## NAFTA-GAZ

Nafta-Gaz 2025, no. 2, pp. 117-127, DOI: 10.18668/NG.2025.02.04

## Impact of biochar from sewage sludge on vegetable growth and metal uptake: an example of radish and butterhead lettuce

# Wpływ biowęgla z osadów ściekowych na wzrost warzyw oraz pochłanianie metali na przykładzie rzodkiewki i sałaty masłowej

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ABSTRACT: This paper presents the results of research on metal migration from the biochar-amended soil to plants with edible root - radish (Raphanus sativus, Saxa 2), and edible above-ground part - butterhead lettuce (Lactuca sativa, Queen of May). The soil was enriched with biochar obtained from municipal sewage sludge through pyrolysis at 750-850°C in a pilot container installation designed for small – and medium-sized sewage treatment plants in agglomerations up to 10,000 population equivalents. The obtained biochar was characterised by a high content of sodium, magnesium, aluminium, potassium, calcium, and iron. The pot experiment was conducted under laboratory conditions at a constant temperature of 22°C, with humidity ranging from 39% to 55%. An additional light source was used to ensure optimal conditions for plant development, emitting light that simulated the insolation conditions typical of the growing season at Poland's latitude. The vegetables were watered three times a week. The leachability test showed that elements were strongly bound to the biochar material and migrated to the aquatic environment in trace amounts. The influence of 5%, 10%, and 15% biochar addition to the soil substrate on vegetable growth and metal content was studied. A positive effect of biochar addition on vegetable yields was observed; the highest biomass of radish and lettuce was obtained in the substrate containing 5% biochar, where the yield increased by 6% and 17%, respectively. It was also observed that the addition of 5% biochar reduced metal concentrations in vegetables compared to the control. The determined content of heavy metals (lead and cadmium) in vegetables did not exceed the permissible levels specified by EU regulations. The high temperature of 750-850°C in the pyrolysis reactor allows for effective sanitation of municipal sewage sludge, resulting in a carbon material that can be successfully used in agriculture to improve soil properties. The use of biochar for agricultural purposes is much safer than the use of raw sewage sludge.

Key words: biochar, sewage sludge, soil amendment, radish, lettuce, metal uptake.

STRESZCZENIE: W pracy przedstawiono wyniki badań migracji metali z gleby wzbogaconej bioweglem do roślin o jadalnym korzeniu – rzodkiewki (Raphanus sativus, Saxa 2) i jadalnej części nadziemnej – sałaty masłowej (Lactuca sativa, Queen of May). Glebę wzbogacono bioweglem otrzymywanym w procesie pirolizy komunalnych osadów ściekowych prowadzonej w temperaturze 750-850°C w pilotażowej instalacji kontenerowej przeznaczonej dla małych i średnich oczyszczalni ścieków w aglomeracjach do 10000 RLM (Równoważnej Liczby Mieszkańców). Otrzymany biowęgiel charakteryzował się dużą zawartością sodu, magnezu, glinu, potasu, wapnia i żelaza. Uprawa doświadczalna była prowadzona w doniczkach w warunkach laboratoryjnych w stałej temperaturze 22°C i w zakresie wilgotności od 39% do 55%. Aby zapewnić roślinie optymalne warunki do rozwoju zastosowano dodatkowe źródło światła. Lampa emitowała światło symulujące warunki nasłonecznienia występujące w okresie wegetacyjnym dla szerokości geograficznej Polski. Warzywa podlewano trzy razy w tygodniu. Badanie wymywalności wykazało, że pierwiastki są silnie związane z materiałem biowęgla i w śladowych ilościach migrują do środowiska wodnego. Badano wpływ dodatku biowęgla do podłoża glebowego w ilości 5%, 10%, 15% na wzrost warzyw i zawartość metali. Zaobserwowano pozytywny wpływ dodatku biowęgla na plony warzyw. Największą biomasę rzodkiewki i sałaty uzyskano na podłożu zawierającym 5% biowęgla, gdzie plon wzrósł odpowiednio o 6% i 17%. Zaobserwowano, że dodatek 5% biowęgla powodowało zmniejszenie zawartości metali w warzywach w porównaniu do próbki kontrolnej. Oznaczona zawartość metali ciężkich (ołowiu i kadmu) w warzywach nie przekraczała dopuszczalnych poziomów określonych przepisami UE. Wysoka temperatura rzędu 750-850°C w reaktorze pirolitycznym pozwala na efektywną sanitację komunalnych osadów ściekowych dając w efekcie materiał węglowy, który może być z powodzeniem stosowany w uprawach warzyw jako dodatek poprawiający właściwości gleby. Rolnicze wykorzystanie biowęgla jest znacznie bezpieczniejsze niż użycie surowych osadów ściekowych.

