Article

Assessment of Greenhouse Gas Emissions in Soybean Cultivation Fertilized with Biochar from Various Utility Plants

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Abstract: Organic matter is an indispensable element of soil. Its quantity and quality affect its properties, e.g., structure, buffering, sorption capacity, air–water relations, and thermal properties. The purpose of the research was to assess greenhouse gas (GHG) emissions in soybean cultivation, fertilized with biochar from various crops. Two experimental factors were included: the dose of biochar and the type of biochar used as per raw material used in its production. The adopted functional unit was 1 ton of soybeans. To reach the adopted goal, a strict field experiment was carried out. The total amount of GHG emitted by the cultivation was calculated according to the ISO 14040 and ISO 14044 standards. The system boundaries included: GHG emissions from fertilizers and seeds used, GHG emissions related to biochar production, emissions related to fossil fuel combustion, and emissions related to the decomposition of crop residues and soil organic matter and the decomposition of biochar. The results of the research indicate a significant potential of biochar to reduce GHG emissions in agricultural production. From the environmental and production perspective, the addition of biochar at 60 Mg ha^{−1} is the most advantageous. A further increase in the addition of biochar was related to a decrease in plant yield and an increase in GHG emissions per functional unit of the product. The use of biochar in soybean cultivation resulted in a 25% reduction in GHG emissions compared to the object without the biochar addition. The amount of GHG emissions for soybeans ranged from 846.9 to 1260.1 kg of CO₂/Mg. The use of biochar from forest biomass resulted in a higher yield, 12% on average, compared to sunflower husk biochar. The introduction of biochar to soils can be an effective improvement in the economic and environmental efficiency of plant production, as it increases the use of nutrients by the plant and intensifies carbon sequestration in soils.

Keywords: greenhouse gas emission; soybean cultivation; biochar; fertilization

1. Introduction

Organic matter is an indispensable element of soil. Its quantity and quality affect its properties, e.g., structure, buffering, sorption capacity, air–water relations, and thermal properties. The intensification of plant cultivation and the related increase in the number of agricultural treatments, as well as the use of mineral fertilizers and limited organic fertilization cause a constant decrease in organic matter in agricultural soils. Reduced organic matter is one of the most important causes, as well as effects of soil degradation [1,2]. Technologies used in modern agriculture lead to a permanent reduction in the amount of organic matter in the soil. The decrease in the amount of organic carbon in the soil is the result of the mineralization of the humus. Its further intensification is a consequence of the increased aeration of the soil caused by many tillages combined with the limited use of fertilizers containing organic carbon. Moreover, soil organic matter is a carbon reservoir in the biogeochemical cycle of this element [3,4]. Therefore, the carbon contained in the soil positively impacts the fertility of the soil and its yield potential, and on the other hand, it reduces the environmental impact of agriculture. Enriching the soil with organic matter is a strategic element of the sustainable development of agriculture and is in line with the principles of all primary production quality management systems: GLOBAL GAP, Integrated Production, or SAI Platform [5–7]. Carbon introduced to the soil with organic fertilizers undergoes mineralization and humification. The share of individual processes depends on the chemical form of carbon introduced into the ecosystem, as well as soil pH, its particle size composition, its level of microbiological activity and the production technology [8,9]. The primary production stage is critical in terms of environmental impact. Eldor and Paul [10] and de Sousa Lima et al. [11] point out the significant impact of the carbon-to-nitrogen ratio on the course of the transformation of carbon compounds in the soil. External means of production containing carbon impact on the properties of soils and the development of microbiological biocenoses. The intensification of humification processes, which leads to permanent binding of organic carbon, could be the consequence of the development of certain species of microorganism [12,13]. The remedy could be the concept of transforming organic fertilizers to increase their potential for permanent carbon fixation in the soil. Wang et al. [14] point to the positive effect of biochar mixtures with zeolites, which intensifies the humification processes in the soil. Agegnehu et al. [4] report that the effects of fertilization increases when biochar is mixed with compost, compared to the use of biochar alone. A mixture of biochar with natural fertilizers yielded better effects of the permanent binding of organic carbon [15]. Similarly, Oliveira et al. [16] and Awasthi et al. [17] indicate a much higher efficiency of humification processes after the introduction of biochar compared to other organic carbon materials. The authors found the relevant (40%) reduction in carbon dioxide emissions when using biochar mixtures and unprocessed natural fertilizers. A reduction in GHG emissions was observed with the addition of biochar to the composting process [17]. Where permanent sequestration is concerned, using mixtures of biochar and mineral additives based on mineralization processes that lead to the decomposition of organic compounds and the emission of carbon in the form of carbon dioxide to the atmosphere could be more suitable. From the point of view of permanent carbon sequestration, mineralization processes are not favorable. Mineralization under full aerobic conditions leads to the formation of simple mineral compounds (CO_2 , SO_2 , H_2O , NO , etc.). With a limited access to oxygen, it is a decaying process, which, when running in anaerobic conditions, leads to the rotting of organic matter. Increasing the amount of organic matter permanently bound in the soil depends on the rate and direction of transformations of carbon compounds introduced into the soil with organic fertilizers. As part of the rationalization of natural resource management, it is critical to manage the soil in such a way so as to reduce its carbon emissions or, in special cases, to pursue a policy of soil carbon management in such a way as to permanently increase its accumulation in the soil. The effect of such actions is the reduction of agricultural activity-related anthropopressure [18,19].

