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Analysis of the effect of sandy soil amendment with biochar on its physical and chemical properties and the quantity and quality of biomass yield of energy crops

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ABSTRACT

This study attempted to analyze the effect of biochar fertilization with the biomass of Virginia fanpetals (*Sida hermaphrodita*) on selected physical and chemical properties of sandy soil. The biomass yield of three energy crop species grown on such fertilized soil was evaluated. The content of heavy metals accumulated in the biomass of selected energy crops and the soil after crop cultivation was also determined. The examinations were carried out under conditions of the lysimeter experiment (natural conditions). Sandy soil was used for fertilization, with biochar doses of 0.5%, 1%, 1.5%, and 2% (by weight). The control material was non-fertilized soil. The study was carried out for 3 y. After each growing season, selected soil properties, the volume of biomass obtained, and the bioaccumulation of heavy metals were analyzed. Fertilization of the sandy soils with biochar caused a significant increase in the yield of all three energy crops studied, including *Sida hermaphrodita*. Of all the species cultivated, this plant responded best to biochar amendment. An optimum dose of this fertilizer was 1.5%, which, in the first year of cultivation, caused an increase in yield by 21.1% compared to control plants. The study showed that the use of biochar as a fertilizer did not cause an increase in contamination of the sandy soils with heavy metals. The application of biochar to sandy soil with all doses resulted in an improvement of selected sorption properties including a statistically significant increase in pH (active acidity), a decrease in hydrolytic acidity (potential acidity), an increase in the content of phosphorus, nitrogen, total carbon, and organic matter.

Keywords: Fertilization; Biochar; *Sida hermaphrodita*; Soil; Biomass; Heavy metals

1. Introduction

Biochar is a material that in some respects resembles charcoal and can be used in many industries and agriculture. It is produced by burning wood or green waste [1] at a minimum temperature of 350°C or higher without the presence of oxygen. This process is called pyrolysis. It modifies the chemical structure of the initial material, making it less biodegradable. This extends the time it can be present and function in the soil until decomposition [2].

Biochar can be used to improve soil fertility and in general, it has a positive effect on its physical, chemical, and microbiological properties. However, there is a likelihood that undesirable amounts of pollutants such as heavy metals, polycyclic aromatic hydrocarbons, or phenolic compounds may be introduced into the soil with it [3,4]. Recent studies have also reported that metal cyanides, which are very dangerous for the environment, can be released from biochar into the soil [5]. It is therefore recommended that the quality and properties of this soil improver be subject to constant and stringent controls. Harmful components

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that may be present in biochar (due to improper preparation or from contaminated biomass) can adversely affect the crops grown.

Toxic substances in biochar can come from biomass feedstock or can be produced during pyrolysis [6]. Contaminants accumulated in biochar can also be released into the soil environment during aging and degradation [7]. Biochar can also in some cases inhibit the biodegradation of contaminants in soil. Some studies have shown that the toxicity of biochar on microorganisms was closely related to the content of phenolic compounds and organic acids in lignin and cellulose [8]. Also, the microbial composition of the soil and its biological activity and fertility after the application of biochar containing harmful compounds can be changed [2].

Despite many studies, the biotoxicity of biochar for the soil ecosystem remains unclear. Some studies on the effects of biochar on microorganisms have indicated that the biotoxicity of this material varies depending on the source of processed biomass. The experiments discussed here showed that, for example, biochar derived from rice hulls and sawdust has a negligible toxic effect on all soil organisms tested. This suggests that biochar derived from agricultural waste is safe for use in soil. Furthermore, biochar formed from *Acorus calamus* shows significant toxicity to all tested organisms at relatively high doses, indicating that it is necessary each time to assess the risk before its use in the environment [6].

Biochar is not a common fertilizer in Poland and other countries. However, this material may be exceptionally considered an organic fertilizer or soil conditioner [1,2].

Its use requires a market authorization in accordance with the legal acts such as the Act of 10 July 2007 on fertilizers and fertilization [9] and with the Regulation of the Minister of Agriculture and Rural Development of 18 June 2008 on the implementation of certain provisions of the Act on Fertilizers and Fertilization [10]. The act defines the following limits on the materials used as fertilizers: Cr (100 mg), Cd (5 mg), Ni (60 mg), Pb (140 mg), Hg (2 mg) per kg of dry matter of the fertilizer or soil conditioner. However, the regulation does not include pollutants such as polycyclic aromatic hydrocarbons, furans, dioxins or polychlorinated biphenyls, with their contents regulated by the respective United States of America (USA) or European recommendations [2].

It is often thought that biochar is a homogeneous material. However, there are different types of biochar. Its physical and chemical properties can be very different depending on the biomass from which it is made. This property significantly affects the behavior of biochar after its application to the soil. As shown by many studies [1], biochar most often increases the ability of sandy soils to retain water.

The use of biochar for fertilizing has an effect on plant yield. Most often, this process increases the volume of biomass produced. Due to its valuable properties such as high organic carbon content, high chemical stability, extended specific surface area, and porosity, biochar can be used to sequester carbon in soil and optimize composting [11]. Biochar can be used as a basis for the production of fertilizers used for the remediation of soils contaminated with organic and inorganic compounds. These fertilizers can also be used to improve soil properties, stimulate plant growth, reduce groundwater, surface water pollution, and remove various pollutants. Reports are also available on the positive effects of biochar in soil on the long-term degradation of persistent organic pollutants [8].

The use of biochar as a fertilizer can also significantly affect the soil pH. Some studies [12] have shown that the higher the temperature of biomass combustion during biochar formation, the stronger the deacidification effect when introduced into the soil. Other important soil buffer properties are also modified, such as sorption capacity, migration of various chemical pollutants in the soil profile, and their bioaccumulation in plant biomass.

There are many low-productivity soils in the world. They are often sandy, acidified and easily degradable. The use of biochar could be one of the ways to fertilize them and enrich the sorption complex. For example, in Poland, light sandy soils cover most of the country. This is due to natural and anthropogenic causes. Depending on the origin, they are characterized by low organic matter content and very poor resistance to chemical degradation, and strong or very strong acidification. This is observed in up to about 40% of soils [13]. They often contain high levels of heavy metals. This contributes to increasingly lower production efficiency and negatively affects the environment [14]. On sandy soils of low agricultural suitability, it is often recommended to grow crops for energy purposes.

In the present study, the problems of the evaluation of the physical and chemical properties of biochar obtained during the pyrolysis of biomass of the energy plant *Sida hermaphrodita*. Its influence on the yielding of energy crops as well as the physical and chemical characteristics of fertilized soils was also analysed. As part of vegetation experiments, its usefulness for fertilizing sandy soils was examined and the optimum dose that can be used for growing selected species of energy crops was determined. The aim of this study was to analyze the effect of using different doses (0%, 0.5%, 1%, 1.5% and 2%) of biochar for fertilization on selected properties of sorption complex and the content of heavy metals in sandy soils. The yielding of three selected plant species was also studied and the bioaccumulation of selected heavy metals in plant biomass was determined. The experiment was carried out for 3 y.

