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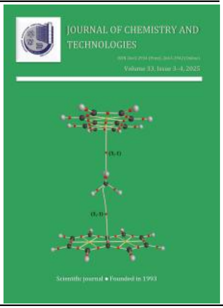

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PREPARATION AND STUDY OF ACID-BASE AND ION EXCHANGE PROPERTIES OF RICE HUSK BIOCHAR

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Abstract

Odesa region is a leader in Ukraine in rice production, which makes the issue of utilizing rice by-products particularly relevant. Rice husks are considered as a promising raw material for the production of biochar. The aim of this study is to synthesise biochar, which is used as a carrier for immobilizing the isolated soil microbial complex for the treatment of oil-containing wastewater, and to study its acid-base and ion-exchange characteristics. The analysis of potentiometric titration curves indicates the contribution of different ionized groups to the general properties of biochar, which allows it to be classified as a polyfunctional ion exchanger. It is proved that due to the properties of ampholytes, biochar can be used as a matrix for immobilization of microbial complexes, capable of acting as a buffer by regulating the pH level.

Key words: rice husk; biochar; pyrolysis; microwave biotransformation; heat treatment; acid-base properties; ion exchange properties.

ОТРИМАННЯ ТА ДОСЛІДЖЕННЯ КИСЛОТНО-ОСНОВНИХ ТА ІОНООБМІННИХ ВЛАСТИВОСТЕЙ БІОЧАРУ З РИСОВОГО ЛУШПИННЯ

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Анотація

Одеська область займає провідні позиції з виробництва рису в Україні, що робить особливо актуальним питання утилізації побічних продуктів його переробки. Рисове лушпиння розглядається як перспективна сировина для отримання біочару. Метою цього дослідження є синтез біочару, який використовується як носій для іммобілізації виділеного мікробного комплексу ґрунту для очищення нафтовмісних стічних вод, вивчення його кислотно-основних та іонообмінних характеристик. Аналіз кривих потенціометричного титрування свідчить про внесок різних іонізованих груп у загальні властивості біочару, що дозволяє класифікувати його як поліфункціональний іонообмінник. Доведено, що завдяки властивостям амфолітів та регулювання рівню pH, біочар може використовуватись у якості матриці для іммобілізації мікробних комплексів, здатної виконувати функцію буфера.

Ключові слова: рисове лушпиння; біочар; піроліз; мікрохвильова біотрансформація; термічна обробка; кислотно-основні властивості; іонообмінні властивості.

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Introduction

As our previous studies on buckwheat husk biochar [1] and coffee grounds biochar [2] show, the production, study of properties and use of plant-based biochars in environmental protection technologies is a promising area for obtaining high value-added products.

Biochar, a pyrogenically produced carbonaceous material from biomass, has attracted considerable attention from researchers and practitioners due to its unique physical and chemical properties. These properties, in particular its acid-base and ion exchange characteristics, determine its potential in a wide range of applications, including soil reclamation, water purification, carbon sequestration and microbial activity support. Understanding and controlling these properties is key to optimizing the effectiveness of biochar for specific purposes [3].

The properties of biochar, including its acid-base balance and ion exchange capacity, are highly dependent on the choice of feedstock and pyrolysis conditions [4]. Different types of biomass have a unique chemical composition that directly affects the final properties of biochar. Wood biomass (e.g. pine, oak) usually contains a high percentage of cellulose, hemicelluloses and lignin. Wood biochar is often characterized by a developed porous structure and a less acidic pH compared to some other types of biomass, especially at high pyrolysis temperatures [5].

Agricultural wastes (e.g. straw, corn stalks, rice husks) can have a significant content of silicon, potassium and other mineral elements that affect the pore structure and alkalinity of biochar [6; 7]. Biochar from these sources often has a relatively high pH value. Animal waste (e.g., poultry manure, manure) is rich in nitrogen, phosphorus, and other nutrients. Biochar from such waste can have an increased concentration of nutrients and specific surface functional groups that promote anion exchange [8; 9].