The role of agricultural sciences and production practice is to find methods of permanent binding of carbon introduced into the soil as organic fertilizers. Organic matter introduced with traditional fertilizers such as manure, slurry, or green manure in agricultural soils is primarily mineralized, which is pointless from the point of view of permanent carbon sequestration.

The introduction of organic carbon in the form of biochar is more beneficial in terms of improving soil fertility and in terms of permanent carbon binding in the soil [20,21]. Yuan et al. [22] report that the efficiency of biochar introduced into the soil depends on the level of decomposition of organic matter, which, in turn, depends on the type of raw material of biochar and the temperature of biochar production. Raya-Moreno et al. [23] point out that the efficiency of permanent carbon bonding depends on the raw material from which biochar is made. These authors observed the long-term binding effect of the organic carbon contained in the biochar within two years of incubation, with a much better effect observed in the case of wood biochar than in the case of manure biochar. The transformation of carbon compounds in the soil also depends on the mineral fraction of the material, as pointed out by Xu et al. [24]. Melas et al. [25] proved that biochar added to soil had a statistically significant effect on intensification of humification in the incubation experiment. According to the above authors, increasing the content of phosphorus and other elements in biochar can increase the potential of soil humus formation, while limiting the oxidation processes [26]. Awad et al. [27] found that the addition of the mineral fraction to biochar in the form of oyster shells or polymer compounds significantly increased the potential of the material to reduce GHG emissions from agroecosystems. Apart from reducing carbon dioxide emissions as part of the impact on soil properties and microorganism colonies, the potential of this material for carbon dioxide chemisorption is also important, as it can also reduce the emission of this compound from the soil. Xu et al. [28] report that the sorption capacity of biochar in relation to carbon dioxide is as high as 34 mg g^{-1} of biochar, where the capacity depends on the content of metallic elements.

A very important aspect of the use of biochar on agricultural land is the improvement of soil fertility, which results in the improved use of nutrients. The use of biochar on intensively used land reduces the emission of nitrogen oxides, considered the most important agricultural GHG [29].

The organic carbon contained in soil is a component of organic matter (humus). Its amount is of key importance for soil fertility and GHG emissions [30,31]. The double benefit of the permanent binding of organic carbon to soil has led to numerous scientific studies, not only on methods of processing organic matter prior to application to the soil. The research included the application methods themselves and the impact of specific soil properties on humification processes, which are the most important from the point of view of permanent carbon binding in the soil. Numerous research cited in this study confirm that the introduction of carbon into the soil as a biochar improves permanent binding of this element compared to unprocessed biomass. The positive effect of biochar is related to the induction of humification processes, the reduction of nitrogen oxide emissions, and the chemical binding of carbon dioxide emitted by soil microorganisms and plant roots. Maucieri et al. [32] found that the addition of biochar to the soil reduced carbon dioxide emissions by 28% and nitrogen oxide emissions by 12% compared to the control. The authors estimate that the use of biochar can reduce the level of GHG emissions by approx. 10%, in addition to permanent carbon fixation in soil. The presented research clearly demonstrates the potential of thermally processed biomass in the process of carbon sequestration. Numerous authors point out the possibility of increasing the sequestration potential of the element due to the valorization of biochar with additives containing phosphorus, calcium, or magnesium. Thermal conversion of biomass is related to the emission of various gases into the atmosphere. Therefore, when calculating the potential for permanent carbon binding, one should take into account GHG emissions in the biochar production phase, as pointed out by [33,34]. In light of the data published in the scientific literature, attention should be paid to the potential of using biochar in the sequestration

of this element in the soil. Data in the literature clearly show that the use of organic matter subjected to pyrolysis affects the permanent bonding of this element in the form of persistent organic compounds. To accurately assess the environmental effects of the use of biochar, studies related to the permanent carbon bonding potential should be carried out using biochar made from a specific raw material. When designing a biochar-based products, the possibility of valorizing biochar with mineral additives should be taken into account to increase the efficiency of the product in terms of permanent carbon bonding and reducing GHG emissions.