2. Material and methods

The research was conducted within the framework of a large development project, with one of the objectives being to demonstrate the fertilizing usefulness of biochar obtained during the pyrolysis of biomass of *Sida hermaphrodita*. The main element of preliminary research presented in the paper was to determine the optimal dose that promotes the development of biomass of energy crops. Many hectares of land with predominantly poor soils of low fertility on which no additional fertilization is carried out were provided for the target crop. In the research presented in the paper, sandy soil (S) derived from selected areas of a large plantation of *Sida hermaphrodita* cultivation was used for fertilization with biochar. Biochar (B) was introduced once to the analyzed soils at doses of 0.5%, 1%, 1.5% and 2% (in the dusty form after fragmentation). The doses used were determined by weight. They were determined on the basis of other available studies and own research (preliminary phytotoxicity tests). The control substrate was non-fertilized soil (marked as C).

The examinations were carried out under conditions of the lysimeter experiment. The initial pH of the sandy soil used in the lysimeter experiment was 6.02, and, according to Polish Fertilization Recommendations [15], it is defined as a weakly acid reaction. The concentration of heavy metals tested in soil according to the above recommendations and presented in Table 4 was at a low level and was below the permissible content of these elements in the cultivated soils [16].

The experiment was carried out in polyethylene lysimeters with a capacity of 10 kg (Figs. 1 and 2). Three plant species with energy potential were planted into the prepared soil mixtures with different doses of biochar. These were: Virginia fanpetals (*Sida hermaphrodita*), maize (*Zea mays*), and common sunflower (*Helianthus annuus*). All plants used in the experiment were seedlings prepared earlier from seeds (in peat multiple trays on nutrient-poor substrate). Of the obtained seedlings, plants with equal growth potential were selected and planted into experimental vases in prepared mixtures of 10 plants each in the case of sunflower and maize, and 5 plants in the case of *Sida hermaphrodita*.

In the lysimeter experiment, no additional mineral fertilization was applied except for fertilization with biochar. This was aimed to demonstrate its fertilizer suitability and long-term impact on the soil. In all experimental sites, moisture content was maintained at 60% of the maximum water capacity by watering with well water. The experiment was carried out in a foil tunnel. The experiment lasted 3 y. After each growing season, the aboveground parts of plants were harvested from the experimental sites for testing (the root system was also removed in the case of sunflower and maize). The volume of aboveground biomass obtained from individual fertilizer combinations was determined. The yield was reported in grams of fresh biomass per pot. The heavy metal content of individual plants was also analyzed. In the following two growing seasons, new maize and sunflower seedlings were replanted. *Sida hermaphrodita* was left to overwinter in lysimeters and was considered a perennial plant. The experiments were repeated three times. The results presented in the paper are means from these repetitions.

Analysis of the results was performed by means of a statistical software package STATISTICA 9.0. The significance of statistical differences was analyzed compared to control samples. The test probability was considered significant at $p < 0.05$, whereas the test probability of $p < 0.01$ was highly significant.

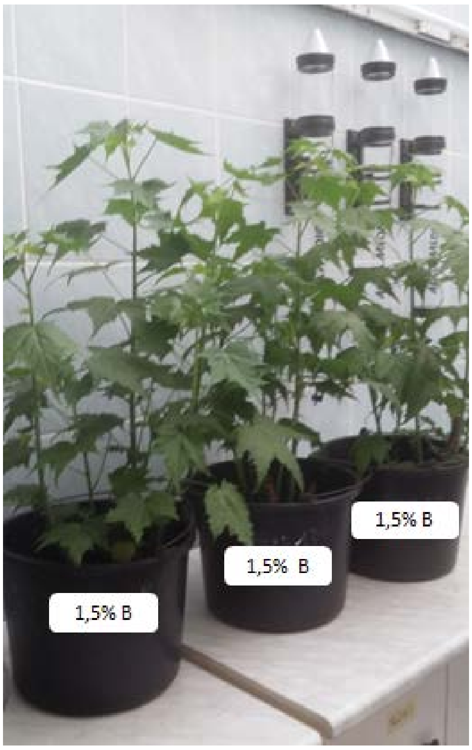

Fig. 1. Examples of experimental pots in the first year of research (three repetitions from the cultivation of *Sida hermaphrodita* with 1.5% biochar added to sandy soil).

2.1. Methodology for chemical determinations

Biochar was produced by the author of research on biomass *Sida hermaphrodita* at the Czestochowa University of Technology (as part of a research project). Tested samples of biochar, which was formed after pyrolysis of biomass of *Sida hermaphrodita* at 400°C, were initially dried at room temperature. Next, they were sieved through a sieve with a mesh diameter of 2 mm. They were dried at 105°C to constant weight, ground in a mortar, and sieved using a sieve with a mesh diameter of 0.6 mm (Fig. 3). Three research samples were prepared for analysis. Soil and biomass samples were handled similarly.

The following parameters were determined in biochar and soil (after cultivation of *Sida hermaphrodita*):

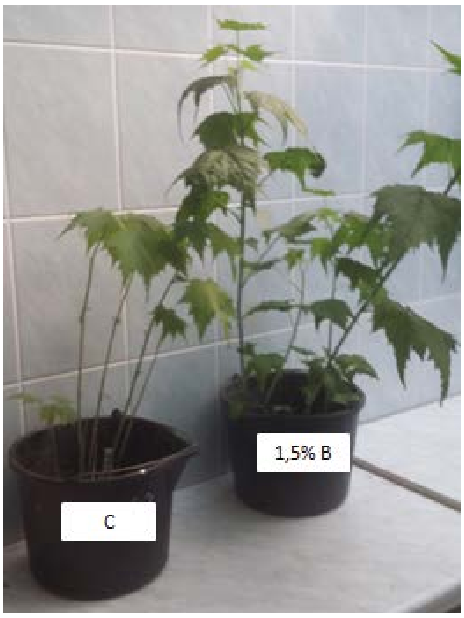

Fig. 2. Examples of experimental pots in the third year of research (on the left: the cultivation of *Sida hermaphrodita* in a pot on control soil; on the right: with 1.5% biochar added to sandy soil).

Fig. 3. Biochar from *Sida hermaphrodita* biomass obtained by pyrolysis at 400°C was used to fertilize sandy soil (on the right – after fragmentation).