Słowa kluczowe: biowęgiel, osady ściekowe, środki poprawiające właściwości gleby, rzodkiewka, sałata, migracja metali.

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Article contributed to the Editor: 28.09.2023. Approved for publication: 28.01.2025.

### Introduction

Sewage sludge resulting from wastewater treatment is a relatively small amount of waste. However, it is difficult to manage due to its physical and chemical properties as well as the presence of pathogenic bacteria or parasite. Moreover, sewage sludge may contain hazardous compounds, including polycyclic aromatic hydrocarbons (PAHs), furans, dioxins, endocrine disruptors, pesticides, and aliphatic hydrocarbons (Eriksson et al., 2008). The legal regulations in force in Poland regarding municipal sewage sludge management mandate the complete cessation of sewage sludge treatment before its release into the environment.

Pyrolysis or fermentation of biowaste are methods for managing the increasing amounts of waste generated by modern society. The use of processed biowaste in agriculture allows for the recycling of carbon, nitrogen, and minerals back into the soil, potentially replacing commercial synthetic fertilizers in the future (Monterumici et al., 2015). Biochar is a stable substrate made from organic material that has been oxidized/ burnt under low or zero oxygen conditions (Atkinson et al., 2010; Karhu et al., 2011). According to the available literature, the application of biochar obtained from pyrolysis of various feedstock sources, including sewage sludge, improves soil conditions (Khan et al., 2013b; Melo et al., 2019). Apart from sewage sludge, traditional raw materials such as nutshells (Pereira et al., 2017; Servin et al., 2017; Liu et al., 2019), wood (maple, pine), bark (Lévesque et al., 2020), willow, hemp (Turunen et al., 2020), rice straw (Guo et al., 2018), as well as straw and grains of triticale, rye, oats, wheat, and barley (Caban et al., 2020) have been used for biochar production.

The quantity and quality of the obtained biochar depend on the feedstock type and pyrolysis conditions (Oni et al., 2019). One of the main factors affecting the yield of biochar, as well as its physical and chemical properties, is the pyrolysis temperature (i.e., the end pyrolysis temperature or peak temperature). It has been observed that biochar yield and energy conversion efficiency decrease with increasing pyrolysis temperature (Yuan et al., 2013). The carbonization rate, or growth rate, and carbonization time also influence biochar properties (Zimmerman and Gao, 2013). The effectiveness of biochar as a soil amendment depends on its characteristics, such as adsorptive properties, which can potentially alter surface area, pore size distribution, bulk density, water-holding capacity, and penetration resistance (Bhupenchandra et al., 2019). The use of biochar can reduce the bulk density of various soils (Chen et al., 2011), thereby improving soil structure or aggregation and aeration, which enhances soil porosity. The higher the total porosity (including micro- and macropores), the higher the physical quality of the soil. This is because micropores are involved in molecular adsorption and the transport of water and nutrients, while macropores affect aeration and drainage (Atkinson et al., 2010). The addition of biochar has been documented to improve the available water holding capacity and water retention (Jones et al., 2010; Uzoma et al., 2011).

Biochar obtained from various types of raw biomass subjected to pyrolysis under different conditions results in a material with diverse physical and chemical properties. It can effectively reclaim soil, increase the intensity of photosynthesis, improve carbon sequestration, reduce greenhouse gas emissions, and remove contamination from the soil. Moreover, it can also reduce the bioavailability of organic and inorganic pollutants in the soil (Ahmad et al., 2014; Kavitha et al., 2018).

Soils enriched with biochar obtained from sewage sludge are characterised by increased pH, higher total nitrogen content, and enhanced levels of organic carbon and available nutrients (Khan et al., 2013a). Studies have shown that sewage sludge-derived biochar, when used as an additive to improve soil properties, positively affects the availability of phosphorus, nitrogen, and sodium (Khan et al., 2013a; Sousa and Figueiredo, 2016; Faria et al., 2018). However, the content and bioavailability of heavy metals may pose a potential issue with sewage sludge-derived biochar. A relationship has been observed between increased pyrolysis temperature and the concentration of heavy metals in biochar. Biochar obtained through slow pyrolysis has been found to better stabilize heavy metals (Cd, Cr, Cu, Mo, Ni, Pb, Zn) (Barry et al., 2019).

The available literature highlights the beneficial effects of biochar addition to soil on plant cultivation, in particular the size of obtained crops. Research by Lévesque et al. (2020) showed that replacing perlite with three different types of biochar up to 15% by volume (v/v) improved soil properties, leading to an increase in plant biomass and fruit yield (dwarf tomato, sweet pepper). An increase in tomato shoots biomass and dry fruit mass yield was observed. Vegetables also contained more nitrogen and phosphorus as compared to the control (Lévesque et al., 2020). However, Van Zwieten et al. claim that biochar does not act as a nutrient source but that its carbon microstructure, formed during carbonization, provides a high surface area that functions as a cation exchanger, thereby stimulating nutrient availability and uptake by plants (Van Zwieten et al., 2010).

