




Article

Economic Analysis of Biochar Use in Soybean Production in Poland

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Citation: Latawiec, A.E.; Koryś, A.; Koryś, K.A.; Kuboń, M.; Sadowska, U.; Gliniak, M.; Sikora, J.; Drosik, A.; Niemiec, M.; Klimek-Kopyra, A.; et al. Economic Analysis of Biochar Use in Soybean Production in Poland. *Agronomy* **2021**, *11*, 2108. <https://doi.org/10.3390/agronomy11112108>

Academic Editor: Lukas Trakal

Received: 7 September 2021

Accepted: 13 October 2021

Published: 21 October 2021

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Abstract: Soybean (*Glycine max* L.) is one of the most important crops grown globally. Biochar has been proposed as an alternative to aid sustainable soybean production. However, comprehensive studies that include both the economic aspects of soybean production and biochar are scarce. Poland, with an economy largely based on agriculture, is an interesting case to investigate the cost-effectiveness of using biochar in soybean production. We show that the use of biochar at rates of 40, 60 and 80 t/ha is unprofitable compared with a traditional soil amendment, such as NPK fertilization. The breakeven price for biochar to be economically viable should be USD 39.22, USD 38.29 and USD 23.53 for 40, 60 and 80 Mg/ha biochar, respectively, while the cost of biochar used for this experiment was USD 85.33. The payback period for doses of 40 and 60 Mg/ha was estimated to be three years. With a carbon sequestration subsidy of USD 30 per ton of CO₂, the use of biochar may be profitable in the first year of soybean production. This is the first comprehensive economic analysis of the use of biochar in soybean production in Poland and one of the few published worldwide.

Keywords: sustainable agriculture; novel soil enhancers; economic analysis

1. Introduction

Enriching soils with biochar, a carbon-rich product derived from the pyrolysis of biomass residues [1], has been proposed as an alternative for enhancing the ecosystem services provided by soils [2,3]. Numerous studies have shown that the use of biochar improves soil conditions by increasing soil pH, macronutrient and organic matter contents, water regulation and the stability of soil aggregates and may have a positive effect on crop productivity [4–9]. Among soil amendments, biochar is distinguished by its ability to rapidly increase soil carbon sequestration and, thus, by diminishing CO₂ emissions, contributing to the mitigation of climate change, and possibly may be used in the carbon market [3,10]. It is expected that by 2030, the price of allowances under the European Commission's (EU's) emissions trading system could rise to EUR 65/t of CO₂ equivalent (CO₂eq) under the EU's most ambitious scenario for greenhouse gases (GHG) reduction. Among the estimated scenarios, the MIX-50 scenario would raise prices to EUR 36/t CO₂eq but would reduce GHG emissions by 51 percent due to increase in carbon prices and an increase in energy and transport policy. MIX and MIX non-CO₂ scenarios, both of which would reduce GHG by around 55 percent, leading to an EU ETS price of EUR 44/t CO₂eq in 2030 [11]. In the absence of a fixed carbon credit market, the benefits resulting from the increase in crop yield are the fundamental factors determining the economic profitability of biochar application [1].

Economic assessment of the use of biochar in the agricultural sector is frequently overlooked. Moreover, among studies that considered biochar economic viability, only a few dozen conducted comprehensive cost–benefit analyses (CBA) or life cycle assessments (LCA) of using biochar as a soil amendment, e.g., [2,7,12,13]; (Supplementary Material, Table S1, Word file). This may be due to several factors. First, market prices for biochar are not established, and the costs of its application are estimated based on the cost of the raw material, production process, transport and application methods [14,15]. Second, there are discrepancies between the observed short-term agricultural benefits and the expectations of biochar as a sustainable soil improvement in the long term [2]. The properties and efficiency of biochar differ depending on the initial soil condition [16,17], plant species [6,18], climate [19], type of feedstock, pyrolysis temperature and biochar dose [16,20–23]. In addition, there are inconsistencies in the results of yields from pot and field trials, and often, only those from pot studies are considered [7,17]. Considering that the available data from long-term field studies may be insufficient and that the application rates of biochar are still not well defined to provide general recommendations for its use, the results of short-term experiments may not seem financially encouraging to introduce biochar on a commercial scale [15].

Soybean (*Glycine max* L.) is one of the most nutritionally and economically valuable legumes in the world. It is widely used and contains high-quality protein and oil, essential for human health [24–26]. Symbiosis with nodule bacteria (*Bradyrhizobium japonicum*) enables the fixation of atmospheric nitrogen and enrichment of the soil with this macronutrient [27]. Moreover, the cultivation of soybean enriches the soil with organic matter in the form of crop residues rich in macro- and microelements, thus improving its physical properties. In addition, soybean cultivation reduces the development of pests and cereal diseases, it plays a key role in crop rotation, and positively influences higher yields of subsequent crops, especially rapeseed and cereals [28,29]. Introducing legumes into the crop rotation every four years causes a significant decrease in CO₂ emissions [30].

Global soybean production has been increasing significantly over the last decades [31] and is forecasted to continue increasing at least until 2030 [32]. Its global production is approximately 176.6 million tons over 75.5 million hectares of arable land [28,33,34]. Increasing the soybean cultivation area in Europe, including for fodder purposes, is one of the assumptions of the European Soy Declaration signed by 13 member states in Brussels on 17 July 2017, during the meeting of the Council of Agriculture Ministers of the European Union [35].

Understanding of the economic potential generated by the use of biochar in soybean cultivation is still poorly evidenced. At the same time, if synergies are observed, biochar could be an important ally in the European plans to increase soybean production. Comprehensive analysis is fundamental for the decision-making process on the adoption of biochar at the national and international levels [2,36].

To this end, this study aims to: (i) evaluate the agronomic efficacy of biochar relative to all the control and conventional synthetic fertilizer treatments; (ii) analyse economic benefits from soybean yield increases versus the costs of biochar; (iii) evaluate the potential long-term benefits of biochar stemming from carbon sequestration in soil. This is the first study in Poland that performs a cost–benefit analysis of the use of biochar for soybean production and one of the few worldwide. In addition, the conditions required to enhance the economic feasibility of using biochar in soybean production and in climate change mitigation strategy are discussed. The results presented here can support the decision-making process for different stakeholders and for development of guidelines to the implementation of biochar at a commercial scale.