- pH in H_2O: the potentiometric method,
- pH in KCl: the potentiometric method,
- hydrolytic acidity (Hh): was determined by the Kappen method,
- total carbon (TC): examined using a Multi N/C 2100 Analytik Jena carbon analyzer,
- Kjeldahl nitrogen: evaluated using distillation after prior mineralization of the samples in a Buchi K-435 mineralizer,
- content of organic matter: the weighing method,
- content of available forms of phosphorus: the Egner–Riehm method,
- total phosphorus: using the spectrophotometric method with ammonium molybdate (samples were mineralized in a Berghof high-pressure microwave mineralizer).

The total content of heavy metals was also determined in the biochar used for the experiments. The contents of mercury (Hg), copper (Cu), lead (Pb), cadmium (Cd), zinc (Zn), nickel (Ni), chromium (Cr), arsenic (As), and molybdenum (Mo) were evaluated. Results are given in milligrams per kilogram of dry matter of biochar.

The content of 5 selected heavy metals was determined in fertilized sandy soils and plant biomass: lead (Pb), zinc (Zn), copper (Cu), nickel (Ni), and cadmium (Cd).

Aqua regia was used to extract heavy metals (it is a mixture of concentrated hydrochloric and nitric acids at a recommended volumetric ratio of 3:1). Mineralization was performed at a temperature of 180°C for 30 min, in a high-pressure microwave mineralizer (Berghof, Germany).

The contents of heavy metals in the samples were determined using inductively coupled plasma optical emission spectrometers SPECTRO ARCOS FHX22.

The total organic carbon (TOC) content in water extract was evaluated using a Multi N/C 3100 Analytik Jena carbon analyzer.

The content of mercury (Hg) was measured directly in the samples using the AMA254 mercury analyzer (atomic absorption spectrometer).

There are no requirements in Poland for the determination of polycyclic aromatic hydrocarbons (PAHs) in biochar, which is used, for example, for soil amendment. However, due to the presence of tarry compounds (which can be hazardous to plants and soil organisms) in the aqueous extracts of this material, PAH determinations were also conducted.

Before the chromatographic determination of PAHs in biochar, the initial stage was extraction with organic solvents with different polarities. The organic matrix was separated using sonolysis of a mixture of cyclohexane and dichloromethane solvents (5:1 v/v). Solvent extracts were separated from the samples using a high-speed centrifuge. Silica gel was employed to isolate the analyzed components from other simultaneously extracted organic substances (purification under vacuum conditions). The obtained extracts were concentrated in the nitrogen stream. Determinations of polycyclic aromatic hydrocarbons were performed using a gas chromatograph coupled to a mass spectrometer (Fisons GC800/MS800). Sixteen PAHs from the EPA list indicated for environmental analyses were evaluated. These were: naphthalene, acenaphthylene, acenaphthene, fluorene, phenanthrene, anthracene, fluoranthene, pyrene, benz[a]anthracene, chrysene, benzo[b]fluoranthene, benzo[k]fluoranthene, benzo(a)pyrene, dibenz[a,h]anthracene, benzo[ghi]perylene, and indeno[1,2,3-cd]pyrene [17].

3. Results and discussion

The physical and chemical characterization of biochar (Fig. 3) used in the study is presented in Tables 1–3. Table 1 also shows a comparison of the results of the examinations of biochar obtained from *Sida hermaphrodita* with other current standards for such products used in some European countries (European Biochar Foundation – EBF) and the USA (International Biochar Initiative – IBI) [18]. Table 2 compares the pollutant standards for fertilizer materials used in Poland, with the values determined in the biochar studied. The results of other determinations in the analyzed material are presented in Table 3. Table 4 compares the results of determinations of physical and chemical parameters of the sandy soil used in the study. The results of the examinations of sandy soil after fertilization with biochar and the obtained biomass are presented in Tables 5–8.

A general definition of biochar was provided in the recommendations of the European Biochar Certificate (EBC) [2]. Substantial discrepancies are observed in the nomenclature and classification of biochar. Depending on the properties and suitability, biochar can be regarded as an organic fertilizer or soil conditioner. Drying, pyrolysis, and gasification of the biomass is performed during the process termed torrefaction. This process leads to an average 30% loss of mass, formation of so-called torgas, and biochar. The obtained product is similar to charcoal, but there are some differences. These data show that biochar is a heterogeneous material, rich in aromatic carbon and minerals, which is a material formed during biomass pyrolysis. The recommendations also specify the temperature range at which the thermal conversion process should be carried out (from 350°C to 1,000°C). This document excludes material obtained from low-temperature torrefaction or

Table 1
Comparison of the results of chemical analyses of the tested biochar from the *Sida hermaphrodita* with the guidelines for biochar in selected European countries and the USA [18,19]

Type of contaminant present in biochar (mg/kg d.m.)	Content of contaminants determined in biochar	Permissible values according to the European Biochar Certificate (EBC)	Permissible values according to the International Biochar Initiative (IBI)
Arsenic (As)	1.8 ± 0.4	13	13–100
Cadmium (Cd)	1.5 ± 0.76	15	1.4–39
Chromium (Cr)	22.0 ± 5.3	90	93–1,200
Copper (Cu)	21.0 ± 6.22	1,000	143–6,000
Mercury (Hg)	0.02 ± 0.01	1	1–17
Nickel (Ni)	2.1 ± 0.6	50	47–420
Lead (Pb)	5.7 ± 0.5	150	121–300
Zinc (Zn)	60.0 ± 11.3	400	416–7,400
Selenium (Se)	n.m.	–	2–200
Molybdenum (Mo)	4.1 ± 2.2	–	5–75
Fluorine (F)	2.71 ± 0.3	–	–
PAHs (16)	1.435	12	6–300
PCB	n.m.	0.2	0.2–1
Dioxins and furans (ng/kg d.m.)	n.m.	20	20

n.m. – not marked;
d.m. – dry mass;
±standard deviation.

Table 2
Results of determinations of heavy metals in the biochar studied obtained from *Sida hermaphrodita* and the comparison with the contents of these elements in materials used as fertilizers permissible in Poland

Heavy metal	Content in the biochar studied (mg/kg d.m.)	maximum content of contaminants in fertilizers permissible in Poland (mg/kg d.m.) [10]
Chromium (Cr)	22.0 ± 5.3	100
Cadmium (Cd)	1.5 ± 0.76	5
Nickel (Ni)	2.1 ± 0.6	60
Lead (Pb)	5.7 ± 0.5	140
Mercury (Hg)	0.02 ± 0.01	2

n.m. – not determined;
±standard deviation.

Table 3
Characteristics of other selected physical and chemical properties of biochar from *Sida hermaphrodita* used for fertilization of sandy soil

Type of determination	Value
pH in H_2O	5.10 ± 0.58
pH in KCl	4.94 ± 0.46
Total carbon (TC), %	66.7 ± 8.6
Nitrogen content (N), %	0.8 ± 0.3
Phosphorus content (P), %	0.3 ± 0.1
Potassium content (K), %	0.4 ± 0.1
TOC (in water extract), mg/L	3,710 ± 52
Calcium content (Ca), %	1.6 ± 0.3

±standard deviation.

hydrothermal carbonization. A criterion of carbon content was also adopted in the recommendations used by the European Biochar Certificate. It is assumed that biochar is a material containing more than 50% carbon in dry matter. A combustion product that contains less than 50% carbon is considered a pyrogenic carbon material.