The influence of biochar derived from spent coffee grounds on biomass production and Zn, Cu, and Fe content in lettuce (*Lactuca sativa*, Longifolia) has been studied. It was observed that the addition of biochar obtained by pyrolysis at 400°C significantly decreased Zn, Cu, and Fe content, unlike biochar obtained at 270°C (Cervera-Mata et al., 2020). A reduced Zn, Cu, and Fe concentration in lettuce grown in alkaline soil supplemented with poultry manure-derived biochar at 300°C was also observed by Gunes et al. (2014). The available literature describes the effectiveness of biochar in remediating various organic/inorganic contaminants (Ahmad et al., 2014). In the case of inorganic ions, metals can be physically trapped or chemically adsorbed onto biochar (Inyang et al., 2016). Additionally, biochar's alkalinity increases soil pH , which stabilises metals, except for arsenic (Beesley et al., 2011; Ahmad et al., 2014). Elevated pH values following biochar addition can lead to metal precipitation in soil (Duwiejuah et al., 2020), thereby reducing their availability to plants (Zhang et al., 2012).

The aim of this study was to assess the usefulness of sewage sludge biochar obtained from a pilot container installation for pyrolysis as a soil amendment. The influence of biochar on vegetable growth and, most importantly, the migration of metals, including heavy metals, from biochar-enriched soil to plants was investigated. Two different plant species were selected: radish (*Raphanus sativus*, Saxa 2) and butterhead lettuce (*Lactuca sativa*, Queen of May). Lettuce serves a very good indicator of leaf contamination due to its large absorbent surface and small root system. In contrast, the edible part of the radish is in direct contact with the soil. To assess the safety of biochar as an agricultural additive and its impact on human health, the heavy metal content in the tested vegetables was determined and compared with the applicable EU standard.

#### Materials and Methods

#### The installation for pyrolysis, production of biochar

Biochar was produced in a pilot container installation for the pyrolysis of sewage sludge developed and manufactured by MetalExpert Sp. z o.o. Sp. J. (Figure 1). The installation was designed for small – and medium-sized sewage treatment plants in agglomerations up to 10,000 population equivalent (PE). In Poland, most of them have an average sewage flow of less than 1,000 m<sup>3</sup> per day.

Due to the applicable legal requirements and high costs, most sewage treatment plants are unable to build their own installations or transport sewage sludge to incineration plants. Placing the installation in a container allows it to be periodically moved, which means that it can be transported directly to the treatment plant, where the sludge can be thermally transformed by pyrolysis.

After mechanical dehydration in centrifuges (humidity approx. 80%), the sludge was subjected to drying. The obtained dry sludge (humidity <5%) was then sent to the pyrolysis reactor. The pyrolysis was carried out at a temperature of 750– 850°C. The residence time in the reaction environment was 25 min, which gave a biochar yield of 8–12 kg/h. Thermal energy obtained from the combustion of pyrolysis gas was recycled and used to dry the sewage sludge (Figure 1).



**Rysunek 1.** Schemat działania pilotażowej instalacji kontenerowej do pirolizy osadów ściekowych opracowana i wyprodukowana przez Metal Expert Sp. z o.o. Sp. J.



## Determination of physicochemical biochar properties pH analysis – conductometric measurement

The pH measurement was carried out using CX-701 multifunction meter (ELMETRON) equipped with an ion-selective electrode (IJ SERIES Intermediate Junction Electrode). The device was calibrated at three points (pH of 4; 7; 9) using standard buffer solutions (Reagecon). A biochar sample was mixed in a 1:10 ratio with deionized water and subjected to mixing for 30 min. The pH of the obtained suspension was then measured.

## Analysis of material absorbency – Westinghouse method

The Westinghouse method was used to determine the absorbency of biochar. A sample (10 g) of dried biochar was placed in a cone (70 mm in diameter and 75 mm high), made of a steel mesh with a mesh size of 0.25 mm, and immersed in a beaker with deionized water. After 10 min, the cone was removed from the water and allowed to drain (fixed above the liquid level) for 30 min. The absorbency of the material was calculated based on the weight difference.

## Heat of combustion

The heat of combustion was determined calorimetrically using a KL-11 "Mikado" calorimeter (PRECYZJA-BIT PPHU Sp. z o.o.) and benzoic acid for calorimetry (ChemPur) as a reference material.

## *Total Organic Carbon (TOC) and Total Inorganic Carbon (TIC) measurements*

The measurements were taken using TOC-LCPH/CPN Total Organic Carbon Analyzer with SSM-5000A Solid Sample Module, a Total Nitrogen (TN) Analysis Module, and an Autosampler (SHIMADZU). The certified reference material CRM029-50G Sewage Sludge 2 (Sigma-Aldrich RTC, Inc.) was used for validation.