2. Materials and Methods

2.1. Systematic Literature Review

A systematic literature review was conducted in the Web of Science database to identify articles that performed a comprehensive CBA of biochar. The following script was used: ‘biochar’ AND (‘cost–benefit*’ OR ‘life cycle assessment’). The search resulted in 272 articles, yet most of the articles were not related to the subject. Adding ‘soybeans’ resulted in three articles ($n = 3$) that presented a CBA or life cycle assessment of biochar using soybeans as a test crop or in mixed cropping. Publications on the effects of biochar on soil ecosystem services (SES) in soybean farming were identified using the keywords: ‘biochar’ AND ‘soybean*’, without restriction to year (until February 2021). This research returned 219 hits of which 69 were carried towards further analysis based on the title, abstract and the methods (Supplementary Material Table S3, Excel file).

2.2. Agronomic Methods

The current research was based on the data from a field experiment located at the experimental station of the Agricultural University of Kraków (50°04′ N, 19°51′ E). The experiment was carried out over 2018 and 2019. The soils were Calcaric/Dolomitic Leptosols (Ochric), according to the WRB soil classification [37], mostly composed of sand (56.7%), silt (32%) and clay (10.4%) with a gravel fraction (0.9%). Chemical properties of the soil are presented in Table 1. Two types of biochar were assessed: sunflower husk (BA) and woodchips (BB), obtained during the batch pyrolysis at the temperature of 450–550 °C. Experimental plots had dimensions of 1.2 × 1.2 m with three rates of biochar addition (40 Mg/ha, 60 Mg/ha and 80 Mg/ha) plus control (with no soil amendments applied) with four replicates for each treatment.

Biochar was applied manually to the plots to a depth of 20 cm with a hand-operated rotary cultivator. The soybean (*Glycine max* L., the variety Elegance F1) was sown in the second week of April 2019. Plantings (80 seeds per m²) were used. NPK mineral fertilization was applied in the following doses: 30 kg N, 70 kg P₂O₅, 100 kg K₂O. Before sowing, the soybeans were inoculated with bacteria of the genus *Bradyrhizobium japonicum*. The seed yield was determined based on the structure of the soybean yield and the degree of pod pinching as a parameter of plant adaptation to habitat conditions. A detailed description of the experiment, methodology, chemical composition of biochar used in the experiment and data on soil properties can be found in Klimek-Kopyra (2021) [38] and Kuboń et al. [39].

Table 1. Chemical properties of the experimental soil. Adapted from Kuboń [39].

pH In H ₂ O	pH In KCl	Chemical Nutrients						
		N Total (g·kg ⁻¹)	C org	N min	P	K (mg·kg ⁻¹)	Mg	Ca
6.73	6.28	0.116	1.33	32.1	99.4	81.9	42.01	836.9

2.3. Economic Analysis

The benefits (crop yield) from using biochar were compared to the control and fertilizer use. The crop yields resulting from the three doses of both biochars were compared with the average crop yield and its price in 2019 and 2020. Additionally, we adopted data from organic soybean production and added this as a scenario to our analysis. The calculation of profitability did not include the costs of weeding crops; the experimental field was weeded manually. In addition, other agrotechnical costs related to cultivation, such as costs related to tillage (for instance ploughing, harrowing or use of a cultivator, including fuel, lubricants, depreciation of the tractor and machine, human labour) were not considered, since they did not differ regardless of the treatment (Supplementary Materials Table S4, Excel file).

Following data were used for economic analyses: the yield of soybean in tonnes (Mg) being the average yield for four plots; doses of biochar derived from sunflower husks (BA) and wooden chips (BB) applied at 40, 60 and 80 Mg/ha; price of biochars, which is the same for both BA and BB (USD 85.33/Mg); costs of mineral fertilizers, that include ammonium nitrate (USD 368.00/Mg), superphosphate (USD 394.67/Mg) and potassium sulphate (USD 706.67/Mg); costs of lime (USD 80.00/Mg); price of soybeans in 2019 (USD 368.00/Mg); price of soybeans in 2020 (USD 342.00/Mg); price of organic soybeans in 2019 (USD 625.60/Mg); price of a ton of organic soybeans in 2020 (USD 581.40/Mg) and soybean seed price USD 49.30/pack (USD 197.20/ha). We used calculations for lime as another scenario. This is because most of the soils in Poland are acidic, and the use of lime is one of the common agricultural practices in Poland. Data for subsidies in Poland for the agricultural production of field crops of leguminous seeds, including for organic production, were as follows: for single-area payment in 2019 (USD 125.77/ha) and in 2020 (USD 129.01/ha); payment for legumes (up to the first 75 ha) in 2019 (USD 204.21/ha) and in 2020 (USD 193.20); subsidies for certified seed material in 2019 (USD 86.65) and in 2020 (USD 90.64) and greening subsidies in 2019 (USD 84.41) and in 2020 (USD 86.36).

In addition, an analysis of the optimal price (breakeven) for biochar use in soybean production was performed. Breakeven price illustrates a situation in which sales incomes cover fixed and variable costs. When calculating, the incomes from the sale of the crops were compared with the costs of their production. In the search for the breakeven price, these two indicators have been used over time. Breakeven is the value of the item or service as expected by both the buyer and the seller. This is the point where the marginal revenue (MR) equals the marginal cost (MC) (Equation (1)).

$$MR = MC, \quad (1)$$

For the purposes of estimating the optimal price of biochar, the remaining costs of soybean cultivation, as well as incomes, will be constant in value. Another alternative for this analysis is a stochastic breakeven analysis, which addresses the sensitivity and uncertainty of all factors. Thereof, the probability distribution defined in stochastic breakeven analysis enables refined accuracy in obtaining various profit levels.

Demand and supply as well as price are elements of the agricultural product market. The fluctuations of the power elements can be described as long, medium, short and noticeably short. Short periods are up to one year, medium periods are several production cycles, approximately 5 years on average, and long periods are 10 years or more [40]. Biochar is generally applied once every few years, since soil pH is regulated, and the soil

physical–chemical parameters do not change significantly over several years [41]. In the case of conventional fertilization, systematic liming and soil fertilization are prerequisites for good plant yield. Liming is usually carried out once every four years, and fertilization with macronutrients, depending on the crop, occurs 2–3 times during the cultivation period [42]. Here, the payback period (PBP) was calculated as the ratio of the capital invested to the estimated annual net cash flow covering the cost of the investment, assuming that the next year will have flows equal to those in the previous year.