The plant from which the studied biochar was derived is *Sida hermaphrodita*. This plant has low soil requirements and can be successfully grown on soils of bonitation class V and VI to obtain biomass. *Sida hermaphrodita* is a perennial plant, which spreads strongly and grows up to 4 m in height. There are usually up to 20 hollow stems growing from one rootstock, with a diameter of 5–30 mm. The shoots produced die back each year and can be harvested for energy. However, *Sida hermaphrodita* quickly regrows and renews the aboveground mass. Consequently, it does not have to be planted every year, and once established, the plantation can be used for up to 20–30 y. An additional advantage is that the plant develops a strong root system and therefore tolerates periodic droughts well (which can often occur on sandy soils). Depending on the prevailing soil conditions, biomass energy plantations can yield an average of 7–20 t of dry matter per hectare per year. Biomass yield is obtained from the second year of cultivation (usually two harvests per growing season) [20]. Most researchers recommend the use of *Sida hermaphrodita* on soils of low fertility, so-called marginal land. Bury et al. [21], have reported that *Sida hermaphrodita* yields better on soils even

Table 4
Physical and chemical characteristics of sandy soil used for fertilization with biochar derived from *Sida hermaphrodita*

Determination	Physicochemical parameters of the sandy soil
pH in H_2O	6.02 ± 1.2
pH in KCl	5.54 ± 0.42
Hydrolytic acidity (Hh), me/100 g	3.1 ± 1.1
P_2O_5, mg/100 g soil	19.1 ± 6.3
Kjeldahl N, mg/kg	2,452 ± 354
Total carbon, mg/g	41.0 ± 9.3
Organic matter content (loss on ignition), %	5.6 ± 1.3
Lead (Pb), mg/kg d.m.	31.0 ± 5.23
Zinc (Zn), mg/kg d.m.	82.4 ± 9.8
Copper (Cu), mg/kg d.m.	6.5 ± 2.7
Nickel (Ni), mg/kg d.m.	4.1 ± 1.1
Cadmium (Cd), mg/kg d.m.	0.3 ± 0.1
Chromium (Cr), mg/kg d.m.	6.8 ± 1.9
Mercury (Hg), mg/kg d.m.	n.d.

n.d. – not detected;
±standard deviation.

contaminated with heavy metals than on land very poor in nutrients. Therefore, this plant can be used to remediate contaminated soils. The *Sida hermaphrodita* plants may also be used for high-yield methane fermentation [22].

In addition to its use as a typical energy crop, the biomass of *Sida hermaphrodita* can be used to produce biochar, which is also of great economic importance. There are not many reports on this topic in the available literature. However, the attempts made are very promising [23].

The results of the examinations of biochar obtained from *Sida hermaphrodita* presented in the paper (Table 3) indicate that the material can be characterized as biochar because the content of total carbon exceeds 50% (66.7%). The calcium content of 1.6% in this fertilizer is very important, which can have a positive effect on acid soils, including sandy soils. However, a disturbing phenomenon observed was the low reaction of the tested biochar (Table 3) of 5.1 (in H_2O). During the laboratory examinations and in other studies on this material [24], brown colouring of water extracts obtained from biochar was also observed, which may indicate the presence of tarry compounds. This can also be evidenced by the high contents of TOC in the biochar tested, amounting to 3,710 mg/L. It is likely that the biomass was incompletely burnt during combustion. Under these conditions, increased content of PAHs can be observed, which can be a threat to the soil environment after the fertilization with biochar. However, the analysis of the results of the evaluation of the total content of 16 standard PAHs in the biochar (Table 1) showed that the value of 1.435 is within the recommended standards for this type of product [18,19].

The total content of heavy metals in the biochar studied was lower than the permissible recommended values in both European countries and the USA (Table 1). A comparison of the content of heavy metals in the biochar

Table 5
Characteristics of physical and chemical parameters in podzolic soils from individual experimental sites fertilized with biochar (after cultivation of *Sida hermaphrodita*)

Determination	Unit	1 y of experiment					2 y of experiment					3 y of experiment				
		Type of fertilizer combination														
		S (C)	S+B 0.5%	S+B 1%	S+B 1.5%	S+B 2%	S (C)	S+B 0.5%	S+B 1%	S+B 1.5%	S+B 2%	S (C)	S+B 0.5%	S+B 1%	S+B 1.5%	S+B 2%
pH	(H_2O)	6.00	6.33 s.i.	6.45*	6.55*	6.71**	5.80	6.31*	6.47*	6.52**	6.40*	5.60	6.20*	6.39*	6.46**	6.32*
pH	(KCl)	5.38	5.70 s.i.	5.82 s.i.	5.94*	5.99*	5.49	5.64 s.i.	5.84*	5.85*	5.80*	5.48	5.68 s.i.	5.78*	5.90*	5.85*
Hydrolytic acidity (Hh)	(me/100 g)	3.10	2.93 s.i.	2.70*	2.65*	2.59*	3.22	3.20 s.i.	2.65**	2.60**	2.95*	4.10	3.65**	2.95**	2.76**	3.10**
P_2O_5	(mg/100 g soil)	11.2	11.6 s.i.	12.3*	12.9*	13.1*	7.2	10.3*	10.8*	11.0**	11.9**	7.8	8.1 s.i.	10.0**	10.1**	11.6**
Kjeldahl N	(mg/kg)	1926	2,031*	2,038*	2,064**	2,088**	1,799	1,820 s.i.	1,954**	2,011**	2,047**	1,717	1,765 s.i.	1,899*	2,001**	2,005**
Total carbon	(mg/g)	43.22	46.39 s.i.	48.00*	51.77**	53.02**	40.10	42.90 s.i.	46.70*	49.30*	50.22**	35.69	41.66*	44.50**	49.44**	48.40**
Organic matter content (loss on ignition)	(%)	6.07	6.12 s.i.	6.48*	7.74**	8.10**	4.95	4.85 s.i.	5.10 s.i.	6.55**	7.22**	4.60	4.54 s.i.	5.65*	5.34*	6.85**

Significance of differences: $*p < 0.05$, $**p < 0.01$, s.i. – statistically insignificant difference.

