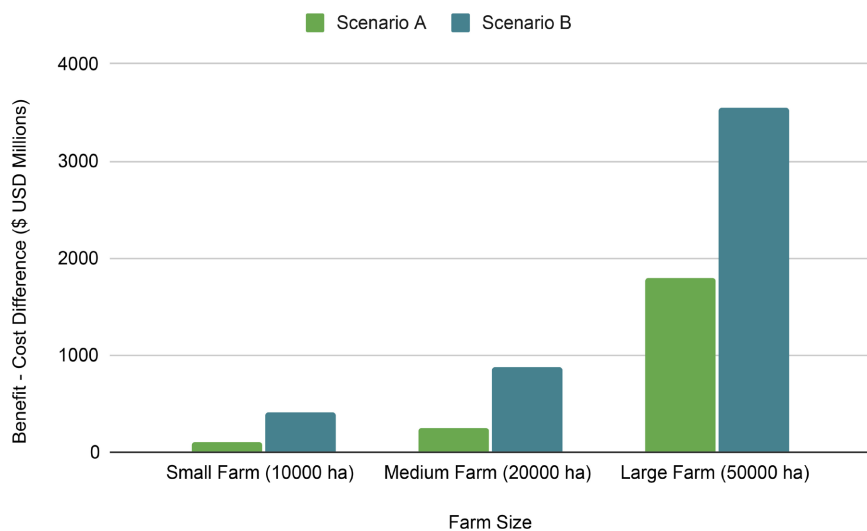


Figure 4. Cost-benefit comparison in \$ USD millions over 20 years for studied scenarios.

The difference between the total revenues and total cost for all scenarios was positive, and for each one (increasing farm size, Scenario A then B), came out to 100, 408, 255, 873, 782, and 2326 million \$ USD, respectively. Again, Scenario B farms outperform their Scenario A counterparts for all farm sizes, and large farm scenarios are the highest performing.

It can be noted that the fertilizer and crop management savings that result from

biochar land application for Scenario B farms considered as a benefit in the analysis greatly exceed the land application cost that Scenario B farms spend.

3.5. Net Present Value and Internal Rate of Return

Figure 5 details the net present value of 20 years for each of the studied scenarios.

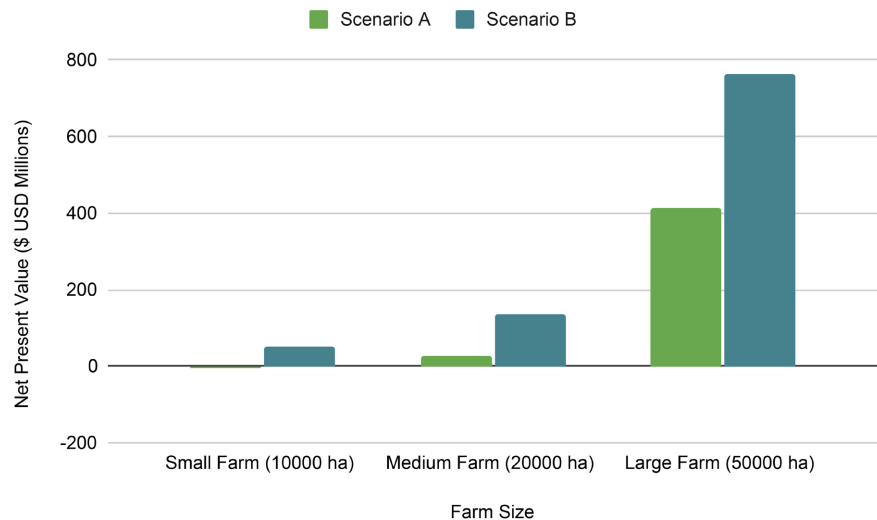


Figure 5. Net present value in \$ USD millions over 20 years for studied scenarios.

The net present value for all scenarios except for small farm Scenario A is positive, indicating a rate of return above the discount rate, and, in general, a positive investment. For small farm Scenario A, the net present value is negative, indicating a negative investment and rendering the biochar implementation in the scenario not economically viable for the purposes of this study's evaluation. For each scenario, (increasing farm size, Scenario A then B), the net present value is -6, 50, 25, 136, 158, and 436 million \$ USD, respectively. Scenario B farms, due to their increased revenue streams, had a higher net present value than their Scenario A counterparts, and large farm scenarios had net present values about 5 times greater than the medium farms, and over 8 times greater than the small farms depending on the scenario.

The internal rate of return over 20 years for all studied scenarios are detailed in **Figure 6**.