The cash flow for biochar use in soybean farming was calculated based on Equation (2).

$$\text{PBP} = \left(r_{(n-1)} \right) + \frac{K_t}{\text{CF}_t} \quad (2)$$

where:

PBP is payback period.

$\left(r_{(n-1)} \right)$. is a year before the end of the repayment.

K_t . is uncovered cost at the beginning of the year in which the repayment takes place.

CF_t . is a cash flow in the year of repayment.

t is for time.

2.4. Carbon Sequestration in Soil

Biochar has carbon sequestration potential and a long-term effect on soil organic matter [43]. Here, the scenarios for the use of subsidies at the levels of USD 10, USD 20 and USD 30 [44,45] are presented. The amount of fixed carbon in the biochar was 80% and 77% for BA and BB, respectively. The assumed fraction of persistent carbon was 70% based on the H:C ratio (0.03) and on Woolf et al. [46]. The sequestered carbon in soil (Cseq) was calculated based on Equation (3):

$$\text{Cseq} = D \times \text{CB} \times \text{PB}, \quad (3)$$

where:

D is the dose of biochar.

Cseq is for carbon sequestered in soil in biochar treatments.

CB is the proportion of fixed carbon in biochar (BA = 80% and BB = 77%).

PB is the fraction of persistent biochar (70% for both biochars, based on Woolf et al.) [46].

3. Results

3.1. Systematic Literature Review

Our literature review showed that papers that discuss comprehensive cost–benefit analyses for biochar application in soybean production are scarce. Three studies were retrieved: Dokoohaki et al. [1], Dumortier et al. [47] and Aller et al. [48] (Supplementary Material Table S1, Word file). Moreover, the estimates from these studies were based on modelling. The study of Dokoohaki et al. [1], based on previous meta-analyses, with the use of a probabilistic graphical model shows that for the United States, the use of biochar in corn areas is the most profitable in terms of income compared to soybeans and wheat because the additional income raised by farmers is not sufficient to cover the cost of biochar applications in many regions in the country. The results obtained by Dumortier et al. [47], using the global model of agricultural prospects, indicate that biochar is most profitable for use in farmland (soybean, corn and wheat were evaluated) in the Southeastern United States due to the combination of high yield growth and availability of biomass to produce biochar in this region. The cost–benefit analysis presented by Aller et al. [48] by applying the Agricultural Production Systems Simulator (APSIM) biochar model includes soybean, but only as part of corn–soybean rotation, not for soybean as a tested plant.

The results of the review regarding soil ecosystem services using biochar in soybean production are presented in Figure 1. The most common soil ecosystem services that were evaluated related to soybean and biochar were productivity (crop yields, $n = 55$), soil

fertility (nutrient use efficiency, $n = 37$) and acidity regulation ($n = 27$), while the fewest studies concerned greenhouse gas (GHG) emissions ($n = 5$), nutrient leaching ($n = 3$) and carbon sequestration ($n = 1$). Most of the studies included multiple ecosystem service assessments (Supplementary Material Table S3, Excel file).