Table 6
Yield of fresh biomass of selected energy crops on mixtures of sandy soil fertilized with biochar

Type of plant grown	1 y of experiment					2 y of experiment					3 y of experiment				
	Mean biomass weight obtained from individual mixtures of sandy soil with biochar (g/pot)														
	S (C)	S+B 0.5%	S+B 1%	S+B 1.5%	S+B 2%	S (C)	S+B 0.5%	S+B 1%	S+B 1.5%	S+B 2%	S (C)	S+B 0.5%	S+B 1%	S+B 1.5%	S+B 2%
Virginia fanpetals (*Sida hermaphrodita*)	332.5	337.1 s.i.	392.6**	402.5**	351.6*	278.5	320.3*	369.1**	387.8**	310.5*	210.6	253.6*	287.8**	352.3**	302.6**
Maize (*Zea mays*)	227.2	255.5**	230.6 s.i.	226.3 s.i.	218.3*	205.8	234.6**	217.3*	203.8 s.i.	201.5 s.i.	168.3	218.5**	201.8**	187.3**	179.4*
Common sunflower (*Helianthus annuus*)	242.5	253.3*	275.2**	244.6 s.i.	230.3*	211.6	228.9**	245.3**	230.6*	216.4*	187.3	238.6**	258.3**	218.7**	209.5*

Significance of differences: *$p < 0.05$, **$p < 0.01$, s.i. – statistically insignificant difference.

Table 7
Results of the determination of the content of selected heavy metals in sandy soil fertilized with biochar

Element in the soil after plant cultivation		1 y of experiment					2 y of experiment					3 y of experiment				
		Mean content of heavy metals in particular mixtures of sandy soil fertilized with biochar (mg/kg d.m.)														
		S (C)	S+B 0.5%	S+B 1%	S+B 1.5%	S+B 2%	S (C)	S+B 0.5%	S+B 1%	S+B 1.5%	S+B 2%	S (C)	S+B 0.5%	S+B 1%	S+B 1.5%	S+B 2%
Lead (Pb)	*Sida hermaphrodita*	31.2	32.4 s.i.	35.8*	36.5*	39.7**	26.5	30.0 s.i.	35.1*	37.7*	37.6*	23.8	27.7*	34.0**	33.9**	34.4**
	Zea mays	30.2	30.0 s.i.	33.9*	37.7**	39.6**	29.0	27.5 s.i.	32.1 s.i.	36.2*	40.1**	21.6	23.3 s.i.	30.2**	37.8**	38.9**
	Helianthus annuus	28.7	27.9 s.i.	31.2 s.i.	35.9*	37.8**	26.4	26.1 s.i.	27.2 s.i.	34.4*	36.0**	22.7	22.8 s.i.	24.7 s.i.	32.6**	34.3**
Zinc (Zn)	*Sida hermaphrodita*	85.5	80.7*	81.8*	79.8**	78.7**	71.7	70.4 s.i.	69.9 s.i.	65.2*	61.1**	66.8	65.4 s.i.	55.7**	53.2**	51.0**
	Zea mays	84.9	85.5 s.i.	83.3 s.i.	81.9*	81.6*	78.9	77.3 s.i.	72.8*	71.9*	65.4**	73.2	71.0 s.i.	68.7*	65.4**	62.2**
	Helianthus annuus	82.8	80.7 s.i.	81.5 s.i.	78.6*	77.2*	76.4	72.8 s.i.	70.2*	67.3**	62.5**	71.7	63.0**	62.9**	60.6**	58.5**
Copper (Cu)	*Sida hermaphrodita*	9.2	8.9 s.i.	8.5 s.i.	7.7**	7.9**	9.3	8.1*	7.8**	7.6**	7.0**	7.8	7.5 s.i.	7.1 s.i.	6.9*	6.2**
	Zea mays	8.6	8.2 s.i.	7.0**	6.3**	6.5**	10.1	9.6 s.i.	8.9*	8.1**	8.3**	7.7	7.5 s.i.	7.3 s.i.	7.1 s.i.	7.4 s.i.
	Helianthus annuus	7.9	7.0*	6.9*	7.2*	7.1*	9.8	8.0**	6.8**	6.5**	7.0**	6.9	7.0 s.i.	6.7 s.i.	6.6 s.i.	7.1 s.i.
Nickel (Ni)	*Sida hermaphrodita*	6.2	6.6 s.i.	6.4 s.i.	6.1 s.i.	4.8**	5.4	5.2 s.i.	5.1 s.i.	4.9 s.i.	4.5*	5.0	5.1 s.i.	4.9 s.i.	4.4*	4.2*
	Zea mays	7.8	7.5 s.i.	7.3 s.i.	6.9*	5.3**	5.8	6.5 s.i.	6.3 s.i.	5.7 s.i.	5.4 s.i.	6.1	6.0 s.i.	5.8 s.i.	6.1 s.i.	6.0 s.i.
	Helianthus annuus	5.9	6.1 s.i.	5.5 s.i.	5.7 s.i.	6.0 s.i.	6.2	6.5 s.i.	6.6 s.i.	6.4 s.i.	6.3 s.i.	5.8	5.4 s.i.	5.3 s.i.	5.1*	5.0*
Cadmium (Cd)	*Sida hermaphrodita*	0.55	0.49 s.i.	0.50 s.i.	0.47*	0.46*	0.47	0.45 s.i.	0.42 s.i.	0.42 s.i.	0.39*	0.38	0.38 s.i.	0.36 s.i.	0.35 s.i.	0.29*
	Zea mays	0.48	0.47 s.i.	0.47 s.i.	0.48 s.i.	0.41*	0.52	0.50 s.i.	0.51 s.i.	0.53 s.i.	0.53 s.i.	0.48	0.46 s.i.	0.45 s.i.	0.43 s.i.	0.40*
	Helianthus annuus	0.57	0.52 s.i.	0.50 s.i.	0.51 s.i.	0.47*	0.51	0.48 s.i.	0.49 s.i.	0.47 s.i.	0.45 s.i.	0.36	0.34 s.i.	0.34 s.i.	0.35 s.i.	0.36 s.i.

Significance of differences: *$p < 0.05$, **$p < 0.01$, s.i. – statistically insignificant difference.