The internal rate of return, indicating the annual rate of growth that the investment is expected to generate, of 8%, 16%, 11%, 19%, 17%, and 25% for each scenario (increasing farm size, Scenario A then B) reveal that while all scenarios show positive growth, the larger farm scenarios demonstrate significantly higher returns. While all scenarios have a positive internal rate of return, the large farm scenarios have values around 1.6 times those of the small farm and 1.3 times those of the medium farm. Additionally, the internal rates of return for small farm Scenario A and medium farm Scenario A, being under 15%, indicate an unfavorable investment given the high investment costs found in the life cycle cost analysis.

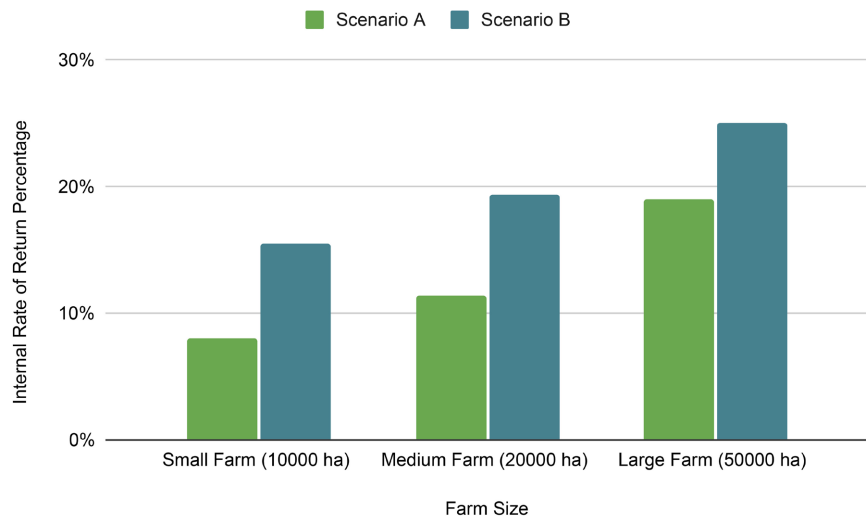


Figure 6. Internal rate of return over 20 years for studied scenarios.

3.6. Sensitivity Analysis

Figure 7 details the sensitivity of the total net result, in present value over 20 years based on a carbon credit market price ranging from \$50 to \$200/tCO₂e.

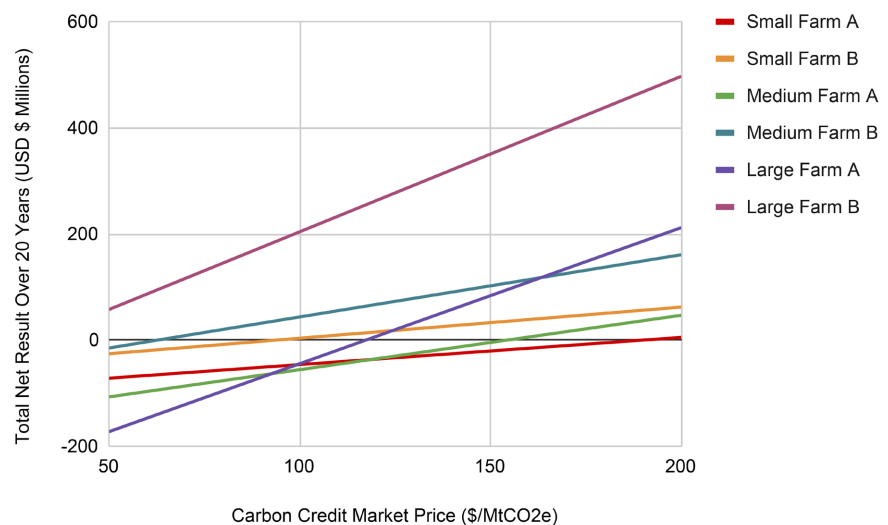


Figure 7. Sensitivity of total net result over 20 years (present value) in \$ USD millions based on carbon credit market prices of 50 to 200 (\$/tCO₂e) for studied scenarios.

For each scenario (increasing farm size, Scenario A then B), the carbon credit market price at which the net result was positive was \$200, \$100, \$160, \$70, \$120, and \$50/tCO₂e, respectively. In general, Scenario A for both small and medium farms produced negative results for any price below the current average market price of \$179/tCO₂e, with small farm Scenario A not resulting in a positive result except when the price was \$200/tCO₂e. This indicates the two scenarios may not be economically viable if the price drops. For the remaining scenarios, all produced a positive net result at about \$120/tCO₂e, indicating an almost \$60 margin

for the market price to drop. This suggests that medium and large farms, particularly those in Scenario B, have a buffer to withstand fluctuations in the carbon credit market without becoming economically unfeasible. The highest performing scenario was large farm Scenario B, which had a positive net result even at \$50/tCO_{2e}, a low price considering today's biochar carbon credit market. Importantly, the highest fluctuation in net result was also observed in the large farm scenarios, with results varying by almost \$450 USD million depending on the price. This highlights the dependence of the economic viability of a biochar operation even in large farms on the price that the generated carbon credits can be sold for.