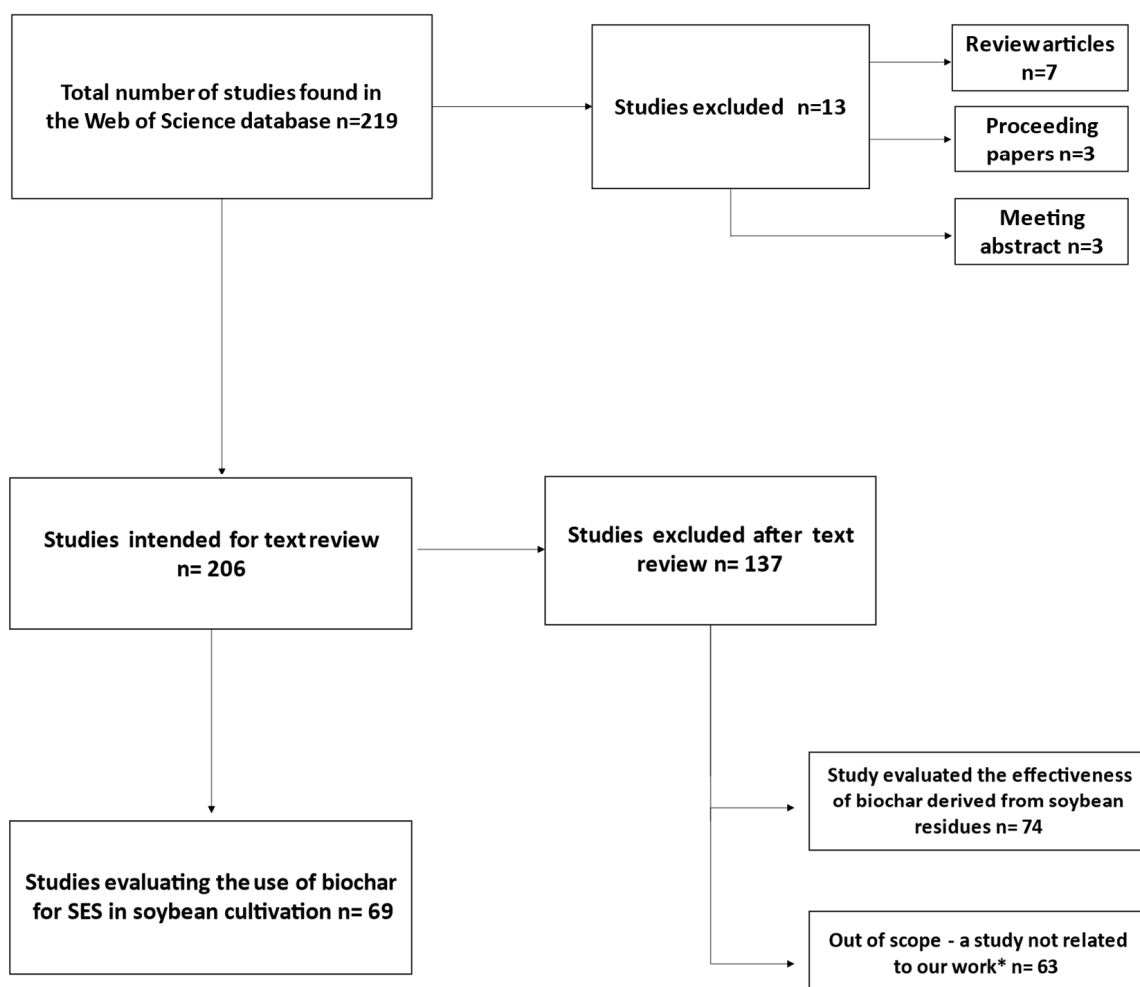


Figure 1. Flow diagram summarizing the systematic literature review for soil ecosystem services (SES) and soybean production with biochar. Out of scope includes, inter alia: modelling $n = 6$, other parameters evaluated $n = 10$ and evaluation of biodiesel production from soybean oil $n = 10$.

3.2. CBA

Regarding crop yields, the dose of 60 Mg/ha was the most effective use of biochar: both for BA and BB types and in both years of use (Figure 2, Table 1). There was a statistically significant difference for this dose, and there was no statistically significant difference between the doses 40 and 80 Mg/ha (Table 2). There were no significant differences on the impact on the yields for both types of biochar. Other statistical analyses can be found in Supplementary Materials, Figures S2–S4 (Word file).

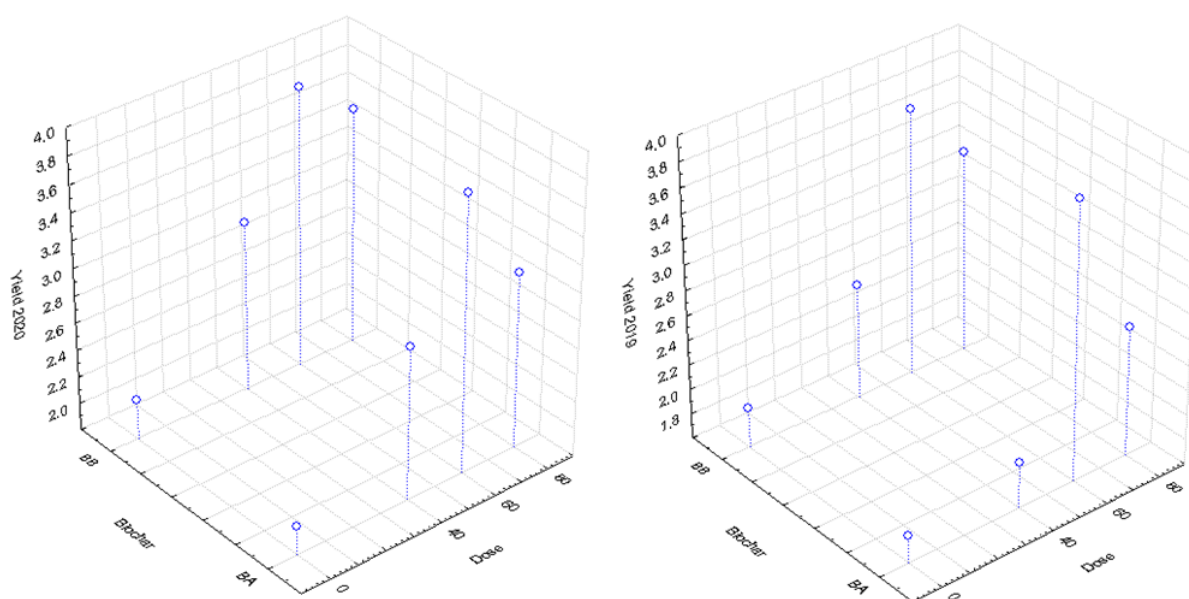


Figure 2. Efficiency of using biochar (in tonnes of soybean per hectare, Y axe) from sunflower husk (BA) and wood chips (BB). Axe X indicates doses of biochar used in the experiment. Wilks Lambda = 0.67323, F (12, 606.17) = 8, 1485, p = 0.00000.

Table 2. Newman–Keuls test. Dependent variable: yield (tones of biochar per hectare). Homogeneous groups, alfa = 0.05000. Error between groups = 1.14358, df = 232.00. Columns numbered 1, 2 and 3 represent homogeneous groups whilst starts show homogeneous treatments for each group.

Type of Biochar	Dose Mg ha ⁻¹	Yield (Average for Two Years)	1 t ha ⁻¹	2	3
Sunflower husk	0	2.232463			****
Wood chips	0	2.326317			****
Sunflower husk	40	3.249853	****		
Wood chips	40	3.387327	****		
Sunflower husk	80	3.468700	****		
Wood chips	80	3.939717	****	****	
Sunflower husk	60	4.242873		****	
Wood chips	60	4.284597		****	

Based on the comparison of revenues from the sales of crops and costs of soybean cultivation using both types of biochar, our results show that the use of both biochars, is unprofitable (Figure 3).

When estimating the use of biochar in organic soybean production, a scenario with an additional cost of 70% [49] was adopted. Organic food production is usually more expensive than conventionally grown food. This is due to the higher costs of production standards, such as the price of raw materials, labour intensity or specific agricultural practices [50,51], which results in higher prices for organic food [49]. Moreover, the organic farming sector and the market for organic products in the European Union are subject to specific regulations and provisions [52]. Figure 4 shows the income and costs that include production subsidies and the increase in the price of seeds from organic farming, because biochar could potentially be used in such systems [53]. For comparison, the income and costs of growing soybeans using conventional fertilizer are also presented (Figure 5). The results show that growing soybean using biochar in annual field trials is unprofitable. It should also be noted that in the field experiment, conventional fertilizers were applied only once, while in the case of legumes, it is recommended to fertilize twice: pre-sowing and as a top dressing [42]. Table 3 summarizes the income, costs and results for two scenarios: single and dual application of conventional fertilizers.