Table 8
Results of the determination of the content of selected heavy metals in plant biomass obtained from sandy soil fertilized with biochar

Element in plant biomass		1 y of experiment					2 y of experiment					3 y of experiment				
		Mean content of heavy metals in the biomass of plants from particular mixtures of sandy soil fertilized with biochar (mg/kg d.m.)														
		S (C)	S+B 0.5%	S+B 1%	S+B 1.5%	S+B 2%	S (C)	S+B 0.5%	S+B 1%	S+B 1.5%	S+B 2%	S (C)	S+B 0.5%	S+B 1%	S+B 1.5%	S+B 2%
Lead (Pb)	*Sida hermaphrodita*	0.39	0.38 s.i.	0.41 s.i.	0.38 s.i.	0.39 s.i.	0.31	0.31 s.i.	0.28 s.i.	0.27 s.i.	0.21*	0.28	0.26 s.i.	0.23*	0.21*	0.19**
	Zea mays	0.27	0.28 s.i.	0.31 s.i.	0.32 s.i.	0.31 s.i.	0.21	0.22 s.i.	0.19 s.i.	0.18 s.i.	0.16*	0.20	0.21 s.i.	0.19 s.i.	0.18 s.i.	0.16*
	Helianthus annuus	0.41	0.39 s.i.	0.37 s.i.	0.42 s.i.	0.42 s.i.	0.38	0.39 s.i.	0.31*	0.21**	0.20**	0.32	0.34 s.i.	0.29 s.i.	0.21**	0.20**
Zinc (Zn)	*Sida hermaphrodita*	56.6	54.4 s.i.	57.8 s.i.	50.1*	48.4**	30.2	31.6 s.i.	32.8 s.i.	21.5**	17.8**	22.1	20.6 s.i.	20.4 s.i.	19.3*	16.5**
	Zea mays	49.7	46.9 s.i.	45.7 s.i.	47.6 s.i.	46.8 s.i.	19.7	17.8 s.i.	17.0 s.i.	17.3 s.i.	14.1*	16.2	16.0 s.i.	15.6 s.i.	12.4*	10.5**
	Helianthus annuus	58.1	56.3 s.i.	55.8 s.i.	49.4*	52.6*	23.5	22.8 s.i.	19.4 s.i.	17.9*	15.4**	20.6	19.7 s.i.	15.2*	13.5**	12.8**
Copper (Cu)	*Sida hermaphrodita*	5.8	6.1 s.i.	7.6*	7.8*	8.9**	4.6	4.8 s.i.	5.1 s.i.	5.9*	6.8**	4.2	4.3 s.i.	4.5 s.i.	4.9 s.i.	5.6*
	Zea mays	4.9	5.1 s.i.	5.9*	7.4**	9.5**	4.2	4.5 s.i.	4.6 s.i.	4.9*	5.1**	3.8	4.0 s.i.	4.1 s.i.	4.5*	4.7*
	Helianthus annuus	6.5	7.0 s.i.	6.9 s.i.	8.2*	11.7**	5.4	5.7 s.i.	5.8 s.i.	7.1*	8.0**	5.2	5.5 s.i.	5.6 s.i.	6.1*	7.9**
Nickel (Ni)	*Sida hermaphrodita*	2.73	3.10 s.i.	2.30 s.i.	2.00*	1.61*	2.11	2.15 s.i.	2.10 s.i.	1.72*	1.60*	1.99	2.11 s.i.	1.74 s.i.	1.59 s.i.	1.00**
	Zea mays	2.10	2.00 s.i.	1.95 s.i.	1.78*	1.56*	1.86	1.77 s.i.	1.90 s.i.	1.59 s.i.	1.11*	1.72	1.60 s.i.	1.40 s.i.	1.00*	0.98**
	Helianthus annuus	2.96	2.94 s.i.	2.40 s.i.	2.90 s.i.	2.15**	2.73	2.65 s.i.	2.54 s.i.	2.56 s.i.	2.28*	2.26	2.24 s.i.	2.19 s.i.	2.24 s.i.	2.11 s.i.
Cadmium (Cd)	*Sida hermaphrodita*	0.040	0.038 s.i.	0.042 s.i.	0.041 s.i.	0.040 s.i.	0.036	0.036 s.i.	0.035 s.i.	0.032 s.i.	0.031*	0.032	0.034 s.i.	0.035 s.i.	0.031 s.i.	0.033 s.i.
	Zea mays	0.035	0.036 s.i.	0.030 s.i.	0.34 s.i.	0.034 s.i.	0.032	0.033 s.i.	0.032 s.i.	0.031 s.i.	0.032 s.i.	0.030	0.031 s.i.	0.031 s.i.	0.030 s.i.	0.022*
	Helianthus annuus	0.043	0.042 s.i.	0.043 s.i.	0.041 s.i.	0.041 s.i.	0.041	0.041 s.i.	0.039 s.i.	0.039 s.i.	0.040 s.i.	0.040	0.039 s.i.	0.037 s.i.	0.038 s.i.	0.040 s.i.

Significance of differences: $*p < 0.05$, $**p < 0.01$, s.i. – statistically insignificant difference.

studied with the permissible standards for fertilizers used in Poland indicates the absence of contamination with these elements and the usefulness for soil fertilizing and soil amendment (Table 2).

The light sandy soil was used in the lysimeter experiment. Its reaction (Table 4) was 6.02, which, according to Polish fertilizer recommendations [15], can be characterized as weakly acid reaction. The content of heavy metals in the control soil was within the range of the permissible concentration in non-contaminated soil. According to the recommended IUNG guidelines used to evaluate the degree of soil contamination with heavy metals, the contents of standardized metals such as zinc (Zn), lead (Pb), copper (Cu), cadmium (Cd), and nickel (Ni) in sandy soil used for fertilization in the lysimeter experiment could be determined as a natural quantity (this was 0 degree of soil contamination) [25]. The determined concentrations of heavy metals were below permissible (indicating contamination) contents of these elements in such sandy soils (group II – 1 – soils intended for cultivation, including agricultural land) [16].

The examined sandy soil was fertilized with biochar obtained from the biomass of *Sida hermaphrodita* at doses of 0%, 0.5%, 1%, 1.5%, and 2%. Analysis of the results of physical and chemical properties of soils (sandy soils from the cultivation of *Sida hermaphrodita* were selected) after fertilization with biochar (Table 5) reveals that its application to sandy soil in all doses caused a statistically significant increase of pH (active acidity), a decrease of hydrolytic acidity (so-called potential acidity), an increase of phosphorus, nitrogen, total carbon, and organic matter. The growth effect was observed in the soil within 3 y after fertilization. The reaction of sandy soils (measured in H_2O) in the first year after application in the control soil was 6.0, while after application of the doses of 0.5%, 1%, 1.5%, and 2.0% biochar, it increased to 6.33; 6.45; 6.55, and 6.71, respectively. The control soil could be classified as weakly acidic soil, while soil mixtures with biochar doses of 0.5%, 1%, 1.5% – as neutral soil. The application of the highest fertilizing dose of biochar (2%) increased the pH in weakly alkaline soils [19]. This phenomenon can be explained by the high calcium content in biochar of 1.6% (Table 3). This effect persisted in sandy soils throughout the 3 y of the experiment.