The sensitivity of the total net result, in present value over 20 years based on bagasse availability ranging from 50% to 90% are detailed in **Figure 8**.

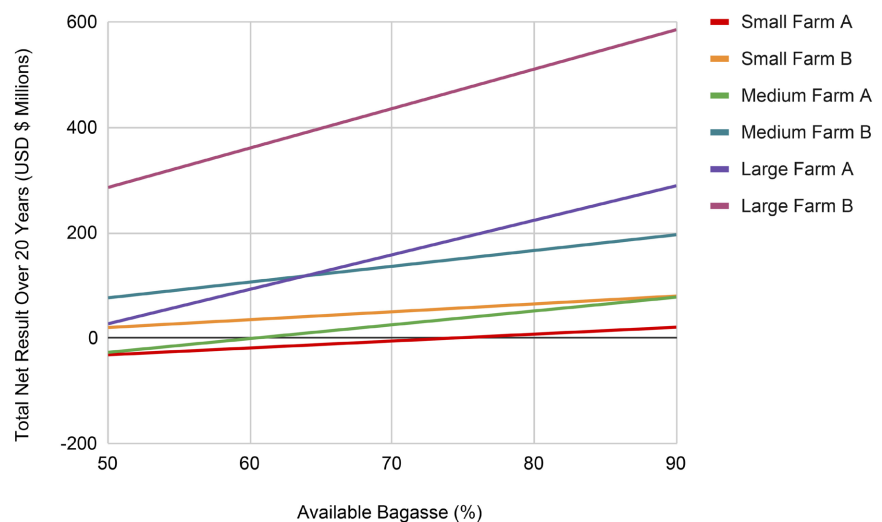


Figure 8. Sensitivity of total net result over 20 years (present value) in \$ USD millions based on bagasse availability of 50 to 90 (%) for studied scenarios.

The only scenarios to produce a negative net result at any value were small farm Scenario A and medium farm Scenario B, producing positive results at 70% and 80% bagasse availability, respectively. For the other scenarios, the net result remains positive for bagasse availability ranging from 50% to 90%, indicating viability in most cases where bagasse availability can be affected by an individual farm's equipment and electricity demands.

3.7. Technical and Economic Challenges

While the results of this study demonstrate the potential economic viability of biochar, particularly for large-scale operations, several technical and economic challenges remain, especially in the context of Brazil's agricultural sector. The pyrolysis process requires specialized equipment with high capital costs, making the initial investment a significant barrier, particularly for small and medium-sized farms.

Economically, the long-term feasibility of biochar production is closely tied to fluctuations in the carbon credit market and the operational costs associated with labor and energy. As demonstrated by the sensitivity analysis, carbon credit prices play a pivotal role in determining profitability. For smaller farms, biochar production becomes financially unfeasible when carbon credit prices fall. This highlights the vulnerability of biochar operations to market volatility, particularly in Brazil, where the carbon credit market is still maturing. Additionally, operational costs, particularly energy for pyrolysis and labor, remain significant, especially in regions where energy prices fluctuate or access to affordable labor is limited.

Moreover, Brazil's fragmented agricultural landscape, characterized by both large agribusinesses and smallholder farmers, makes the uniform implementation of biochar technology difficult. Smaller farms, which could benefit most from the soil-enhancing properties of biochar, are often the least equipped to handle the associated technical and economic burdens. Without targeted financial incentives or subsidies, these farms may struggle to adopt biochar on a meaningful scale.

To address these challenges, policy support is critical. Government intervention in the form of subsidies, financial incentives, or carbon credit guarantees could alleviate some of the economic pressure on smaller operations. Infrastructure development, particularly in regions where transportation costs are high, would also enhance the scalability of biochar production. Without such measures, the broad-scale implementation of biochar in Brazil remains constrained by both technical and economic limitations.

3.8. Limitations of the Study

This study has provided a detailed economic analysis of sugarcane bagasse-based biochar production in Brazil; however, several limitations must be acknowledged. One significant limitation is the lack of large-scale biochar operations implemented or extensively studied in practice. This introduces an inherent uncertainty regarding the real-world applicability and outcomes of the modeled scenarios. While the theoretical models and assumptions used are robust and well-grounded in existing literature, they may not fully capture the operational complexities and unforeseen challenges that might arise in actual biochar production and application.

Moreover, the values concerning the soil-amending and crop yield-increasing properties of biochar are specific to the area of the biochar operation, and significant variations in the effects of biochar application may arise depending on farm location [15]. Finally, the nascent nature of the biochar market, particularly in Brazil, adds another layer of uncertainty. The assumptions regarding market prices, availability of carbon credits, and economic incentives are based on current trends and projections, which can be highly variable and subject to change. While this study attempts to evaluate the impact of any uncertainties by conducting sensitivity analyses, considering these uncertainties and the evolving nature of biochar technology and market dynamics is crucial.