Mona et al. [3] and Klimek-Kopyra et al. [35] note significant differences in the quality of biochar in terms of plant cultivation suitability. These authors stated that microalgae biochar was characterized by a higher sorption capacity, increasing the use of elements applied with fertilizers.

The aim of the research was to assess GHG emissions in soybean cultivation using biochar fertilizer in various doses and from various raw materials.

2. Materials and Methods

2.1. Details of the Vegetation Experiment

The experiment was located in Krakow, at the experimental station of the University of Agriculture (Latitude 50.084796 N, Longitude 19.853968 E). The experiment was set up on 10 April 2019 and the plants were harvested on 16 August 2020. The sowing was done in the soil with a clay sand grain composition. The experimental factor in the conducted experiment were the type of biochar and its dose. The field experiment included 3 doses of biochar at 40 Mg, 60 Mg and 80 Mg per ha. The test plant was soybean *Glicine max* L, the variety Elegance F1. 0.8 million plants per hectare were sown, at 2.5 cm intervals. The methodology of integrated protection and soybean production was applied in plot management. The following agricultural treatments were applied: plowing, biochar application, mixing biochar with soil using an active aggregate (3×), sowing fertilizers, sowing plants, mechanical weed control (2×), mechanical harvesting, transport, drying of seeds.

The experiment was designed using the randomized block method, in four replications. The scheme of the experiment is given in Table 1.

Table 1. The scheme of the vegetation experiment.

Treatments	Type of Biochar	Dose (Mg/ha)
1	n/a	0 (control)
2	from sunflower husk	40
3	from sunflower husk	60
4	from sunflower husk	80
5	from forest biomass	40
6	from forest biomass	60
7	from forest biomass	80

2.2. Weather Conditions and Soil Properties

According to the weather station in Balice, the average annual precipitation from 2018–2019 was 401.9 mm and was higher by 48.7 mm than the 30-year standard (353.2 mm) in the plant growing season (Figure 1). The year 2020 was more similar to the multiannual period. The amount of precipitation was then 337.3 mm. In 2019, abundant precipitation and lower temperature in comparison to the multiannual period was reported. Precipitation in June was under the average from the multiannual period and led to soil draught. 2020 brought a deficiency in precipitation in March and April and abundant rain in May and June.

Figure 1. Average sum of precipitation (A) and temperature (B) in 2019 and 2020 and the long-term average from 1985–2014 (according to the Meteorological Station in Balice).

The analysis of the average monthly air temperature from March to August in 2018–2019 prove that the average values for years 2018–2019 were higher than the standards from March and June. In 2019 the average temperature in May was lower, whereas in June it was considerably higher in the investigated period in comparison to the multiannual period. In 2020 the average temperature was lower than the standard of the multiannual period from April to July. Only in March and August was a slight increase in the average temperature of the air above the standard for the multiannual period observed.

Before setting up the experiment, soil samples were collected and their basic parameters were determined, to estimate the yield potential. The soil pH was determined by the potentiometric method, and the content of organic carbon and total nitrogen was determined by elemental analysis using the Vario Max Cube by Elementar. The determination of mineral nitrogen was determined by distillation after prior extraction with a 1 mol·dm^{−3} solution of potassium sulphate. The content of the available forms of phosphorus and potassium was determined by the Egner–Riehm method. The content of assimilable forms of calcium and magnesium was determined by the Schaschabel method. The production potential of the habitat was estimated at 2.9 Mg of seeds/ha. Prior to setting up the experiment, physicochemical and chemical properties of the soil were analyzed, determining the values for pH, particle size distribution, organic matter content, mineral and Kiejdahl nitrogen content, as well as content of available forms of P, K, Mg, Ca.

The soil properties are given in Table 2. In the experiment, the same level of fertilization was adopted for all objects, which corresponded to the nutritional requirements of plants at the estimated level of the habitat's production potential. The levels of NPK fertilization were as follows: 30 kg/ha, 70 kg/ha and 100 kg/ha. All fertilizers were applied before sowing.