A decrease in the acidity of the fertilized soils was also evidenced by the determination of hydrolytic acidity (potential acidity) in the examined soils which was 3.10, 2.93, 2.70, 2.65, and 2.59 me/100 g in mixtures with 0%, 0.5%, 1%, 1.5%, and 2.0% biochar, respectively. In Poland, mean Hh values in light arable soils (with a small capacity of a sorption complex) usually vary from 1 to 3 me/100 g of soil [25]. Similar results concerning biochar were obtained by Nigussie et al. [26]. These researchers found that biochar made from maize stalks added to poor and degraded soils and those contaminated with heavy metals, in particular, helped improve soil fertility and productivity. Similar to the present paper, studies of these authors showed a statistically significant ($p < 0.01$) increase in pH, organic carbon, total nitrogen, available phosphorus, and cation exchange capacity due to the application of biochar. Similar effects of biochar on a decrease in soil acidity were reported by previous authors [27]. In the examinations discussed in the present paper, biochar had an alkalizing effect on the soil. This is an interesting phenomenon from a scientific point of view since studies of biochar (Table 3) showed an alarmingly low pH of 5.1, which may indicate the inappropriate (too low) temperature of *Sida hermaphrodita* biomass burning [12]. However, it did not affect other parameters of the fertilized soils.

Total carbon (TC) determined in the fertilized sandy soils (Table 5) after the introduction of biochar doses of 1%, 1.5%, and 2% increased statistically significantly compared to the control samples by 11.1%, 19.8%, and 22.7% in the first vegetation year, respectively. This effect persisted in sandy soils for three consecutive years of the experiment. The content of organic matter in the amended soils also increased with the dose of the biochar applied. Similar positive effects of the use of biochar in soil amendment were observed by Prodana et al. [27]. The researchers demonstrated improvements in the physical and chemical properties of soils (including sorption complex properties). However, they found adverse effects of this agent on selected soil microorganisms 18 months after biochar application. Therefore, the authors recommended the analysis of the quality of biochar before its use as a fertilizer and during the vegetation of plants. Increased contents of organic matter and total carbon (and calcium) after the application of biochar in sandy soils improve its structure and sorption properties. Similar results concerning the positive effect of the use of biochar on selected soil sorption parameters (including soil pH) were observed for light soils by El-Naggar et al. [28].

In soils amended with biochar (Table 5), a statistically significant increase was found for phosphorus and nitrogen. The increase relative to the control soil was maintained throughout the experiment. In the first year after biochar application, the content of phosphorus (in the form of P_2O_5) after the application of doses of 1.0%, 1.5%, and 2% increased by 9.8%, 15.2%, and 17%, respectively, compared to the control soil. Furthermore, the content of nitrogen in the amended sandy soil after the application of 0.5%, 1%, 1.5%, and 2.0% biochar doses increased by 5.5%, 5.8%, 7.2%, and 8.4%, respectively, compared to the control. A study by Cao et al. [29] (who applied biochar at 2.63 Mg/ha) found that it also increased the pH of fertilized soils, improved electrical conductivity (EC), and increased the contents of TC and phosphorus in the soil. The authors found that biochar can biologically increase the content of phosphorus in the soil. Grain yield after fertilization with biochar (also in combination with mineral NPK fertilization) reached the highest point and improved maize grain yield by 4.2%–12.5% compared to NPK fertilization alone. In addition, the authors [29] observed that the use of biochar alone instead of phosphorus fertilizer under experimental conditions did not cause a reduction in maize yield.

The results obtained and presented in this paper also proved the positive effect of using biochar as a fertilizer on the biomass yield of energy crops. However, the effect obtained depended on the dose of biochar and the species-specific response of the plants grown. Analysis of the results of the examinations of the volume of the biomass during the pot experiment (Table 6) revealed noticeable differences as a response of selected test plants to soil fertilization with biochar. The greatest volume of biomass was obtained (on all mixtures of sandy soil fertilized with biochar) from the cultivation of *Sida hermaphrodita*. A statistically significant increase in the yield of *Sida hermaphrodita* was found in soil mixtures with biochar at rates of 1%, 1.5%, and 2%. However, the most optimal dose for this plant was a 1.5% addition of biochar. In the first year of the experiment, the increase in the volume of biomass of *Sida hermaphrodita* compared to control samples after the application of biochar was 18.1%, 21.1%, and 5.7% for doses of 1%, 1.5%, and 2%, respectively. Production of common sunflower fertilized with biochar also yielded more biomass after sandy soil amendment. However, this increase was less pronounced and significantly dose-dependent. It was 4.5% and 13.5% after application of 0.5% and 1%, respectively. A small increase in the biomass yield was also found after the application of 1.5% biochar. However, from the statistical point of view, no significant increase was found compared to control samples. However, the application of 2% biochar for sandy soils amendment caused a statistically significant (compared to the control samples) decrease in the yield of *Helianthus annuus* (5.1%). The worst response to soil fertilization with biochar was observed for maize. Only the application of 0.5% biochar dose resulted in an increase in yield by 12.5%. Doses of 1% and 1.5% did not statistically significantly increase yields compared to biomass from control samples. In contrast, the 2% dose significantly reduced the volume of biomass (by 3.9%). However, an interesting phenomenon was found: in the second and third years of plant cultivation, all studied species responded better to biochar fertilization. In the last (third) year of the study, statistically significantly higher yields in energy crops were found for all fertilization combinations compared to control soils. This can be explained by the fact that in the first year after fertilization, certain compounds present in the biochar may have had an inhibitory effect on plant growth. Different data on yielding after biochar application can be found in the available literature. A greater biomass yield and a better growth response of plants to soil amendment with biochar was observed in a study by Gladki [2]. The growth and yielding of plants depend on several factors. Soil reaction is also very important. The biochar studied was characterized by a low pH of 5.1 (Table 3). Different results than those in the present paper were obtained by Soudek et al. [30]. Each time the authors observed an alkaline biochar reaction. They obtained biochar from different plants, which determined its properties. In their experiments, the use of biochar always reduced soil acidification. In this aspect, the results presented are similar. Despite the low pH, biochar did not cause a decrease in pH after application in sandy soil. However, in the first year after fertilization, the properties of biochar may have contributed to lower crop yields, especially after the application of the highest dose. Soudek et al. [30] also observed differences in the germination of selected seeds of sorghum depending on the material used for biochar production. They also observed a reduction in toxic effects of cadmium, copper, and lead on germinated seeds after biochar application. It also depended on the origin of the plant from which the biochar was obtained. The biochar reaction with soil components is also important. Mumme et al. [31] reported, among other things, the increase in the yielding of watercress after fertilization with biochar with compost and its decrease after application of biochar with sewage sludge. The factors responsible for phytotoxicity were pH, salinity, and organic pollutants.

Similar results as in the present paper were obtained by the author in earlier experiments on phytotoxicity of water extracts from biochar and germination of plants on the substrates enhanced with biochar [24]. The biochar formed during the pyrolysis of *Sida hermaphrodita* introduced into soils inhibited germination of a test plant species (*Lepidium sativum*) to a small extent. Optimal doses of biochar (that do not cause noticeable germination disturbances) were 0.5% and 1%. Soil fertilization with biochar led to a significant increase in the yielding of *Sida hermaphrodita* after the application of doses of 1% and 2%. Of all the species used, this plant responded best to biochar fertilization.