4. Conclusions

The results of this study reveal an array of conclusions on sugarcane bagasse-based biochar's economic viability. The economic models used indicate that Scenario B, which includes land application of biochar followed by the sale of surplus biochar (carbon credits), consistently outperformed Scenario A, which only considers the direct sale of biochar (carbon credits). This trend was evident across all farm sizes, with large farms demonstrating the highest economic viability. Specifically, large farm scenarios yielded the most favorable outcomes, underscoring the importance of scale to biochar's viability as a profitable catalyst for agricultural advancement in Brazil. Small farm Scenario A, however, was not economically viable, and medium farm Scenario A was highly susceptible to changes in critical values, making its economic viability questionable.

For medium and large farms, biochar production and application appeared to be economically viable under the condition that sufficient capital investment is available and that the carbon credit market prices remain stable, with some tolerance for fluctuation. The sensitivity analysis highlighted that biochar becomes feasible on average at carbon credit prices above \$120 USD/tCO₂e, providing a buffer against market volatility.

With increasing regulatory interest in carbon removal as a result of many nations's agreement to combat climate change in the United Nations Paris Agreement of 2015 [60], biochar's value as a capable instrument for carbon sequestration continues to increase [16] [22] [42]. When considering the fact that the world has lost a third of its arable land due to pollution and erosion in the past 40 years [19], biochar has become a truly interesting option for the agricultural industry. This, coupled with the scale and potential of sugarcane bagasse as a feedstock, makes sugarcane bagasse-based biochar a unique opportunity for Brazil. Regarding this possibility, key prospects for biochar to expand within Brazilian agriculture include targeted policy support, such as subsidies and carbon credit guarantees, alongside investments in agricultural infrastructure. These measures would mitigate the financial challenges smaller farms face, fostering broader adoption.

It is clear that biochar advocates will have to present a convincing argument to farmers about the benefits of biochar application in agronomy [61]. Through the economic models in this study, relevant economic benefits can be observed. In addition to the revenues and savings analyzed in the cost-benefit analysis, sugarcane producers remove disposal costs and do not incur any extra transportation costs [6], making biochar a logical addition to their business model given the funds to invest in an operation. The final verdict, therefore, lies with the specific details of an individual farm's resources, structure, and goals.

Building on the findings of this study, future research should focus on optimizing biochar production processes, particularly by improving pyrolysis efficiency to reduce energy consumption. Exploring alternative energy sources or refining operational parameters could make biochar production more cost-effective, especially for smaller farms. Additionally, refining the carbon credit certification

process and ensuring stable pricing mechanisms will be crucial to biochar's long-term viability in fluctuating markets.

Further studies on region-specific economic impacts are essential, given the variability in Brazil's agricultural infrastructure and crop cycles. Tailoring biochar solutions to local conditions will enhance scalability and feasibility across diverse farming contexts. Moreover, exploring public-private partnerships could lower the financial barriers for smallholders by introducing innovative financing models, such as shared pyrolysis facilities or co-investment schemes. Finally, studies on other agricultural biomass inputs, such as coffee, corn, and nut shells for biochar production can prove crucial to diversifying the global biochar scene.

Ultimately, with targeted research and supportive policy frameworks, biochar can play a transformative role in Brazil's agricultural landscape, driving both economic and environmental benefits.

Table 6 details the final ranking of studied scenarios based on analysis of the Biochar Economic Viability Model.

Table 6. Ranking of studied scenarios based on an analysis of the Biochar Economic Viability Model.

Rank	Scenario	Comment
1	Large B	Viable given investment availability
2	Large A	Viable given investment availability
3	Medium B	Viable given investment availability
4	Small B	Viable, low IRR for high investment
5	Medium A	Barely viable, easily rendered unviable
6	Small A	Not viable

In conclusion, an evaluation of sugarcane bagasse-based biochar's economic viability reveals that sugarcane bagasse-based biochar can in fact, under the right conditions, be a viable option for Brazil's most notable agricultural and environmental initiatives.