## Metal leaching test

100 ml of deionized water with a specific conductivity of 0.05  $\mu$ S/cm was added to 10 g of biochar and subjected to mixing using laboratory shaker for 24 h. The samples were then filtered using standard paper filters, and obtained filtrate was analysed for metal content using ICP-MS.

## Substrate preparation and vegetable cultivation/pot experiment

Two vegetable species were selected for the research; the edible part of which is the roots (radish) or leaves (lettuce). Radish (*Raphanus sativus*, Saxa 2) and butterhead lettuce (*Lactuca sativa*, Queen of May) seeds were obtained from Przedsiębiorstwo Hodowlano-Nasienne Sp. z o.o., Poland.

The soil substrate used was universal vegetable and flower substrate (PPHU Ark-Pol, Poland). The mixtures of substrate with biochar were prepared on a weight basis and contained 5%, 10% and 15% of biochar. The biochar was distributed on the top layer of the soil substrate. In addition, control samples (soil substrate without biochar addition) were prepared for each of the vegetables as a reference. Each pot contained 10 lettuce seeds or 16 radish seeds, and the test was conducted in duplicate. The pot experiment was conducted under laboratory conditions at a constant temperature of 22°C and humidity ranging from 39% to 55%. To ensure optimal conditions for plant development, a SUNMASTER dual 600W lamp (SUNMASTER) was used as an additional light source. The lamp emitted light at a wavelength of 589.3 nm, simulating the insolation conditions that occur during the growing season for the latitude of Poland. A reflector was installed above the lamp to prevent excessive light dispersion. The set was equipped with an automatic timer that turned the lamp on at 6:30 a.m. and off at 5:30 p.m. (light-dark cycle (11 h:13 h)). The vegetables were watered three times a week.

## **Preparation of vegetable samples for metal determination**

After harvesting, the vegetables were cleaned to remove soil and washed. Then, they were ground in a GM 200 rotary mill (Retsch) and dried in a SLW 115 ECO dryer (POL-EKO--APARATURA Sp. J.). The dried vegetable samples were subjected to mineralization using the Ethos up microwave oven (MILESTONE SRL). An acid of spectral purity (a mixture of HNO<sub>3</sub> and H<sub>2</sub>O<sub>2</sub>, ratio 7:3, 63% HNO<sub>3</sub> and 30% H<sub>2</sub>O<sub>2</sub>) (VWR Chemicals) was used to dilute the samples. The samples were mineralised with increasing temperature up to 200°C for 20 min and then incubated at 200°C for another 20 min. The resulting samples were analysed for selected metal content using ICP-MS.

## Inductively coupled plasma mass spectrometry (ICP-MS)

The samples were analysed using an ICP-MS instrument model 7700x equipped with an ASX-500 Series Autosampler (Agilent Technologies), in accordance with PN-EN ISO 17294-2: 2016-11 standard. Multi Element Aqueous Tuning Solution for Agilent 7500cs, Matrix: 2% HNO<sub>3</sub> (Agilent Technologies) was used for ICP-MS instrument tuning and mass calibration prior to analysis. The device was calibrated with a Multi Element Aqueous CRM Environmental Calibration Standard Blend A, Matrix: 5% HNO<sub>3</sub>/tr. Tartaric Acid/tr. HF and a mercury calibration standard – Single-element Aqueous CRM Mercury (Hg) – 10 µg/ml, Matrix: 5% HNO<sub>3</sub>. Multi Element Aqueous CRM Environmental ICV Standard A Matrix: 5% HNO<sub>3</sub>/tr Tartaric Acid/tr. HF was used to verify calibration. The technical

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gases used were AirProducts – ARGON PRM X50S (purity 99.9992%) for analysis, and, in the collision-reaction chamber, Analytical Helium BIP (purity 99.9997%).

All experiments were carried out in an accredited research laboratory – the Advanced Environmental Analysis Laboratory, Elbląg Technological Park – using methods previously validated in accordance with ISO/IEC 17025 guideline *General requirements for the competence of research and calibration laboratories*, as well as the requirements of the Polish Centre for Accreditation.

### **Results and Discussion**

### Physicochemical properties of biochar

The biochar obtained from the process of sewage sludge pyrolysis was fine-grained, without the characteristic odour of sewage sludge. The absorbency of the biochar was 80% for the raw sample and about 107% for the ground sample. The biochar was alkaline (pH = 8.6). All physicochemical properties of the obtained biochar are presented in Table 1.