The process of pyrolysis – the thermal decomposition of biomass in the absence or limited amount of oxygen – is critical for the formation of biochar properties [10; 11].

The pyrolysis temperature is one of the most important parameters [12; 13]. Low temperatures (up to 400–500 °C) contribute to a higher yield, and biochar obtained under these conditions contains more oxygen-containing functional groups (such as carboxyl (-COOH) and hydroxyl (-OH)), which gives it a more acidic character and a higher cation exchange capacity (CEC). The porous structure is less developed and the organic components of biomass may not be fully carbonized [14].

High temperatures (above 600 °C) lead to significant aromatisation and condensation of carbon structures, a decrease in the number of oxygen-containing groups and an increase in the content of mineral components (carbonates). Such a biochar usually has a higher pH (neutral or alkaline), lower CEC, but more developed porosity and stability [15]. Longer residence time at high temperatures promotes further carbonisation and porosity development [16]. Rapid pyrolysis (flash pyrolysis) can lead to the formation of biochar with different properties compared to slow pyrolysis [17].

To improve specific properties, biochar can be modified [18]. Chemical modification includes oxidation (e.g., with nitric acid, hydrogen peroxide), amination, sulfation, and immobilization of metals or nanoparticles. These methods can significantly increase the number of certain functional groups, improving sorption or catalytic properties [19]. Activation with steam or carbon dioxide leads to an expansion of the porous structure and an increase in surface area [20].

The acid-base properties of biochar are key to its interaction with the environment, especially in aquatic systems and soils. pH of biochar is a basic indicator of its acid-base character [21]. Typically, pH is measured in an aqueous biochar suspension (e.g., biochar:water ratio of 1 : 10). Typically, biochar produced at lower temperatures has a more acidic pH (4–7), while biochar produced at higher temperatures can be neutral or alkaline (pH 7–10 and above) due to decarboxylation and carbonate formation [22].

Potentiometric titration allows determining the number of acidic and basic functional groups on the biochar surface and their pKa values. This gives a detailed picture of the buffering capacity of the material and its ability to give or take up protons depending on the pH of the medium. The titration curves allow for the identification of different types of acid groups (e.g., carboxylic, phenolic) [23].

Modern analytical methods are used to identify and quantify acidic and basic functional groups on the surface of biochar [24]. Fourier transform infrared spectroscopy (FTIR) allows to identify the presence of various functional groups, such as -COOH (1700–1750 cm^{-1}), -OH (3200–3600 cm^{-1}), C=C (1550–1600 cm^{-1}, aromatic rings), C-O (1000–1300 cm^{-1}). X-ray photoelectron spectroscopy (XPS) provides information on the elemental

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composition of the surface and the chemical state of the elements, allowing to distinguish between different types of carbon (aromatic, aliphatic) and oxygen-containing functional groups. Nuclear Magnetic Resonance (NMR, especially Solid-state13C NMR) provides detailed structural data on the chemical environment of carbon atoms, including aromatic and aliphatic structures, as well as carbons bound to oxygen.

Ion exchange properties are fundamental to understanding the ability of biochar to adsorb and release ions from solutions. The cation exchange capacity (CEC) [25] of a biochar is one of the most important indicators of its functionality. It reflects the total amount of exchangeable cations that can be retained on the negatively charged surfaces of the biochar. A high CEC indicates a large number of negatively charged sites that can adsorb metal cations (e. g. Ca^{2+}, Mg^{2+}, K^+, Na^+) or ammonium (NH^{4+}). The anion exchange capacity (AEC) reflects the ability of a biochar to retain negatively charged ions (anions) such as nitrates (NO_3^-), phosphates (PO_4^{3-}), sulfates (SO_4^{2-}). Typically, the AEC of a biochar is significantly lower than the CEC, as most biochars have predominantly negatively charged surfaces. However, the AEC can be increased by introducing positively charged functional groups (e.g., amine groups through modification) [26].