Acknowledgements

The author is grateful for the opportunity and all the support, insights, and expertise provided by PSR Energy Consulting and Analytics, Rio de Janeiro, Brazil.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

References

- [1] (2023, November 23) Biochar Is Carbon Removal's Jack of All Trades. Here's Why. World Economic Forum. <https://www.weforum.org/agenda/2023/11/biochar-carbon-removals-jack-of-all-trades-for-immediate-climate-action/>

- [2] de Almeida, S.G.C., Tarelho, L.A.C., Hauschild, T., Costa, M.A.M. and Dussán, K.J. (2022) Biochar Production from Sugarcane Biomass Using Slow Pyrolysis: Characterization of the Solid Fraction. *Chemical Engineering and Processing—Process Intensification*, **179**, Article ID: 109054. <https://doi.org/10.1016/j.cep.2022.109054>
- [3] Ramirez, J.A. and Rainey, T.J. (2019) Comparative Techno-Economic Analysis of Biofuel Production through Gasification, Thermal Liquefaction and Pyrolysis of Sugarcane Bagasse. *Journal of Cleaner Production*, **229**, 513-527. <https://doi.org/10.1016/j.jclepro.2019.05.017>
- [4] Parmar, A., Nema, P.K. and Agarwal, T. (2014) Biochar Production from Agro-Food Industry Residues: A Sustainable Approach for Soil and Environmental Management. *Current Science*, **107**, 1673-1682. <https://www.jstor.org/stable/24107941>
- [5] Patel, M., Zhang, X. and Kumar, A. (2016) Techno-Economic and Life Cycle Assessment on Lignocellulosic Biomass Thermochemical Conversion Technologies: A Review. *Renewable and Sustainable Energy Reviews*, **53**, 1486-1499. <https://doi.org/10.1016/j.rser.2015.09.070>
- [6] Toscano Miranda, N., Lopes Motta, I., Maciel Filho, R. and Wolf Maciel, M.R. (2021) Sugarcane Bagasse Pyrolysis: A Review of Operating Conditions and Products Properties. *Renewable and Sustainable Energy Reviews*, **149**, Article ID: 111394. <https://doi.org/10.1016/j.rser.2021.111394>
- [7] de A. Sousa, J.G., Cherubin, M.R., Cerri, C.E.P., Cerri, C.C. and Feigl, B.J. (2017) Sugar Cane Straw Left in the Field during Harvest: Decomposition Dynamics and Composition Changes. *Soil Research*, **55**, Article No. 758. <https://doi.org/10.1071/sr16310>
- [8] Ahmed, A., Kurian, J. and Raghavan, V. (2016) Biochar Influences on Agricultural Soils, Crop Production, and the Environment: A Review. *Environmental Reviews*, **24**, 495-502. <https://doi.org/10.1139/er-2016-0008>
- [9] Cardoso, T.d.F., Cavalett, O., Chagas, M.F., Morais, E.R.d., Carvalho, J.L.N., Franco, H.C.J., *et al.* (2013) Technical and Economic Assessment of Trash Recovery in the Sugarcane Bioenergy Production System. *Scientia Agricola*, **70**, 353-360. <https://doi.org/10.1590/s0103-90162013000500010>
- [10] López, B. (2024, January 8) Valorizing Agrifood Waste Streams into Biochar. Cleantech. <https://www.cleantech.com/valorizing-agrifood-waste-streams-into-biochar/>
- [11] Gonçalves, E.V., Seixas, F.L., de Souza Scanduzzi Santana, L.R., Scaliante, M.H.N.O. and Gimenes, M.L. (2017) Economic Trends for Temperature of Sugarcane Bagasse Pyrolysis. *The Canadian Journal of Chemical Engineering*, **95**, 1269-1279. <https://doi.org/10.1002/cjce.22796>
- [12] Tenenbaum, D.J. (2009) Biochar: Carbon Mitigation from the Ground up. *Environmental Health Perspectives*, **117**, A70-A73. <https://doi.org/10.1289/ehp.117-a70>
- [13] Lehmann, J., Pereira da Silva Jr., J., Steiner, C., Nehls, T., Zech, W. and Glaser, B. (2003) Nutrient Availability and Leaching in an Archaeological Anthrosol and a Ferralsol of the Central Amazon Basin: Fertilizer, Manure and Charcoal Amendments. *Plant and Soil*, **249**, 343-357. <https://doi.org/10.1023/a:1022833116184>
- [14] Joseph, S., Cowie, A.L., Van Zwieten, L., Bolan, N., Budai, A., Buss, W., *et al.* (2021) How Biochar Works, and When It Doesn't: A Review of Mechanisms Controlling Soil and Plant Responses to Biochar. *GCB Bioenergy*, **13**, 1731-1764. <https://doi.org/10.1111/gcbb.12885>
- [15] Li, X., Wu, D., Liu, X., Huang, Y., Cai, A., Xu, H., *et al.* (2024) A Global Dataset of Biochar Application Effects on Crop Yield, Soil Properties, and Greenhouse Gas Emissions. *Scientific Data*, **11**, Article No. 57.