Table 2. Properties of the soil on which the experiment was conducted.

pH in H ₂ O	pH in KCl	N Total	C org	N min	P	K	Mg	Ca
		(g/kg)				(mg/kg)		
6.73	6.28	0.116	1.33	32.1	99.4	81.9	42.01	836.9

In terms of the number of objects, the scope of conducted research and geographical location, the experiment was planned based on the adopted qualitative and quantitative goals, as well as technical possibilities [36]. The selection of the test plant variety, individual fertilization variants, the scope of agricultural treatments, the level of irrigation and the time frame of the experiment was established based on a risk analysis, according to the ISO 31000: 2018 standard. The identified risk was the impact of the above-mentioned risk

factors on the yielding of plants in specific environmental conditions. The scope of the investigation was determined based on a literature study, as was the selection of GHG emission sources.

2.3. Qualitative Characteristics of Biochar

Two types of biochar were used in the experiment: biochar from sunflower husk and from the waste biomass of the wood industry (wood chips). In the production of biochar, identical process parameters were used, regardless of the raw material, i.e., pyrolysis at 450–550 °C (36–37) for 15–20 min. The biochar parameters were as follows: specific surface area –80.9 (m²/g), pH KCl –9.2, density (g/cm) –1.4, ash content (%) –35.4, organic carbon (%) –22.5. Biochar is characterized by specific porosity: the average pore radius was 0.24 µm, total surface of the pore was 19.01 m²/g, and the total porosity was 75.92%. The biochar was prepared for SEM by fine grinding. The sample was then transferred under vacuum and imaged by SEM (Zeiss Ultra Plus, Jena, Germany) at 5 kV.

2.4. System Boundry

The experiment was carried out according to the following scheme:

1. Defining the strategic goal;
2. Selection of the experiment factors (a two-way experiment was selected);
3. Selection of the experiment plant (soybean as a plant with high GHG emissions);
4. Selection of the experiment site (a geographic system boundary); the experiment was carried out in the vicinity of large-area vegetable cultivation;
5. The applied treatments (excluding the experimental factor) were selected based on the recommendations of the Integrated Plant Production methodology and were based on production practices in the research area;
6. Determining the levels of experimental factors; 40, 60 and 80 Mg/ha of biochar additives were used;
7. The boundary of the system was selected based on a literature study and a risk analysis in the context of the adopted goal, according to the ISO 31000: 2018 standard.

The system boundary is shown in Figure 2 and included:

1. Production of fertilizers used in plant cultivation;
2. Energy consumption for field work on the farm;
3. Soil emissions (direct and indirect, related to fertilizer use);
4. Emissions from the management of crop residues and from the mineralization of soil organic matter;
5. Emissions related to biochar production;
6. Emissions related to seed production;

2.5. Life Cycle Calculation Methodology

One of the methods of comprehensive and multifaceted assessment of the quality system is to prepare a product life cycle that takes into account the use of energy, means of production as well as renewable and nonrenewable environmental resources [37]. However, the development of a reliable and universal method is very difficult, since farms operate in a specific economic, social and climatic framework, which significantly affects the assessment carried out and is very difficult to interpret. Therefore, the evaluation of agricultural systems is very often done based on a selected part of the activity [38].

To determine the level of the environmental impact of soybean production, the following standards were applied: ISO 14040: “Environmental Management-Life Cycle Assessment-Principles and framework” and ISO 14044: “Environmental Management-Life Cycle Assessment-Requirements”. The analysis was performed according to the recommendations contained in the document [39]. Product transport, packaging, use of agricultural tools, and marketing were excluded from the investigation. The production and transport of seedlings were also excluded from the process due to the lack of data on this process. The adopted functional unit was 1 t of commercial product, and the timeframe for the

system was one year. The potential to generate the greenhouse effect was estimated based on the GHG emissions expressed as a carbon dioxide equivalent (CO_2eq).

Figure 2. System boundaries of the experiment.

As part of the execution of the adopted research objective, the life cycle for the production of biochar from two types of waste (sunflower husk and wood chips) was calculated. The functional unit was 1 Mg of biochar.

Input data for the calculation of the GHG emission value came from 3 experimental objects with plants fertilized with biochar produced from sunflower husk, and from 3 objects where biochar produced from wood chips was used.