 Table 1. Physicochemical properties of obtained biochar

 Tabela 1. Właściwości fizykochemiczne otrzymanego biowęgla

рН	8.6
Absorbency of material	80%
Combustion heat	<6 MJ/kg
Total organic carbon (TOC)	28.3%
Total inorganic carbon (TIOC)	0.2%

The content of selected metals and their leachability from the biochar are presented in Table 2. Biochar obtained from sewage sludge was characterised by high levels of sodium, magnesium, aluminium, potassium, calcium, and iron. The concentration of potassium is particularly important because it plays an important role in plant growth. The research conducted by Yuan et al. (2016) and Cao and Harris (2010) confirmed that the potassium content in biochar largely depends on the pyrolysis temperature. Metal content in the obtained biochar was compared with the values specified in the Polish regulations on the content of metals in the soil at depths below and above 0.25 m and on the content of metals in industrial wastewater (Figure 2, Table 2). The metal content in biochar did not exceed the permissible values for soil for both characterised depths. Moreover, for all metals studied, the concentrations in biochar were lower than the reference values for soils defined by Polish regulations. Only the zinc concentration approached the limit values for soils but it did not exceed the upper limit (Table 2, Figure 2).



Figure 2. Concentrations of metals in biochar in reference to the permitted concentrations of metals in soil at depths 0-0.25 m (range marked in red) and at depths >0.25 m (range marked in black), according to the Regulation of the Minister of the Environment of 1 September 2016 on the method of conducting the assessment of land surface contamination (Journal of Laws 2016, item 1395)

**Rysunek 2.** Zawartość metali w biowęglu w odniesieniu do wartości dopuszczalnych w glebie na głębokości 0–0,25 m (kolor czerwony) oraz na głębokości >0,25 m (kolor czarny) zgodnie z Rozporządzeniem Ministra Środowiska z dnia 1 września 2016 r. w sprawie sposobu dokonywania oceny zanieczyszczeń powierzchni ziemi (Dz.U. z 2016 r., poz. 1395)

Tests showed that metals were leached from the biochar with the following efficiency: Na >K >Mg >Ca >As >Cd >Ni >Cr > Mn > Cu > Zn > Al > Pb > Fe (Table 2). 0.75% of sodium,0.66% of potassium, 0.54% of magnesium, 0.12% of calcium, 0.03% of arsenic, and 0.008% of nickel was washed out of the biochar. Less than 0.002% of each of the remaining metals was leached. It is important to highlight that consequently very small amounts of the elements pass from the soil to the aquatic environment. The results indicate that the elements are strongly bound to the material, which aligns with the results obtained by other authors (Barry et al., 2019; Rogovska et al., 2012; Khan et al., 2013a; Monterumici et al., 2015). A comparison of the obtained results with the metal content in industrial wastewater specified by Polish regulations (Table 2) revealed that only the potassium content was slightly above the permissible level (81.11 mg/l; standard 80 mg/l). The results clearly show that the tested biochar meets Polish legal standards regarding metal content and can be successfully used to enhance agricultural crop production (Table 2, Figure 2).

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Metal	Content [mg/kg]	Leachability [mg/L]	Permissible metal content in the ground at a given depth* [mg/kg]		Permissible metal content in industrial
			0–0.25 m	>0.25 m	wastewater** [mg/L]
Na	5795.97	43.360	_	-	800.00
Mg	12326.48	66.360	-	-	-
Al	21858.76	0.260	-	-	3.00
K	12186.65	81.110	-	-	80.00
Ca	64323.34	75.420	-	-	-
Cr	87.22	0.002	150-1000	300-800	0.50
Mn	917.30	0.020	_	-	-
Fe	22362.79	0.060	-	-	10.00
Ni	60.59	0.005	100–500	100–500	0.50
Cu	323.99	0.006	100–600	150-1000	0.50
Zn	1791.95	0.030	300–2000	300-3000	2.00
As	3.28	0.001	10–100	20–100	0.10
Cd	0.41	0.000087	2–15	3–20	0.40
Pb	51.09	0.000244	100–600	100–1000	0.50
Hg	0.17	_	2–30	3-50	0.06

 Table 2. Content of selected metals in biochar and their leachability from this material

Tabela 2. Zawartość wybranych metali w biowęglu oraz ich wymywalność z materiału węglowego

\* Regulation of the Minister of the Environment of 1 September 2016 on the method of conducting the assessment of land surface contamination (Journal of Laws 2016, item 1395)

\*\* Regulation of the Minister of Maritime Economy and Inland Navigation of 12 July 2019 on substances particularly harmful to the aquatic environment and the conditions to be met when discharging sewage into waters or ground, as well as when discharging rainwater or meltwater into waters or into devices water (Journal of Laws 2019, item 1311)

## The effect of biochar on cultivation and metal content in vegetables

## Cultivation and metal content in radish

Radish was selected for research as a representative root vegetable, where the edible part directly interacts with the substrate and, therefore, can largely accumulate contaminants from the soil. Radish is also characterised by a short growing season.