- <https://doi.org/10.1038/s41597-023-02867-9>
- [16] Sohi, S.P. (2012) Carbon Storage with Benefits. *Science*, **338**, 1034-1035. <https://doi.org/10.1126/science.1225987>
- [17] Zafeer, M.K., Menezes, R.A., Venkatachalam, H. and Bhat, K.S. (2023) Sugarcane Bagasse-Based Biochar and Its Potential Applications: A Review. *Emergent Materials*, **7**, 133-161. <https://doi.org/10.1007/s42247-023-00603-y>
- [18] Hermans, J. (2013) Biochar Benefits: An Introduction to Making Biochar. *ReNew: Technology for a Sustainable Future*, **124**, 76-79. <https://www.jstor.org/stable/renetechsustfutu.124.76>
- [19] Yu, H., Zou, W., Chen, J., Chen, H., Yu, Z., Huang, J., *et al.* (2019) Biochar Amendment Improves Crop Production in Problem Soils: A Review. *Journal of Environmental Management*, **232**, 8-21. <https://doi.org/10.1016/j.jenvman.2018.10.117>
- [20] van de Voorde, T.F.J., Bezemer, T.M., Van Groenigen, J.W., Jeffery, S. and Mommer, L. (2014) Soil Biochar Amendment in a Nature Restoration Area: Effects on Plant Productivity and Community Composition. *Ecological Applications*, **24**, 1167-1177. <https://doi.org/10.1890/13-0578.1>
- [21] Purakayastha, T.J., Bera, T., Bhaduri, D., Sarkar, B., Mandal, S., Wade, P., *et al.* (2019) A Review on Biochar Modulated Soil Condition Improvements and Nutrient Dynamics Concerning Crop Yields: Pathways to Climate Change Mitigation and Global Food Security. *Chemosphere*, **227**, 345-365. <https://doi.org/10.1016/j.chemosphere.2019.03.170>
- [22] Galinato, S.P., Yoder, J.K. and Granatstein, D. (2011) The Economic Value of Biochar in Crop Production and Carbon Sequestration. *Energy Policy*, **39**, 6344-6350. <https://doi.org/10.1016/j.enpol.2011.07.035>
- [23] Chang, Y., Rossi, L., Zotarelli, L., Gao, B., Shahid, M.A. and Sarkhosh, A. (2021) Biochar Improves Soil Physical Characteristics and Strengthens Root Architecture in Muscadine Grape (*Vitis rotundifolia* L.). *Chemical and Biological Technologies in Agriculture*, **8**, Article No. 7. <https://doi.org/10.1186/s40538-020-00204-5>
- [24] Blanco-Canqui, H. (2017) Biochar and Soil Physical Properties. *Soil Science Society of America Journal*, **81**, 687-711. <https://doi.org/10.2136/sssaj2017.01.0017>
- [25] Schmidt, H., Kammann, C., Hagemann, N., Leifeld, J., Bucheli, T.D., Sánchez Monedero, M.A., *et al.* (2021) Biochar in Agriculture—A Systematic Review of 26 Global Meta-Analyses. *GCB Bioenergy*, **13**, 1708-1730. <https://doi.org/10.1111/gcbb.12889>
- [26] Borges, B.M.M.N., Strauss, M., Camelo, P.A., Sohi, S.P. and Franco, H.C.J. (2020) Reuse of Sugarcane Residue as a Novel Biochar Fertiliser-Increased Phosphorus Use Efficiency and Plant Yield. *Journal of Cleaner Production*, **262**, Article ID: 121406. <https://doi.org/10.1016/j.jclepro.2020.121406>
- [27] Champion, L., Bekchanova, M., Malina, R. and Kuppens, T. (2023) The Costs and Benefits of Biochar Production and Use: A Systematic Review. *Journal of Cleaner Production*, **408**, Article ID: 137138. <https://doi.org/10.1016/j.jclepro.2023.137138>
- [28] Lima, I. and White, M. (2017) Sugarcane Bagasse and Leaf Residue Biochars as Soil Amendment for Increased Sugar and Cane Yields. *International Sugar Journal*, **119**, 354-363.
- [29] Brown, T.R., Wright, M.M. and Brown, R.C. (n.d.) Estimating Profitability of Two Biochar Production Scenarios: Slow Pyrolysis vs. Fast Pyrolysis. Iowa State University.
- [30] Jeffery, S., Abalos, D., Spokas, K. and Verheijen, F.G.A. (2014) Biochar for