Three types of mineral fertilizers were used for fertilization, for which the level of GHG emissions was adopted according to the data in the literature. The GHG emission level for nitrogen production in ammonium nitrate was adopted at 7.99 kg CO_2 /kg N, for triple superphosphate at 0.36 kg CO_2 /kg P_2O_5 while for potassium chloride it was at 0.56 kg CO_2 /kg K_2O [40]. The amount of ammonia emitted to the atmosphere was calculated based on the guidelines provided by [41]. Emission factors for crop residues were calculated based on the amount of by-product in soybean cultivation. Based on the experimental results, it was estimated that in soybean cultivation the ratio of commercial yield after drying to by-products and crop residues ranged from 0.78% to 0.89% depending on the research object. The content of carbon fraction in the dry matter of crop residues was adopted based on the analyses. Depending on the research object, it ranged from 48.72% to 54.23% and the nitrogen content in the crop residues ranged from 1.82% to 2.32% per dry matter. The level of decomposition of crop residues was estimated at 25%. The

amount of carbon dioxide and nitrogen oxide emissions from crop residues from soil was calculated according to the methodology included in the IPCC Report [42]. The amount of nitrogen emitted in the form of nitrogen oxides was adopted at 1.25% [43]. The N-N₂O emission value was converted to CO₂ eq by multiplying its quantity by the value of the global warming potential coefficient, i.e., 292 [44]. The soil organic matter mineralization index adopted in the analysis was at 1.6%. Nitric oxide emission values resulting from nitrogen transformations in soil were calculated according to the methodology of the IPCC Report [42]. GHG emissions from the combustion of fossil fuels used for agricultural treatments were also taken into account in soybean life cycle assessment. Fuel consumption in individual agricultural treatments is presented in Table 3.

Table 3. Energy consumption and GHG emissions related to agricultural treatments.

Type of Agrotechnical Treatment	Fuel Use (dm ³)	Energy Use (MJ)	CO ₂ Emissions (kg)
Tillage	57	2308.5	221.1
Mineral fertilization (×2)	15.3	619.7	59.4
Cultivation with an aggregate	28.2	1142.1	109.4
Sowing soybeans	25.2	1020.6	97.8
Mechanical weed control (×3)	43.8	1773.9	169.9
Mechanical harvesting	16.5	668.3	64.0
Biochar application and mixing it with the soil (MJ/Mg)	3.2	129.4	12.04
Transport to the farm (t/km)	0.59	23.9	2.3
Drying soybeans (MJ/t)		482	45.46

Fuel consumption for individual treatments was calculated based on the data presented by Wójcik [45]. On the other hand, the emissions from diesel combustion in farm tractors were adopted at 3.864 kg of CO₂/dm fuel, based on the data provided by the EPA Report [46]. Due to the low amount of nitrogen oxides and methane emitted during diesel combustion in farm tractors, this source of GHG was omitted, as recommended by the EPA Report [46]. The energy consumption for drying the soybeans was based on [47]; the moisture level of the soybeans during harvest was 19.2%. As part of post-harvest activities, seeds were dried to a moisture content of 15% at an energy expenditure of 0.42 GJ/Mg of seed weight. According to the methodology provided by FAO (2017), the amount of nitrogen emitted into the atmosphere from mineral fertilization is 1% direct emission and 0.27% of nitrogen dissipated in the environment. The amount of nitrogen oxides emitted from nitrogen diffused in mineral fertilizers was estimated at 0.75% of the total nitrogen not used by plants during the growing season [48] (Tables 4 and 5).

Table 4. Selected parameters of the torrefaction process and the type of biochar used in the experiment.

Following Parameters	Unit	Sunflower Husk Biomass	Wood Biomass
Efficiency of the torrefaction process	% by weight of the raw material	35.42	38.83
CO ₂ emissions related to the preparation of the raw material	kg CO ₂ eq/Mg of biochar	117	156
Organic carbon content	%	85.32	83.89
Stable carbon content in biochar	% of total carbon	79.87	77.41

Table 5. CO₂ emissions from fertilizers (CO₂ eq/ha).

Treatments	A	B	C	D
1	628.6	810.5	685.3	0.0
2	628.6	814.6	923.3	103.2
3	628.6	900.8	1550.9	154.8
4	628.6	846.2	1346.1	206.5
5	628.6	840.6	1068.1	134.4
6	628.6	897.1	1564.6	201.6
7	628.6	873.5	1479.2	268.9

A-CO₂ eq from fertilizers and seeds [40], B-CO₂ emission from fuel combustion (Wang et al. 2012), C-CO₂ emission from harvest residues and mineralization of organic matter [42,43], D-CO₂ emission related to the production and use of biochar [49–51].