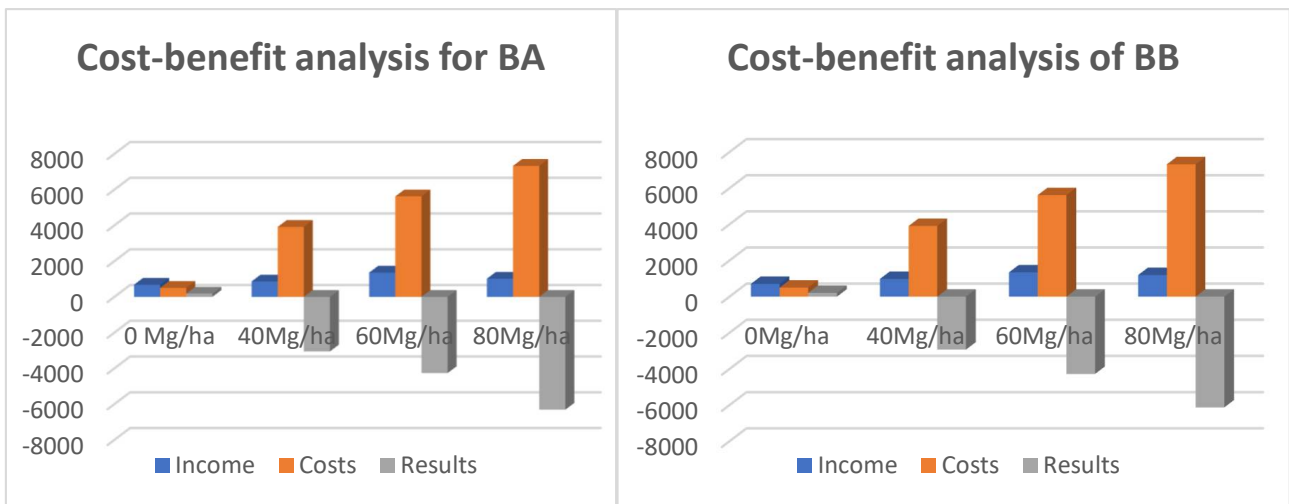


Figure 3. Comparison of the income and costs (in USD) of soybean cultivation using sunflower husk biochar (BA), left panel, and using wood chip biochar (BB), right panel.

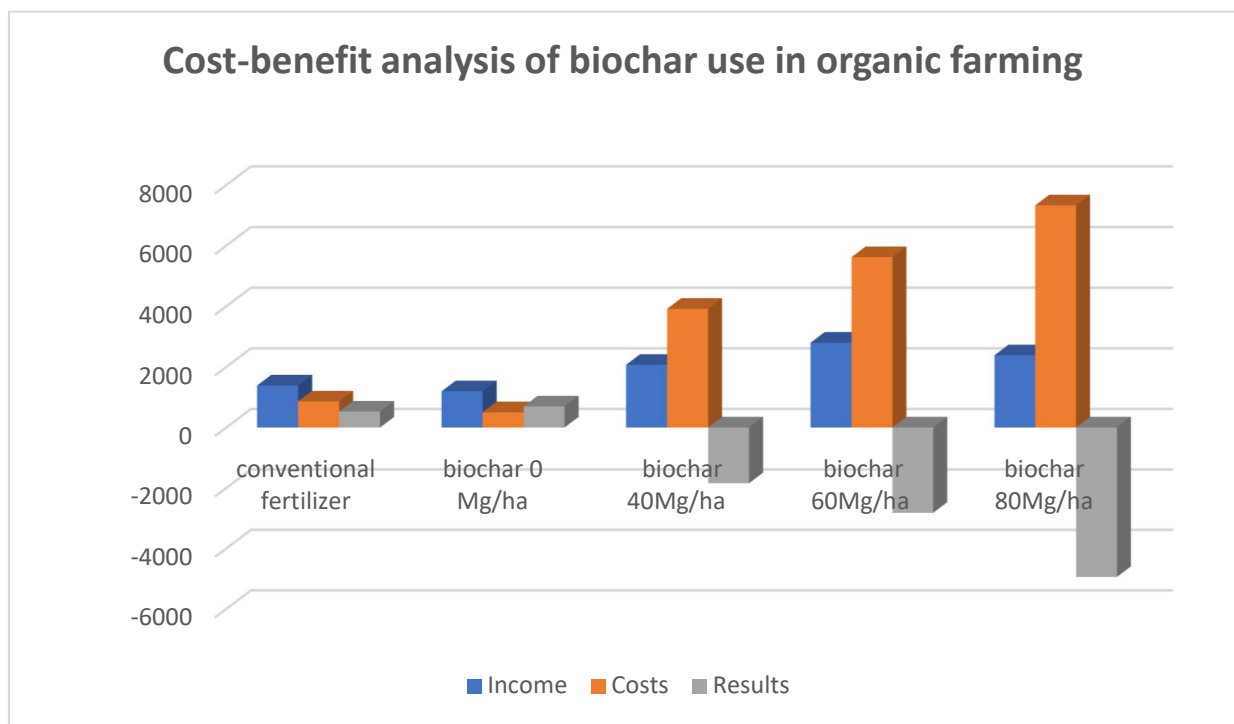


Figure 4. Comparison of the income and costs (in USD) of conventionally amended crops and with the addition of biochar.

Table 3. Comparison of the financial results for single and double soil fertilization with conventional fertilizer.

Frequency of Conventional Fertilization	Financial Results (USD)		
	Income	Costs	Results
Once a year	1387.63	861.60	526.03
Twice a year	1387.63	1221.95	165.68