The use of biochar is due to its acid-base and ion-exchange properties [27; 28]. Understanding and optimizing the acid-base and ion-exchange properties of biochar allows it to be used effectively in various fields: soil amelioration to regulate soil pH, alkaline biochar can be used to increase the pH of acidic soils, and acidic biochar can be used to decrease the pH of alkaline soils; nutrient retention, as high CEC allows biochar to retain nutrient cations (NH^{4+}, K^+, Ca^{2+}, Mg^{2+}) and reduce their leaching; heavy metal immobilization, as negatively charged biochar sites effectively adsorb heavy metal ions (Pb^{2+}, Cd^{2+}, Cu^{2+}), reducing their bioavailability; water and wastewater treatment, as biochar is effective for removing both cationic (heavy metals, ammonium) and anionic (phosphates, nitrates, fluorides) pollutants, the selectivity and capacity of adsorption depend on the functional groups and charge of the biochar surface; adsorption of organic pollutants, although it is not directly related to ion exchange properties, the porous structure and hydrophobic sites of biochar also contribute to the adsorption of organic substances [28].

A comprehensive study of the acid-base and ion-exchange properties of biochar is fundamental to its rational use. The choice of raw materials and pyrolysis conditions, as well as possible modifications, allow biochar to be "tuned" for specific purposes. The continuous development of analytical methods opens up new opportunities for a deeper understanding of the mechanisms of interaction between biochar and the environment, which will contribute to a more efficient and sustainable use of this versatile material.

The *aim of this work* is to produce biochar from rice husk by conventional pyrolysis and microwave irradiation, to study its physicochemical characteristics and to assess the possibility of its use in biotechnology for the treatment of oily wastewater. The study determined the acid-base, ion-exchange properties, particle size distribution, as well as the sorption capacity of biochar for calcium and lead ions and the structural characteristics of the surface of biochar and raw materials.

Methods

The production of biochar by traditional pyrolysis, determination of the particle size distribution of biochar, production of biochar by microwave irradiation, determination of the biopolymer composition of raw materials and biochar, and determination of lignin were performed according to the methods given in our study [1].

The structural characteristics of the feedstock and biochar were determined using a standard vacuum absorption unit with a McBain quartz spring at a temperature of 25 °C [29]. Mercury levels were measured using a KM-8 catheter with an accuracy of 0.5 %. During the experiments, the unit was enclosed in an organic glass enclosure in which the temperature was maintained at 25℃ ± 0.2 °C using a specially designed thermostat. The mass of sorbed water was determined by the formula:

$$Q = \frac{\Delta l}{\Delta L * M}, \qquad (1)$$

where ΔL is the elongation of the quartz helix depending on the mass of the sorbent; Δl is the elongation of the quartz helix depending on the mass of the sorbate; M is the molecular weight of the sorbate.

The surface of the biochar was studied using the Brunauer-Emmett-Teller (BET) method. The coefficient of the BET equation was calculated using a straight-line relationship using Excel software [1]. The equation of the BET polymolecular sorption isotherm translated into a linear form is as follows:

$$\frac{P/Ps}{a(I-P/P_S)} = \frac{I}{a_m*C} + \frac{C-I}{a_m*C}\ P/P_S, \qquad (2)$$

where P_S is the saturated vapour pressure at a given temperature; P/P_S is the relative vapour pressure; a is the surface concentration of sorbate; a_m is the surface concentration of sorbate when all active centres are filled; C is the BET constant.

The specific surface area of the samples was calculated by Eq:

$$S_{yg} = a_m * N_A * S_0 * 10^{-23}, \qquad (3)$$

where $N_A -$ Avogadro's number; $S_0 -$ is the cross-sectional area of the sorbate (water) molecules, equal to 10.6 A.