The value of the carbon footprint for biochar production was adopted according to the data presented by [49] at 105 kg CO₂ eq/Mg biochar. The value of transport-related emissions was adopted at 32 kg CO₂ eq/Mg biochar, provided the transport of raw materials and products was within 40 km from the installation. The efficiency of the torrefaction process for sunflower husks was 35.42%, and for wood biomass 38.83%. The stable carbon content in the sunflower husk biochar was 79.87%, and in wood biomass it was 77.41%. GHG emissions related to biochar production were calculated based on the mass and energy balance of the biochar production process and literature data provided by Llorach-Massan [49]. The time frame for the effect of the applied biochar, i.e., the period in which 50% of the applied biochar should decompose, is 50 years [50,51].

3. Results and Discussion

3.1. Soybean Yield and Total CO₂ Emissions Depending on the Doses of Biochar Applied to the Soil

To verify the effect of biochar fertilization on soybean yield and total CO₂ emissions, a one-way analysis of variance was performed. The significance of the differences between the compared variables is illustrated in the last column (Table 6). As shown by the data, there are significant differences in the soybean yield and total CO₂ emissions depending on the applied doses of biochar.

Table 6. Results of the analysis of variance in single classification: soybean yield and total CO₂ emissions depending on the doses of biochar applied to the soil.

Sum of Squares	Mean of Squares	Test F	p
Soybean yield			
15.1151	2.5192	22.184	0.000 *
Total CO ₂ emissions			
531,865	88,644	13.168	0.0001 *

*—significant dependence at $\alpha = 0.05$.

The assumption that the dose of biochar application affects the yield of soybeans and the total emission of CO₂ was confirmed by statistical analysis (Table 6). The demonstration of statistical significant differences within the above-mentioned indicators shows a significant correlation between the size of the biochar dose and the yield of soybeans and the total emission of CO₂.

Figure 3 is a graphic presentation of the results of the analysis of variance of soybean yield per the type and dosage of biochar. As demonstrated, the type and dosage of biochar has a large impact on the yield of soybean. Soybean fertilized with 60 Mg of biochar per hectare, both types, showed the best yield. This tendency was not confirmed with the use of 80 Mg per hectare biochar doses. To better illustrate the obtained results, Tukey's test

was carried out to determine homogeneous groups within the studied variable. The test results are presented in Table 7.

Figure 3. Average values of soybean yield (Mg) depending on the type and dosage of biochar.

Table 7. The results of Tukey's test for groups of significantly homogeneous grouping factor (****) of biochar dose and soybean yield.

Treatments	Marketable Yield (Mg)	1	2	3
1	1.870	****		
2	1.960	****		
5	2.520	****	****	
4	2.640	****	****	
7	3.230		****	****
6	3.740			****
3	3.820			****

Tukey's test confirmed that there are homogeneous groups of the studied variable and that they include statistically significant relationships. Soybean plants yielded significantly better after applying a biochar dose of 60 Mg per hectare compared to the control, regardless of the type of biochar used. In the objects where biochar fertilization was applied at 40 tons, the yield of soybean was comparable to that of the control plots.

Figure 3 graphically presents the obtained results of the univariate analysis of variance for the total CO₂ emissions for doses and types of biochar applied. The application rates at 60 Mg per hectare (Figure 2) emission can be clearly seen. The highest total CO₂ emissions were recorded in an object where sunflower husk biochar was used at a dose of 40 Mg per hectare.

The Tukey test performed for total CO₂ emissions showed that the objects fertilized with biochar at 60 tons per hectare formed a homogeneous group with the lowest total CO₂ emission. The homogeneous group with the highest CO₂ emissions consisted of objects with sunflower husk biochar doses of 40 and 80 tons per hectare, and a control object. This result proves a significant impact of biochar dosing and type on the total CO₂ emission (Table 8).

Table 8. Results of Tukey's test for groups of the significantly homogeneous grouping factor (****) of biochar dose and soybean yield.

Treatments	Total Emission (kg/CO ₂)	1	2	3	4
3	846.9		****		
6	880.2		****	****	
7	1006.2	****	****	****	
5	1060.2	****		****	
1	1136.0	****			****
4	1146.7	****			****
2	1260.1				****

The obtained results were subject to variance analysis. The significance of the differentiation of mean values was determined using Tukey's test ($\alpha \leq 0.05$). The Statistica 13 program (TIBCO Software Inc., Palo Alto, CA, USA) was used to statistically analyze the results.