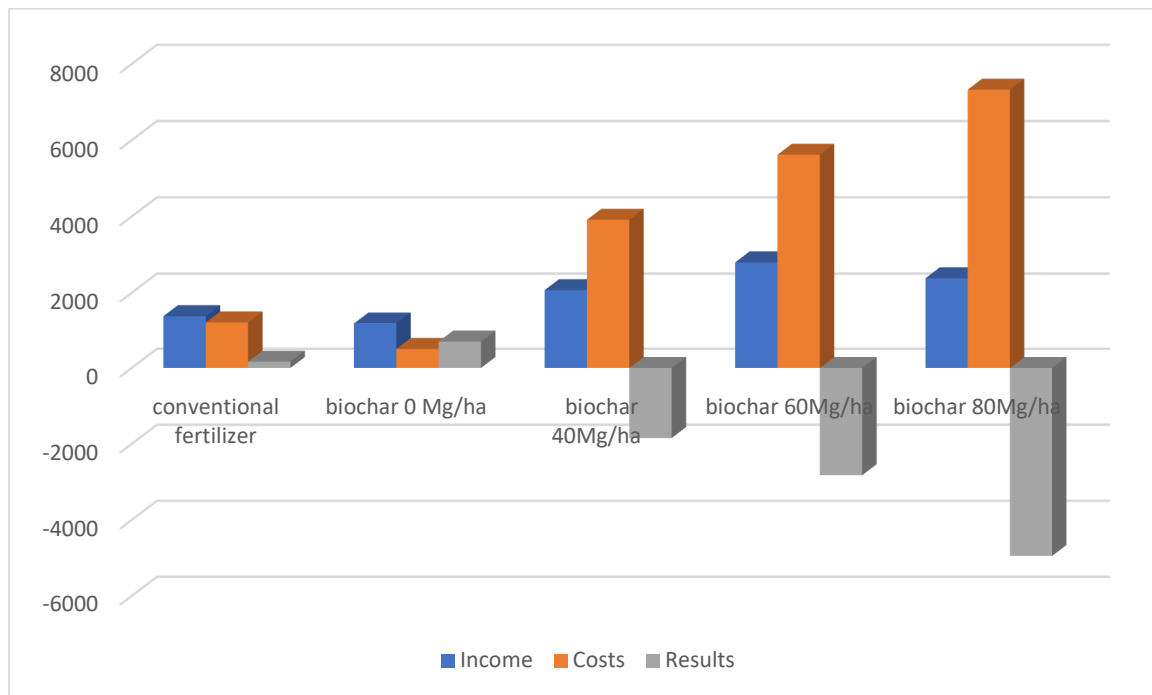


Figure 5. Comparison of the income and costs (in USD) of conventionally fertilized crops (those fertilized twice a year) and with the addition of biochar.

Using conventional fertilizer in soybean production is profitable (Figure 5). Even when applying double fertilization, as recommended, the income is positive. The solution for the deficit of soybean production by using biochar is, for example, setting the optimal price for biochar.

3.2.1. Breakeven Analysis

We found that optimal biochar prices are much lower than the current market price (details can be found in Supplementary Material, Table S4, Excel file). The intersection of the income and cost lines for the individual doses of sunflower husk biochar determines the price at which cultivation becomes profitable (Figure 6). For a biochar dose of 40 Mg/ha, the optimal price is USD 39.22; for a dose of 60 Mg/ha, the optimal price is USD 38.29; for a dose of 80 Mg/ha, the optimal price is USD 23.53.

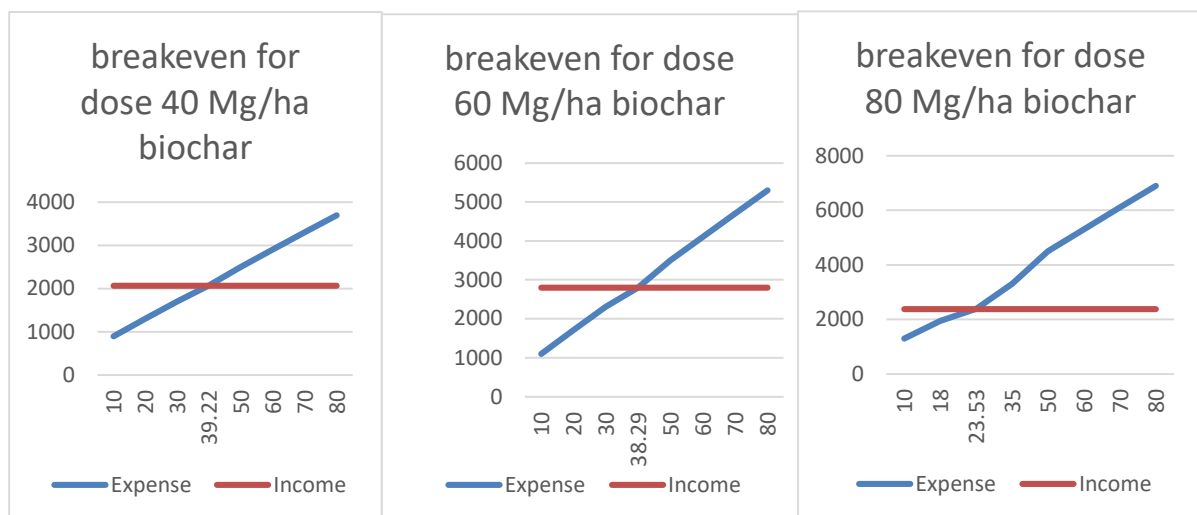


Figure 6. Breakeven price (in USD).

3.2.2. Payback Analysis

We also estimated the costs and benefits of using biochar over a three-year period (Figure 7). Detailed calculations including discount rate at 9% per year are included in the Supplementary Materials.

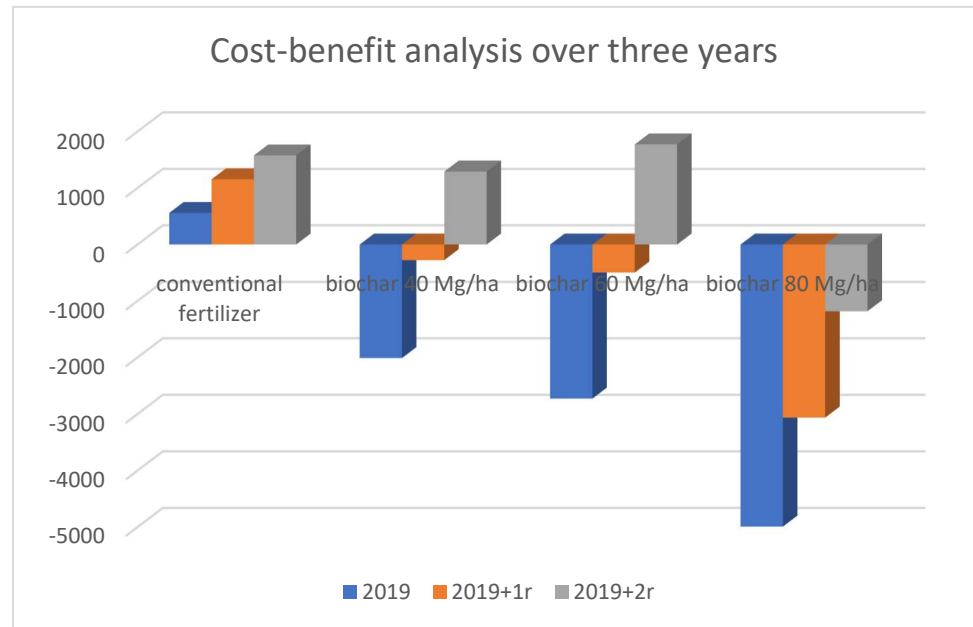


Figure 7. Comparison of the costs (in USD) of soil fertilization with conventional fertilizer and with the addition of biochar over a three-year period.