- Environmental Management 2—Biochar Effects on Crop Yield. 299-324.
- [31] Brazil (2021) World Bank Climate Change Knowledge Portal. <https://climateknowledgeportal.worldbank.org/country/brazil/climate-data-historical#:~:text=Brazil%20experiences%20equatorial%2C%20tropical%20as.to%20the%20planet's%20energy%20balance>
- [32] Martins Filho, A.P., Medeiros, E.V.D., Lima, J.R.S., Costa, D.P.D., Duda, G.P., Silva, J.S.A.D., *et al.* (2021) Impact of Coffee Biochar on Carbon, Microbial Biomass and Enzyme Activities of a Sandy Soil Cultivated with Bean. *Anais da Academia Brasileira de Ciências*, **93**. <https://doi.org/10.1590/0001-3765202120200096>
- [33] Biochar (n.d.) United States Department of Agriculture. <https://www.climatehubs.usda.gov/hubs/northwest/topic/biochar#:~:text=Biochar%20is%20a%20stable%20solid.stalks%2C%20manure%2C%20etc.>
- [34] (n.d.) Biochar—A Strategy to Adapt/Mitigate Climate Change? FAO. https://www.fao.org/fileadmin/templates/rome2007initiative/NENA_Forum_2009/Factsheets/FAO_CCFactsheet_Biochar.pdf
- [35] (2024, February 15) Outlook for the Global Biochar Market. MSCI. <https://trove-research.com/report/outlook-for-the-global-biochar-market>
- [36] (2023, February) Biochar Market (by Technology: Pyrolysis, Gasification, Others; by Feedstock: Woody Biomass, Agricultural Waste, Animal Manure, Others; by Application: Agriculture, Forestry, Electricity Generation, Others)—Global Industry Analysis, Size, Share, Growth, Trends, Regional Outlook, and Forecast 2023-2032. Precedence Research. <https://www.precedenceresearch.com/biochar-market#:~:text=The%20global%20biochar%20market%20size,11.14%25%20from%202023%20to%202032>
- [37] Meadows, R. (2015) Biomass Could Generate Carbon-Negative Power. *Frontiers in Ecology and the Environment*, **13**, 124. <https://www.jstor.org/stable/44000713>
- [38] Cherubin, M.R., Oliveira, D.M.d.S., Feigl, B.J., Pimentel, L.G., Lisboa, I.P., Gmach, M.R., *et al.* (2018) Crop Residue Harvest for Bioenergy Production and Its Implications on Soil Functioning and Plant Growth: A Review. *Scientia Agricola*, **75**, 255-272. <https://doi.org/10.1590/1678-992x-2016-0459>
- [39] (2022, July) OECD-FAO Agricultural Outlook 2022-2031. OECD Data Explorer. [https://data-explorer.oecd.org/vis?fs\[0\]=T%2Co&fs\[1\]=V%2Ce&fs\[2\]=Topic%2C2%7CAgriculture%20and%20fisheries%23AGR%23%7CAgricultural%20trade%20and%20markets%23AGR_TRD%23%7CAgricultural%20market%20outlook%20%28OECD-FAO%20agricultural%20outlook%29%23AGR_TRD_OUT%23&vw=tb&df\[ds\]=dsDisseminateFinaIDMZ&df\[id\]=DSD_AGR%40DF_OUT_LOOK_2022_2031&df\[ag\]=OECD.TAD.ATM&df\[vs\]=1.0&dq=BRA%2BOECD.A.CPC_01802...&pd=2010%2C2031&to\[TIME_PERIOD\]=false&snb=4&fc=Topic&pg=0](https://data-explorer.oecd.org/vis?fs[0]=T%2Co&fs[1]=V%2Ce&fs[2]=Topic%2C2%7CAgriculture%20and%20fisheries%23AGR%23%7CAgricultural%20trade%20and%20markets%23AGR_TRD%23%7CAgricultural%20market%20outlook%20%28OECD-FAO%20agricultural%20outlook%29%23AGR_TRD_OUT%23&vw=tb&df[ds]=dsDisseminateFinaIDMZ&df[id]=DSD_AGR%40DF_OUT_LOOK_2022_2031&df[ag]=OECD.TAD.ATM&df[vs]=1.0&dq=BRA%2BOECD.A.CPC_01802...&pd=2010%2C2031&to[TIME_PERIOD]=false&snb=4&fc=Topic&pg=0)
- [40] Clauser, N.M., Gutiérrez, S., Area, M.C., Felissia, F.E. and Vallejos, M.E. (2018) Alternatives of Small-Scale Biorefineries for the Integrated Production of Xylitol from Sugarcane Bagasse. *Journal of Renewable Materials*, **6**, 139-151. <https://doi.org/10.7569/jrm.2017.634145>
- [41] Cardona, C.A., Quintero, J.A. and Paz, I.C. (2010) Production of Bioethanol from Sugarcane Bagasse: Status and Perspectives. *Bioresource Technology*, **101**, 4754-4766. <https://doi.org/10.1016/j.biortech.2009.10.097>