Processing waste organic matter into biochar before introducing it into the soil is an effective method of stabilizing carbon compounds and increasing the level of sequestration of this element in soil organic matter [52,53]. The problem pointed out by, e.g., [54,55] could be biochar contamination with heavy metals or polyunsaturated aromatic hydrocarbons. The results of the calculations show a significant differentiation in the total GHG emissions converted into CO₂ eq for the adopted system boundary. The factor differentiating the compared production technologies was the type of biochar and its dose. The adopted conversion unit was 1 t of commercial product after drying to a moisture level of 15%. The introduction of biochar into the soil statistically significantly affected the yield of soybeans. The commercial yield of the object without the addition of biochar was 1.87 Mg of seeds, the lowest value among all the objects (Figure 3).

The addition of sunflower husk biochar at 40 Mg/ha did not change the yield. However, increasing the amount of this material to 60 Mg/ha increased the yield by 100% compared to the result obtained in the control object. A further increase in the dose of biochar resulted in a reduction of plant yield; however, higher yields were observed in each object with the addition of biochar as compared to the control object. A lower dose impact on the level of plant yield was found in research objects with the addition of wood chip biochar. The values of this parameter ranged from 2.52 to 3.74 Mg/ha of dry seeds. From the point of view of plant yield, wood chip biochar proved to be a more useful material. The type of raw material used for the production of biochar plays an important role in the formation of the properties of biochar in terms of its functionality [23]. Literature data indicate that the addition of biochar to soil could have a positive effect on the yield of plants, but to a lesser extent than indicated by the results of the author's own research. Floe et al. [56] showed that the use of biochar in maize cultivation increased its yield by 10 to 15% compared to cultivation without the use of biochar, depending on the availability of water. Ndor et al. [57] report that the use of biochar at 5 Mg/ha increased the yield of maize by 40% as compared to the object without biochar. Addition of biochar at 10 Mg ha⁻¹ increased the yield by 66% compared to the control object. These authors point out that the addition of biochar to the soil changes its properties, e.g., air and water conditions, pH, and the availability of nutrients for plants. Similarly, Krause et al. [58] and Gong et al. [53] indicate that the yield potential of biochar is associated with the improvement of plant growth conditions and an increased availability of nutrients. Increasing the yield of plants at the same consumption level of production means directly reducing GHG emissions from plant production. Wang et al. [59] found that the addition of biochar to soil significantly reduced the GHG emissions from agroecosystems.

Sánchez-García et al. [60] also indicate that biochar added to the soil had a positive effect on nitrogen oxide emissions in cabbage cultivation. The reduction of GHG emissions was most noticeable in the periods with increased emissions. The authors stated that the key element that affected the level of nitrogen oxide emissions was the change in air–water properties of the soil after the addition of biochar, which influenced the level of microbial activity in the soil.

3.2. Emission Sources in the Total GHG Emission Related to Soybean Production

The results of the experiments indicate a significant impact of the proposed technological strategies for soybean cultivation on the formation of GHG emissions from both direct and indirect sources. The total GHG emissions given as CO₂ eq ranged from 846.9 to 1260.1 kg of CO₂/Mg of the weight of the commercial product (Figure 4).

Figure 4. Average values of total emissions of 1 kg CO₂ depending on the type and dosage of biochar.

The lowest value of this parameter was obtained for the object with 60 Mg of sunflower husk biochar. The GHG emission value for the control object without biochar was 1136 kg CO₂/Mg. From the point of view of environmental efficiency, the best effects for the adopted system boundary were obtained in the variant with the addition of 60 Mg of biochar, both when the raw material was sunflower husk and wood chips. A further increase in the amount of biochar resulted in a reduction in the yield of plants, which affected the results of GHG emissions. Even taking into account the emission of GHGs into the atmosphere related to the process of biochar production, as well as the transport of raw materials and the product itself, the results of the presented studies indicate that the introduction of such materials into the soil is environmentally justified. The results obtained in the authors' own research in specific variants of the experiment are much higher compared to the data presented by other authors. The factor with the greatest impact on the GHG emissions was the level of crop yield. The effects comparable to the data in the literature were obtained in the treatment with the addition of biochar at 60 Mg/ha (Figure 3). Zortea et al. [61] report the value of CO₂ eq emissions from soybean production in basil at 734 kg CO₂/Mg of seeds. These authors report that over 40% of the total emissions are related to emissions from soil, both from the fertilizers used and the mineralization of organic matter. Rajaeifar et al. [62] report the level of GHG emissions from soybean cultivation at the level observed in objects with the addition of biochar at 60 Mg/ha. Gerdales Castanheir and Freire [63] calculated the CO₂ eq emissions for soybean cultivation