It was observed that the highest radish yield (144.6 g) was obtained when the substrate with a 5% biochar addition was used (Table 3, Figure 4). Quantitatively, the most (14) radish seeds germinated on this substrate, while the fewest (7) radish seeds germinated on the substrate with 15% biochar. Considering the size of the vegetables, the largest radishes were grown on the substrate containing 15% biochar (Figure 3A). Similar results were obtained by Sousa and Figueiredo (2016). The authors observed that the addition of biochar to the soil in the range of 10 to 50 g/kg stimulated radish growth, leading to increased dry weight, vegetable size, and number of leaves. The highest radish yield was recorded for the sample containing 10 g of biochar per 1 kg of soil. Melo et al. (2019) showed that increasing biochar doses negatively correlated with the dry biomass of radish (*Raphanus sativus*).

The biomass of vegetables grown on soil enriched with sewage sludge-derived biochar differed depending on the biochar

dose and plant type (Melo et al., 2019). Similarly, Monterumici et al. (2015) reported that soil enriched with biochar from the biowaste pyrolysis (residues of tomato seedlings) positively affected radish growth, particularly root diameter. However, Chan et al. (2007) observed no improvement in radish growth when biochar derived from the thermal processing of so-called green waste containing 36% elemental carbon was applied, even at a dose of 100 t/ha. Studies on biochar from animal origins showed that poultry litter-derived biochar, applied at a rate of 3.5 t/ha, had no effect on radish biomass (Monterumici et al., 2015), whereas applications of 10 and 50 t/ha of biochar increased radish dry weight yield (Chan et al., 2008). Based on findings from other studies (Khan et al., 2013a; Sousa and Figueiredo, 2016; Faria et al., 2018), it can be concluded that adding biochar produced from sewage sludge to agricultural soil enhances the productivity of crops such as corn, radish or rice. According to Sousa and Figueiredo, due to the ability of biochar to supply macro- and microelements to plants, the yield increase resulting from sewage sludge-derived biochar application is comparable to the yield improvement achieved with NPK mineral fertilizers (Sousa and Figueiredo, 2016).

According to EU regulation No 1881/2006 of 19 December 2006, the permissible lead and cadmium content in radish is 0.1 mg/kg fresh weight, while the remaining metals are not

 Table 3. Effect of biochar on dry weight and selected metal content in radish

 Tabela 3. Wpływ zawartości biowęgla na suchą masę oraz zawartość wybranych metali w rzodkiewce

	Control	5% biochar	10% biochar	15% biochar	
Metal	Dry weight of radish [g]				
	136.4	144.6	99.8	101.7	
	Metal content per fresh weight of radish [mg/kg]				
Na	322.224 196.881 268.473 269.42				
Mg	76.145	62.831	85.678	90.597	
Al	0.139	0.156	0.213	0.233	
K	3563.967	2545.584	3471.251	3528.279	
Ca	164.327	112.082	152.839	159.292	
Cr	0.030	0.025	0.034	0.027	
Mn	0.461	0.351	0.479	0.480	
Fe	1.520	1.161	1.584	1.659	
Ni	0.039	0.017	0.023	0.024	
Cu	0.085	0.054	0.073	0.084	
Zn	1.506	0.877	1.196	1.480	
As	0.004	0.001	0.001	0.002	
Cd	0.003	0.002	0.003	0.005	
Hg	0.004	0.003	0.004	0.003	
Pb	0.023	0.015	0.021	0.046	

regulated for this vegetable. The results of this study showed that cadmium and lead levels in radish grown on biocharenriched substrate did not exceed the permissible concentration levels in any case (Table 3). Cadmium content in radish ranged from 0.002 to 0.005 mg/kg, with the lowest contamination found in radish grown on a substrate containing 5% biochar and the highest in radish grown on a substrate with 15% biochar. Lead content in radish ranged from 0.015 to 0.046 mg/kg, and similar to cadmium, a positive correlation was observed between lead content and the amount of biochar added to the soil (Table 3, Figure 5A).