- [42] Nematian, M., Keske, C. and Ng'ombe, J.N. (2021) A Techno-Economic Analysis of Biochar Production and the Bioeconomy for Orchard Biomass. *Waste Management*, **135**, 467-477. <https://doi.org/10.1016/j.wasman.2021.09.014>
- [43] Brownsort, P.A. (2009) Biomass Pyrolysis Processes: Performance Parameters and Their Influence on Biochar System Benefits. University of Edinburgh.
- [44] Homagain, K., Shahi, C., Luckai, N. and Sharma, M. (2015) Life Cycle Environmental Impact Assessment of Biochar-Based Bioenergy Production and Utilization in North-western Ontario, Canada. *Journal of Forestry Research*, **26**, 799-809. <https://doi.org/10.1007/s11676-015-0132-y>
- [45] Kung, C., McCarl, B.A. and Cao, X. (2013) Economics of Pyrolysis-Based Energy Production and Biochar Utilization: A Case Study in Taiwan Region. *Energy Policy*, **60**, 317-323. <https://doi.org/10.1016/j.enpol.2013.05.029>
- [46] Hammond, J., Shackley, S., Sohi, S. and Brownsort, P. (2011) Prospective Life Cycle Carbon Abatement for Pyrolysis Biochar Systems in the Uk. *Energy Policy*, **39**, 2646-2655. <https://doi.org/10.1016/j.enpol.2011.02.033>
- [47] Lefebvre, D., Williams, A., Meersmans, J., Kirk, G.J.D., Sohi, S., Goglio, P., *et al.* (2020) Modelling the Potential for Soil Carbon Sequestration Using Biochar from Sugarcane Residues in Brazil. *Scientific Reports*, **10**, Article No. 19479. <https://doi.org/10.1038/s41598-020-76470-y>
- [48] (2024, July 5) Focus-Market Readout. Banco Central Do Brasil. <https://www.bcb.gov.br/en/publications/focusmarketreadout>
- [49] (2024, April) Average Inflation Rate in Brazil from 2007 to 2029. Statista. <https://www.statista.com/statistics/1391880/average-inflation-rate-brazil/#:~:text=The%20average%20inflation%20rate%20in,to%202.99%20percent%20in%202029>
- [50] (2024, April) Sugar Annual-Brazil. United States Department of Agriculture. https://apps.fas.usda.gov/newgainapi/api/Report/DownloadReportByFileName?fileName=Sugar%20Annual_Brasilia_Brazil_BR2024-0008.pdf
- [51] (2023, July 7) Gold Standard Fee Schedule [Fact Sheet]. Gold Standard for the Global Goals. <https://globalgoals.goldstandard.org/fees/>
- [52] Amorim, F.R.d., Patino, M.T.O. and Santos, D.F.L. (2022) Soil Tillage and Sugarcane Planting: An Assessment of Cost and Economic Viability. *Scientia Agricola*, **79**, e20190317. <https://doi.org/10.1590/1678-992x-2019-0317>
- [53] (2023, December) Price Level Index of Selected Countries Worldwide in 2022. Statista. <https://www.statista.com/statistics/426431/price-level-index-comparison-imf-and-world-bank-by-country/>
- [54] (2023, may 2) Medida provisória aumenta salário mínimo para R\$ 1.320 a partir de maio. Câmara Dos Deputados. <https://www.camara.leg.br/noticias/957339-medida-provisoria-aumenta-salario-minimo-para-r-1-320-a-partir-de-maio/>
- [55] (2023, May 30) 2022-2023 Annual Wage Review. Fairwork Australian Government. <https://www.fairwork.gov.au/about-us/workplace-laws/award-changes/annual-wage-review/2022-2023-annual-wage-review>
- [56] (2021, September) Financial Assumptions. EPA. <https://www.epa.gov/system/files/documents/2021-09/chapter-10-financial-assumptions.pdf>
- [57] (2024, April 23) Brazil Analysts Raise Key Rate Forecasts for This Year and Next.

- Bloomberg.
<https://www.bloomberg.com/news/articles/2024-04-23/brazil-analysts-raise-key-rate-forecasts-for-this-year-and-next>
- [58] (2023, October 30) Markets Raise Brazilian Interest Rate Projections amid U.S. Tightening.
<https://brazilian.report/liveblog/politics-insider/2023/10/30/interest-rate-projections-2024/>
- [59] (2024, March 1) Toucan Launches World's First Liquid Market for Biochar Carbon Credits. Carbon Credits.
<https://carboncredits.com/toucan-launches-worlds-first-liquid-market-for-biochar-carbon-credits/>
- [60] Xia, L., Cao, L., Yang, Y., Ti, C., Liu, Y., Smith, P., *et al.* (2023) Integrated Biochar Solutions Can Achieve Carbon-Neutral Staple Crop Production. *Nature Food*, **4**, 236-246. <https://doi.org/10.1038/s43016-023-00694-0>
- [61] Kulyk, N. (2012, May) Cost-Benefit Analysis of the Biochar Application in the U.S. Cereal Crop Cultivation. University of Massachusetts Amherst.
<https://www.semanticscholar.org/paper/Cost-Benefit-Analysis-of-the-Biochar-Application-in-Kulyk/097a06c804497314fc4447b828fe8e554a97860d>