at 200–400 kg per Mg of dry weight of seeds. These authors did not include within the system boundaries the emissions related to the mineralization of organic matter and crop residues. Increasing the yield of plants, which is associated with increasing the efficiency of nutrient and water use, indicates a positive assessment of soil enrichment with biochar in terms of production economics. According to the data presented by Lehmann et al. [50], Llorach–Massana et al. [49] or Wang et al. [63], biochar introduced into the soil reduces the emission of nitrogen oxides and carbon monoxide by increasing the sorption capacity of these gases. This element was not taken into account in these studies; however, it should not be omitted when developing recommendations for the management of organic carbon resources in agricultural soils. Increasing the efficiency of the use of plant nutrients is a strategic element of sustainable development in agriculture [64–66] and increasing the amount of organic matter in soils is one of the most environmentally effective methods of intensifying plant production [12,16,32,63]. Figure 5 demonstrates the percentage share of individual GHG sources in the total emission for the adopted system boundary. The sources were divided into 5 groups: (i) Burning fuels; (ii) Production and use of fertilizers and seeds; (iii) Ghg emissions from the soil resulting from the decomposition of crop residues and soil organic matter; (iv) Emissions from energy consumed to dry seeds; and (v) Emissions related to the production and use of biochar as well as its distribution in the soil ecosystem.

Figure 5. Share of individual emission sources in the total GHG emission related to soybean production.

Among all the groups of sources of GHG emissions in soybean cultivation, in all research objects the emission from mineralization of soil organic matter, both from crop residues and from mineralization of humus compounds, had the highest share. The level of GHG emissions in individual research objects ranged from 366.4 to 509.9 kg of CO₂/Mg of seeds (Figure 6). The highest value of this parameter was found in the objects with the highest addition of biochar, while the lowest emission from this source was observed in the control object. The emission from this source constituted 32.26% of the total emission in the control object and 47.94 in the object with the addition of sunflower husk biochar at 60 Mg/ha (Figure 3). Fertilization was the second most important source of GHG emissions. Costantini and Bacenetti [67] report that the GHG emissions for soybean

cultivation resulting from the use of fertilizers constituted 45% of the total calculated emissions. Emissions from the decomposition of crop residues reported by these authors accounted for approximately 13% of the total production emissions. The production and use of fertilizers, especially nitrogen fertilizers, is the most important source of GHG emissions in agricultural production [68,69]. This is due to the high energy expenditure in ammonia synthesis and the emission of unused nitrogen to the atmosphere in the form of nitrogen oxide, which has an almost 300 times greater potential to generate the greenhouse effect compared to carbon dioxide. In the cultivation of legumes, with optimal soil properties and a sufficient supply of macro- and microelements, generally less nitrogen fertilization is used, as this element can be bound by symbiotic bacteria. Promoting the production of legumes is therefore an element of reducing not only the amount of GHG emissions, but also of the energy consumption in the food production process, which is now a priority in the optimization of production processes [70].

Figure 6. Share of individual emission sources in the total GHG emission related to soybean production (kg CO₂/kg).

The outcome of the conducted studies proves a positive environmental impact of biochar application as a soil improver in case of soybean cultivation. Soil additives in the form of biochar resulted in a statistically significant increase in yield and reduction of greenhouse gases emission per accepted functional unit. Biochar production and application costs are one of the most important factors limiting the biochar use in agriculture. Latawiec et al. [21] indicate that there is no economic profitability in biochar application as it improved in soybean cultivation in the amount of 40, 60, and 80 Mg/ha. These authors emphasise that the popularity of biochar application as a soil enhancer is determined by subsidy programs for farms, which introduce biochar to soil. On the other hand, Majumder et al. [71] and Owsianiak et al. [72] draw attention to the need of searching

for energetically effective methods of the conversion of biomass into biochar in order to increase its use in agriculture. According to these authors, the use of low-emission biomass torrefaction methods will result in the considerable increase in popularity of biochar application as a soil fertilizer.

4. Conclusions

1. The introduction of biochar to the soil had a statistically significant effect on the level of soybean yield.
2. The use of biochar in soybean cultivation resulted in a 25% reduction in GHG emissions compared to the object without the biochar addition. The amount of GHG emissions for soybeans ranged from 846.9 to 1260.1 kg of CO₂/Mg.
3. The impact of the type of biochar raw material on the yield and the level of GHG emissions per functional unit of the product was identified.
4. From the environmental and production perspective, the addition of biochar at 60 Mg/ha is the most advantageous. A further increase in the addition of biochar was related to a decrease in the plant yield and an increase in GHG emissions.
5. Introducing biochar to soil can be an effective improvement of the economic and environmental efficiency of plant production, as it increases the plant's use of nutrients and intensifies carbon sequestration in soils.

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