In the third year of cultivation, at doses of 40 Mg/ha and 60 Mg/ha, the financial result was positive. These doses are also more effective in terms of yield than a dose of 80 Mg/ha. Assuming that choosing a more expensive biochar compared to a conventional soil amendment is an investment, it is possible to calculate its payback period (PBP), i.e., the period during which the net investment income will cover the cost of the investment [54]. Noteworthy, soybean production is often intercropped with wheat, or the field can be left fallow. For the modelling reasons, consecutive production was assumed, as the interpretation of the result is the time needed to return the invested capital. The shorter it is, the more profitable it is to produce. The cash flow for the simulation will be equal to the financial result (Table 4).

Table 4. Payback period for biochar doses of 40 Mg/ha and 60 Mg/ha calculated for the three-year period (t), at a discount rate of 9% per year.

Biochar Dose	Year			
	0	1	2	3
$CF_{40\text{ Mg/ha}}$	-2010.09	-253.0832	1088.1315	998.2858
CF_{cum}	-2010.09	-2263.174	-1175.042	-176.756
$CF_{60\text{ Mg/ha}}$	-2726.249	-455.7599	1492.2826	1369.067
CF_{cum}	-2726.249	-3182.009	-1689.726	-320.66

$$\text{PBP for a biochar dose of 40 Mg/ha} = 3 + \frac{176.76}{915.86} = 3.19 \text{ years.}$$

$$\text{PBP for a biochar dose of 60 Mg/ha} = 3 + \frac{320.66}{1256.02} = 3.26 \text{ years.}$$

3.2.3. Carbon Sequestration

The cost–benefit results of carbon sequestration from biochar are presented in Table 5 and in Supplementary Materials, Figures S4–S6 (Word file).

Table 5. Cost–benefit scenarios of carbon sequestration for both biochars, BA and BB, at doses of 40 Mg/ha, 60 Mg/ha and 80 Mg/ha considering the following CO₂ prices: USD 10, 20 and 30.

Carbon Price USD tCO ₂ ^{−1}	Biochar BA Dose			Biochar BB Dose		
	40	60	80	40	60	80
10	821	1232	1643	791	1186	1581
20	1643	2464	3285	1581	2372	3162
30	3696	3696	4928	2372	3557	4743

We found that soybean production with the addition of biochar (both types) at rates of 40 Mg/ha and 60 Mg/ha would be profitable after one year if the subsidy of USD 30 t/ha from carbon sequestration was USD 30/ha (Supplementary Material Table S4, Excel file). Lower subsidies are not profitable. In accordance with the international projections [44], the carbon price would have to be in the range of USD 40 to USD 80 in 2020 and USD 50 to USD 100 in 2030 to achieve the goals of the Paris Agreement. When considering a two-year period, with a one-time addition of biochar, including the remaining costs occurring annually, production is profitable for all doses and amounts of subsidies for carbon sequestration in the soil. This was true for all treatments except for a biochar dose of 80 Mg/ha sunflower husk biochar.

4. Discussion

Soybean production may bring a range of environmental and economic benefits [28,29,54], and its production is predicted to increase over the next decades [32]. The cultivation of soybean can, therefore, play a significant role in the pursuit of more sustainable agriculture in Europe. Combining soybean with biochar amendment can further magnify the environmental, social and economic benefits of agricultural production. Biochar may improve soil physical properties such as water regulation and respiration, porosity, texture, aggregate stability and bulk density as well as soil chemical properties [55]. Furthermore, biochar has considerable carbon sequestration potential and a long-term effect on soil organic matter [43]. Moreover, the production of biochar may contribute to diminishing CO₂ emissions, as the raw materials used to produce biochar would normally be landfilled or combusted in a conventional manner, consequently increasing CO₂ emissions to the atmosphere [56]. However, the high costs of biochar application may limit its adoption for carbon sequestration and other environmental and economic benefits on a large scale [1]. To leverage these costs, subsidies related to soil carbon sequestration may be a promising strategy. Indeed, our results show that with the subsidies at the rate of USD 30 per tonne of CO₂, the production of soybeans may be profitable after the first year of cultivation.

Biochar can also be considered an important tool for promoting a circular bioeconomy [57,58]. Bioeconomy covers the exploration and exploitation of bioresources, for example, organic waste from the agri-food industry, which involves the use of technology to create new bio-based products that have economic value [59]. Biochar is a marketable bioproduct that can be used in many sectors, including agriculture. Therefore, efficient use of biochar can improve soil properties, increase crop yields and provide opportunities for additional income, hence generating economic and agronomic benefits [60]. For biochar to be considered in developing wider environmental applications within a circular bioeconomy, it is necessary to consider the economic impacts [58].

The price of biochar may significantly increase the cost of cultivation, especially at high doses. In our study, such doses were adopted given that our pilot experiment also showed the best improvements in ecosystem services other than food production, such as

water retention. The potential solutions to reducing the disproportions in profitability of biochar use in soybean production compared with other soil amendments could be using lower doses (supposing they lead to an increase in productivity), reducing the purchase costs of biochar, increasing the purchase price of organic soybeans or adopting subsidies. Regarding the price of biochar, we show that the optimal biochar price for biochar to be economically viable should be USD 39.22, USD 38.29 and USD 23.53 for 40, 60 and 80 Mg/ha biochar, respectively, and the payback period for doses of 40 and 60 Mg/ha was approximately three years. The application of biochar should, therefore, be treated as a medium to long-term investment, where the rate of return is increasing over time [4]. In the medium term (3–4 years), the use of biochar is profitable and may be competitive with other soil amendments, such as lime or conventional fertilizers, especially when biochar is loaded with additional nutrients [61–64], as conventional amendments are commonly applied several times a year, depending on the soil and crop type. It is also possible that the price of biochar will diminish over time, given the search for alternative methods in sustainable land management, the relative novelty of biochar in Poland and the scarcity of research that goes beyond environmental analysis and includes comprehensive cost-benefit analysis. For example, in case of agricultural production in an organic system, its development is related to profitability and competitiveness compared to other agricultural production systems.