Different findings were reported from the experiment by Bouqbis et al. [32]. These authors added 0%, 0.5%, 1%, 2%, 4%, and 8% biochar from argan shells (*Argania spinosa*) and studied its effect on the germination of lettuce seeds. During the study, they did not observe any negative effect of using argan biochar on the germination rate of lettuce seeds or the volume of fresh plant biomass. Furthermore, the application of biochar led to an increase in germination rate and the volume of fresh biomass. No toxic or adverse effects of biochar use on plant growth were reported for all biochar doses.

Analysis of the data presented in Table 7 revealed no increase in heavy metal contamination of the sandy soils above the standards for this type of soil after the use of biochar as a fertilizer [16]. All soil mixtures with biochar can be classified as not contaminated with lead, zinc, copper, nickel, and cadmium. These heavy metals usually represent the biggest toxicological problem. However, an interesting response of soils was observed after biochar application. After the application of all biochar doses in sandy soil mixtures and cultivation of all three species of energy crops, a statistically significant increase in the content of lead was found compared to the control samples (especially after the application of doses of 1.5% and 2%). This effect persisted for 3 y of the experiment. This could probably be due to the effect of biochar on lead immobilization in the soil (e.g., increase in pH). The cultivated plants did not collect it intensively from the ground, since it is likely that the biochar itself, due to the low content of lead, did not cause an increase in the content of this element in the soil. Lead mobility in soils is usually very low (higher in acidic soils). It is easily sorbed by clay minerals and organic matter present in the soil). The contents of this element in sandy soils after biochar fertilization in all experimental combinations were within the range of values most commonly observed in Poland (32–152 mg/kg d.m.), which are characteristic for sandy soils (in the arable layer) [14,15]. Different results (Table 7) were obtained after biochar fertilization of sandy soils for the other heavy metals (zinc, copper, nickel, and cadmium). The fertilization with biochar, especially at doses of 1.5% and 2%, caused a statistically significant decrease in the content of heavy metals in soils (observed during 3 y of the experiment). It is likely that the application of this material caused increased migration of the analyzed elements in the soil profile (especially in the 1st year of the experiment). Although the sandy soil used in the study did not show any features of heavy metal contamination, the plants grown on this soil collected significant amounts of these elements. It is possible that the migration of pollutants with the air and their settling on the plants is responsible for this phenomenon (however, the plants were rinsed before drying). The experiment was conducted in natural conditions.

The data presented in Table 8 on bioaccumulation of heavy metals in biomass of energy crops improved with biochar indicate the statistically higher collection of lead compared to control samples by maize biomass only after application of doses of 2% in the first year of the experiment. In later years, the level of accumulation of this element in plants decreased statistically significantly. Lead uptake from substrates fertilized with biochar in all three species of energy crops was at a similar level.

Zinc uptake by the tested plants from samples fertilized with biochar decreased (compared to the control) statistically significantly in each year of the experiment. This was especially noticeable after applying doses of 2% biochar. A similar phenomenon was observed for nickel bioaccumulation. Cadmium accumulation in plants from most experimental sites was at a similar level. Bandara et al. showed in their study [33] that biochar applied to soil controls the mobility of cadmium over a wide range of soil pH in the same soil matrix.

A different response was observed for copper. Doses of 1.5% and 2% biochar added to sandy soils caused a statistically significant increase in copper accumulation in plant biomass (this effect persisted for 3 growing seasons). The bioaccumulation of analyzed contents of heavy metals in plants determined for all fertilizer combinations was within the limits for plants grown in natural conditions [15].

To use the biomass, for example, for energy purposes, the content of heavy metals should be controlled and compared with the reference values for this type of product. Comparison of the results obtained for the determination of heavy metals in the biomass of plants from sandy soils amended with biochar derived from *Sida hermaphrodita* with the permissible levels in Poland for biofuels indicates some limitations on the possibility of their use if the most stringent references are applied [34]. A major problem that is often encountered in biomass production is cadmium content. The reference values for this element in wood pellets are 0.10 mg/kg d.m. The content of this component in the biomass of the energy crops in the analyzed experiment did not exceed permissible values. The recommendation for lead content in pellets used for energy purposes is 0.5 mg/kg d.m. The biomass of *Sida hermaphrodita* obtained from all mixtures of sandy soil with biochar did not exceed the permissible values of this element. However, according to the proposed recommendations, the obtained biomass of three energy crops was characterized by an increased content of copper and zinc. Similar results of heavy metal determination for energy crops were obtained by Kabała et al. [35]. These researchers reported, for example, that the copper content in energy crops (including miscanthus and *Sida hermaphrodita*) grown on unpolluted soils ranged from 5 to 10 mg/kg d.m. However, taking into account the most restrictive references [34] for such energy materials for the content of heavy metals in biomass (copper: 2.0 mg/kg d.m., zinc: 10 mg/kg d.m.), these values were exceeded. The quality of biomass improved in the following years of cultivation.

The results of other studies by the author of the paper [36] on the determination of heavy metals in water infiltrating from soils fertilized with biochar showed, that there was no significant increase in pollution with these elements and no deterioration in the quality of the environment. This was probably due to the low content of impurities in the sandy soil and the biochar used.

4. Conclusion

- The results obtained from the study of the chemical and physical composition of biochar obtained from the biomass of *Sida hermaphrodita* at 400°C showed the absence of contamination with heavy metals and polycyclic aromatic hydrocarbons (quantities within acceptable limits) and the potential for its use as a fertilizer.
- Fertilization of the sandy soils with biochar caused a significant increase in the yield of all three energy crops studied, including *Sida hermaphrodita*. Of all the species cultivated, this plant responded best to biochar amendment. An optimum dose of this fertilizer was 1.5%, which, in the first year of cultivation, caused an increase in yield by 21.1% compared to control plants.
- The application of biochar to sandy soil with all doses resulted in an improvement of selected sorption properties including a statistically significant increase in pH (active acidity), a decrease in hydrolytic acidity (potential acidity), an increase in the content of phosphorus, nitrogen, total carbon, and organic matter. The growth effect of these parameters was observed in the soil for 3 y after fertilization.
- The study showed that the use of biochar as a fertilizer did not cause an increase in contamination of the sandy soils with heavy metals. All the soil mixtures with the addition of biochar used in the study can be classified as not contaminated with lead, zinc, copper, nickel, and cadmium.
- Analysis of the quality of the biomass of energy crops compared to the content of heavy metals revealed that the accumulation of cadmium and lead in all combinations used to fertilize plants during the 3 y of the experiment did not exceed the recommended standards for similar products (wood pellets). However, exceeding permissible values was found for copper and zinc (especially in the first year after fertilization). The quality of biomass improved in the following years of cultivation.

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