## Cultivation and metal content in lettuce

Lettuce was selected for research as an example of a leafy vegetable. Similar to radish, it is characterised by a short growing season. Due to its small root system and large leaf surface, lettuce serves as a good model vegetable for studying metal accumulation in leaves. The highest biomass (66 g) was obtained for lettuce grown on a substrate containing 5% biochar, while a greater proportion of biochar in a soil substrate inhibited plant growth (Table 4, Figure 3B, Figure 4). The positive effect of biochar on lettuce cultivation was previously described by Cervera-Mata et al. (2020), who observed a significant increase in lettuce growth after applying biochar obtained by pyrolysis at 270°C and 400°C from spent coffee grounds. The results of our study are also consistent with those of Khan et al. (2013b), who achieved an increased yield of lettuce after applying sewage sludge-derived biochar in crop production. The authors tested substrates supplemented with 2%, 5%, and 10% biochar and observed that the addition of 5% biochar increased lettuce growth by 93% compared to the control. Similarly, Barber et al. (2018) demonstrated the positive effects of maple biochar used as a soil additive on lettuce and basil growth. Steiner et al. (2018) showed that adding biochar derived from corn cobs, nutshells, rice hulls, and wood to standard agricultural practices increased lettuce yield by 93%. Research conducted by Pereira et al. revealed that biochar application improved lettuce nitrogen use. However, the effect of biochar on plant cultivation varied depending on the level of fertilization and the growing season (Pereira et al., 2017).

It was observed that an increase in the amount of biochar inhibited lettuce growth. The lowest vegetable biomass (11 g) was obtained from a substrate supplemented with 15% biochar (Table 4). Additionally, the smallest leaves were observed in this sample, whereas lettuce grown on substrate containing 5% and 10% of biochar did not differ significantly from the control



**Figure 3.** The effect of biochar on the cultivation of radish (A) and lettuce (B); (a) control, (b) substrate with 5% biochar, (c) substrate with 10% of biochar, (d) substrate with 15% of biochar

**Rysunek 3.** Wpływ zawartości biowęgla na uprawę rzodkiewki (A) i sałaty (B); (a) próba kontrolna, (b) podłoże z zawartością 5% biowęgla, (c) podłoże z zawartością 10% biowęgla, (d) podłoże z zawartością 15% biowęgla





**Figure 4.** Changes in the fresh weight of vegetables grown in soil with the addition of biochar compared to the control

**Rysunek 4.** Zmiany masy warzyw uprawianych w glebie z dodatkiem biowęgla w stosunku do próby kontrolnej

sample (Figure 3B). The results obtained by Liu et al. (2019) showed that the use of composted biochar with the addition of shell powder, humic acids, polyaspartic acid, and a mixture of urea and superphosphate increased lettuce yield, but only at a specific concentrations, i.e. 1.5–3% added to the soil (Liu et al., 2019). Increasing the biochar content beyond this level had the opposite effect, leading to reduced yields. In the present study, a positive effect was obtained only for the substrate with 5% biochar. The yield was lower for the substrate with 10% biochar, and in the sample with 15% biochar, biomass was reduced by 81% compared to the control (Figure 4).

**Table 4.** Effect of biochar on dry weight and selected metal content in lettuce

**Tabela 4.** Wpływ zawartości biowęgla na suchą masę oraz zawartość wybranych metali w sałacie

	Control	5% biochar	10% biochar	15% biochar	
Metal	Dry weight of lettuce [g]				
	56.6	66.0	49.3	11.0	
	Metal content per fresh weight of lettuce [mg/kg]				
Na	251.391 217.675 142.544 231.163				
Mg	333.994	356.453	214.801	337.232	
Al	1.100	4.890	5.287	4.176	
K	5510.861	6006.430	5801.533	6588.546	
Ca	912.142	1097.151	649.086	908.496	
Cr	0.043	0.090	0.191	0.115	
Mn	4.912	6.297	4.071	5.429	
Fe	5.024	10.147	11.002	9.629	
Ni	0.027	0.138	0.099	0.065	
Cu	0.196	0.460	0.229	0.242	
Zn	2.409	3.320	2.771	2.980	
As	0.004	0.006	0.004	0.004	
Cd	0.011	0.013	0.010	0.018	
Hg	0.013	0.017	0.009	0.017	
Pb	0.022	0.035	0.028	0.120	

The EU regulation No. 1881/2006 of 19 December 2006 specify the permissible levels of lead and cadmium in lettuce, which are 0.3 mg/kg and 0.2 mg/kg fresh weight, respectively. As with radish, the content of other metals is not standardised. The cadmium content determined in lettuce ranged from 0.010 to 0.018 mg/kg fresh weight an did not exceed the permitted concentrations. The lead content in lettuce ranged from 0.022 to 0.120 mg/kg fresh weight, also remaining within the



Figure 5. Change in elemental content of radish (A) and lettuce (B) grown in biochar-enriched soil compared to the control **Rysunek 5.** Zmiana zawartości pierwiastków w rzodkiewce (A) i sałacie (B) uprawianej na glebie wzbogaconej biowęglem w stosunku do próby kontrolnej

regulatory limits. The lowest concentrations of both heavy metals were found in lettuce grown on a substrate containing 10% biochar, while the highest concentrations were observed in the sample with 15% of biochar. The use of alkaline biochar has been reported to reduce the bioavailability of Hg in the soil and, consequently, the uptake of Hg by lettuce. The accumulation of Hg in the roots of lettuce growing in soil with biochar addition was lower compared to the control (Turull et al., 2019).