We also observed in our experiment that on the plots with biochar, soybean grew quicker as compared with control and in a compact canopy, which led to better shading and consequently limited the growth of weeds. On industrial plantations, this could reduce the need to use pesticides. The production of soybean involves the use of large amounts of pesticides, which poses a direct risk to humans and the environment in soybean plantations.

Nevertheless, it should also be noted that the study has some limitations. The experiment was performed on a relatively small scale and over a short term. We evaluated impacts only on one crop. It should also be acknowledged that biochar produced from different input material might give different results. Additionally, we suggest that the future research on soybean could include a treatment wherein biochar is applied along with fertilization to verify how much fertilizer doses could be reduced. The costs of biochar may also vary if the commercial scale is taken into account.

Finally, the economic aspects relating to the use of biochar in soybean cultivation should be considered in a broader social and political context. Farmers' interest in using biochar in agriculture increases along with farmers' knowledge about benefits and costs of using biochar [65]. This directly relates to effective communication about the benefits of biochar, for instance, through wider social campaigns, field visits and local events [7,65]. The economic profitability of using biochar in soybean production may be achieved through the system of subsidies for carbon sequestration as presented in this study. Such solutions, however, depend on political decisions. In the case of countries belonging to the European Union, they are related to the Common Agricultural Policy EU (CAP). One of its most important goals and challenges is to support environmentally sustainable agriculture, which is to combine food production with the protection of nature and biodiversity. According to the assumptions of the European Commission, CAP is to be one of the foundations of the European Green Deal [66]. Therefore, effective and transparent communication about opportunities and limitations regarding the use of biochar and possible subsidies may give a real chance to shape pro-environmental attitudes in line with the values expressed in the European Green Deal.

5. Conclusions

To recommend the use of biochar in agriculture, socioeconomic evaluation is pivotal. Biochar use in soybean production is an interesting alternative in the context of a circular economy and sustainable agriculture. To the best of our knowledge, our study presents the first cost-benefit analysis in Europe based on the results from experimental trials, exclusively for soybean production. Although the results of our study are promising, there

is a need to expand such types of analyses both in Poland and elsewhere. In particular, biochar production may have serious environmental and socioeconomic impacts, including accelerated large-scale expansion of intensive soybean cultivation in biodiversity hotspots, such as the Brazilian Cerrado. Soybean production has been increasing globally. Helping make this production more sustainable; ideally, with important benefits for a range of ecosystem services, should be a priority for researchers and decision makers at the policy level. Therein, landowners may be advised on the best solutions that will maximize agricultural production whilst leaving the environment, especially soils, in the best quality for future generations.

Supplementary Materials: The following are available online at <https://www.mdpi.com/article/10.3390/agronomy11112108/s1>. 1. Supplementary Material Word file. The document contains information about a field trial in which two types of biochar at different doses were used to produce soybeans. Additionally, the Word document presents examples from the scientific literature that discuss what conditions must be met for the use of biochar in commercial agriculture to be viable, as well as examples of studies that provided a cost–benefit analysis of biochar (CBA). The results of the statistical analysis of the effectiveness of biochar use are presented in graphical form in the further part of the document. 2. Supplementary Material Table S3, Excel file. This file contains the result of a comprehensive literature review (scientific papers published up to January 2021) on the impact of biochar use on ecosystem services in soybean production (e.g., impacts on yield, soil fertility, carbon sequestration, etc.). The purpose of this literature review was to identify a scientific gap in the use of biochar in soybean production, especially regarding carbon sequestration. 3. Supplementary Material Table S4, Excel file. This file contains comprehensive calculations for the economic analysis (cost–benefit analysis) of the following: biochar yield (two types of biochar) in different doses (for 40, 60 and 80 Mg ha^{−1}); comparison of revenues and costs of using conventional fertilizer with biochar in soybean production; optimal price and payback period for the use of biochar and cost–benefit analysis of carbon sequestration in soybean production.

Author Contributions: Conceptualization, A.E.L.; methodology, A.E.L., A.K., K.A.K., M.K., U.S., M.G., J.S., A.K.-K. and M.N.; formal analysis, A.E.L., A.K., K.A.K. and M.S.; investigation, A.E.L., U.S., M.G., M.K., J.S., A.K., K.A.K., M.N., and A.K.-K.; resources, B.U., A.E.L. and M.K.; data curation, U.S., M.G., M.N. and J.S.; writing—original draft preparation, A.E.L., A.K. and K.A.K.; writing—review and editing, A.E.L., K.A.K., M.K., J.S., M.S., M.G., U.S., A.D., B.M. and M.N.; visualization, K.A.K., A.K. and M.S.; supervision, A.E.L.; project administration, M.K.; funding acquisition, A.E.L., M.K. and B.U. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Polish National Centre for Research and Development in the framework of ‘Environment, agriculture and forestry’–BIOSTRATEG strategic R&D programme, grant no. BIOSTRATEG3/345940/7/NCBR/2017(‘Water in soil–satellite monitoring and improving the retention using biochar’), which was.

Institutional Review Board Statement: Non applicable.

Informed Consent Statement: Non applicable.

Data Availability Statement: Non applicable.

Acknowledgments: We thank Alvaro Iribarrem for his help with economic analyses. Magdalena Markowicz and Maiara Mendes are gratefully acknowledged for their help with manuscript formatting.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

APSIM: Agricultural Production Systems Simulator; CAP, Common Agricultural Policy EU; CBA, cost–benefit analysis; CO₂eq, CO₂ equivalent; Cseq, sequestered carbon in soil; EU’s, European Commission’s; ETS, emissions trading system; GHG, greenhouse gas; LCA, life cycle assessment; MC, marginal cost; MR, marginal revenue; PBP, payback period; SES, soil ecosystem services.

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