#### Conclusions

This paper discusses the management of biochar produced by the pyrolysis of sewage sludge in a pilot container installation. The usefulness of the obtained biochar as a soil amendment was evaluated and its influence on vegetable cultivation was tested. Physicochemical parameters of biochar were analysed, including the content of metals essential for plant growth. The cultivation tests were conducted in pots using a universal vegetable and flower substrate enriched with biochar at concentrations of 5%, 10% and 15% by weight. Two types of vegetables were used in the experiment: leafy lettuce and root radish. The limit values for cadmium and lead, as specified in EU regulation No. 1881/2006 of 19 December 2006 were not exceeded in any of the samples. Therefore, it can be concluded that the addition of up to 15% biochar to the soil does not result in the migration of large amounts of heavy metals to the edible parts of the vegetables. In addition, the yield of vegetables was highest in the sample with 5% biochar, supporting the hypothesis that biochar significantly improves growing conditions and enables the proper growth of lettuce and radish. The high temperature of 750-850°C in the pyrolysis reactor allows for effective sanitation of municipal sewage sludge, resulting in a carbon material that can be successfully used in agriculture to improve soil properties. The use of biochar for agricultural purposes is much safer than the use of raw sewage sludge.

In conclusion, the addition of 5% biochar improves the quality of the soil substrate, leading to the intensification of both radish and lettuce production, while maintaining safe levels of heavy metals in the tested vegetables.

#### **Acknowledgements**

The study was conducted in cooperation between the Faculty of Chemistry of the University of Gdańsk, Metal Expert Sp. z o.o. Sp. J. and the Elblag Technological Park. Analytical tests were carried out in the Advanced Environmental Analysis Laboratory of the Elblag Technological Park. The prototype installation for the pyrolysis of sewage sludge was provided by Metal Expert Sp. z o.o. Sp. J.

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## Akty prawne i dokumenty normatywne

Commission Regulation (EC) No 1881/2006 of 19 December 2006 setting maximum levels for certain contaminants in foodstuffs, Official Journal of the European Union L 364/5. PN-EN ISO 17294-2:2016-11 Water quality – Application of inductively coupled plasma mass spectrometry (ICP-MS) – Part 2: Determination of selected elements including uranium isotopes.
Regulation of the Minister of Maritime Economy and Inland Navigation of 12 July 2019 on substances particularly harmful to the aquatic environment and the conditions to be met when



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Regulation of the Minister of the Environment of 1 September, 2016 on the method of conducting the assessment of land surface contamination (Journal of Laws 2016, item 1395).



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- analiza zagrożeń środowiska naturalnego, związanych z działalnością przemysłu naftowego i gazowniczego,
   inwentaryzacja wielkości emisji metanu z sektora poszukiwania, wydobycia, magazynowania oraz przesyłu
- i dystrybucji gazu wraz oceną możliwości jej redukcji,
- inwentaryzacja wielkości emisji gazów cieplarnianych,
- weryfikacja i ocena wpływu technologii na środowisko w przemyśle naftowym i gazowniczym, zgodnie z najnowszymi trendami,
- wyznaczanie śladu węglowego (Carbon Footprint) w przemyśle naftowym i gazowniczym,
- monitoring i badania laboratoryjne elementów środowiska (powietrza, wód i gleby) na terenach poszukiwania i eksploatacji złóż węglowodorów i innych terenach przemysłowych,
- badania laboratoryjne ścieków i odpadów (w tym odpadów wiertniczych, odpadów po zabiegu hydraulicznego szczelinowania, odpadowych wód złożowych i cieczy technologicznych) oraz ocena ich potencjalnej szkodliwości dla środowiska,
- klasyfikacja odpadów wydobywczych wraz ze sporządzaniem charakterystyki odpadu, zgodnie z obowiązującymi regulacjami,
- oznaczanie wybranych nanocząstek metali i tlenków metali w próbkach środowiskowych,
- analiza zawartości rtęci w próbkach środowiskowych (stałych i ciekłych), mieszaninach gazowych i materiałach przemysłowych,
- ocena jakości paliw węglowodorowych, w tym gazu ziemnego i jego mieszanin z wodorem, a także gazów
- wytwarzanych w przemyśle (np. koksowniczego),
  kompleksowa analiza biogazu, w tym analiza związków krzemu, chloru i fluoru oraz amoniaku,
- monitoring jakości gazu ziemnego w systemie gazowniczym,
- sporządzanie oraz aktualizacja kart charakterystyki substancji i mieszanin niebezpiecznych, zgodnie z obowiązującym prawodawstwem,
- akredytowany pobór próbek odpadów oraz gazu ziemnego, biogazu i innego typu mieszanin gazowych.





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