The average effective pore radius is calculated by Eq:

$$S = \frac{v_{max}}{2\,S_{yg}}, \qquad (4)$$

Where $v_{max} -$ is the maximum volume of sorbed moisture.

The acid-base and ion-exchange properties of biochar and raw materials were studied according to the methods described in our study [1].

Statistical processing of the experimental results was performed using R, Prism, and Excel software.

Results and discussion

The vast majority of food processing waste is lignocellulosic biomass, the main components of which are cellulose, hemicellulose and lignin. Cellulose is a linear polysaccharide constructed from glucose residues arranged in structures with a high degree of crystallinity. Hemicelluloses, in contrast to cellulose, are branched heteropolysaccharides composed of several types of monosaccharides. Lignin is an aromatic biopolymer formed by phenolic monomers connected by a complex network of bonds, and acts as a cementing agent between cellulose fibres, ensuring the rigidity and hydrophobicity of cell walls [1].

During the thermal processing of biomass under conditions of limited oxygen access (pyrolysis), organic components are broken down to form gases, condensed organic matter and a solid residue – biochar. The nature and ratio of pyrolysis products depend on a number of factors, including the process temperature, the time spent in the reactor, the nature of the feedstock, and the heating rate [2].

The thermal decomposition of different components of lignocellulosic biomass occurs in different temperature ranges. In particular, hemicelluloses begin thermal degradation at a temperature of about 220 °C and are almost completely decomposed by 315 °C; cellulose undergoes thermolysis at temperatures exceeding 315 °C and is completely converted into volatile components by 400 °C; lignin, unlike polysaccharides, begins to decompose at 160 °C, but the process is extended in time and lasts up to 900 °C, which leads to its higher thermal stability [7].

Table 1 shows the results of the analysis of the chemical composition of the feedstock and biochar produced by three different methods:

✓ pyrolysis at 300 °C (designated as biochar-300);

✓ pyrolysis at 500 °C (biochar-500);

✓ microwave irradiation (designated as biochar-MX).

Table 1

Chemical composition results of raw materials and biochar samples

Biomass	Protein, %	Pectin substances, %	Hemicellulose, %.	Cellulose, %.	Lignin, %.	Ash, %
Rice husk	4.7 ± 0.1	3.0 ± 0.1	15.7 ± 0.2	27.5 ± 0.2	36.4 ± 0.1	3.5 ± 0.2
Samples obtained by pyrolysis of raw materials						
Biochar-300	1.4 ± 0.2	1.6 ± 0.2	8.0 ± 0.3	32.7 ± 0.2	42.0 ± 0.1	5.5 ± 0.2
Biochar-500	-	0.9 ± 0.1	1.6 ± 0.2	29.0 ± 0.2	50.6 ± 0.2	7.0 ± 0.1
Samples obtained by microwave irradiation of raw materials						
Biochar-MX	0.6 ± 0.1	2.2 ± 0.1	10.1 ± 0.1	32.3 ± 0.1	40.2 ± 0.1	3.9 ± 0.1

The results of the analysis of the chemical composition of the feedstock and biochar obtained by pyrolysis at different temperatures and using microwave irradiation indicate distinct changes in the structure of the biomaterial. In particular, with an increase in pyrolysis temperature, an increase in the content of lignin and ash residue is observed, indicating an increase in the degree of thermal degradation of polysaccharides and the concentration of heat-resistant components. At the same time, an increased cellulose content was recorded in the biochar samples obtained by microwave irradiation, which may be due to the peculiarities of energy distribution in the microwave field and a lower intensity of thermal destruction of the cellulose fraction.

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In order to increase the specific surface area of biochar and improve its adsorption properties, the carbonaceous material of biochar-500 was subjected to grinding in a ball mill after carbonisation. After mechanical processing, the particles were classified by size. The results of the particle size distribution analysis are presented in Table 2.

Table 2

Particle size distribution of biochar after grinding

Particle size, mm	> 1	1 – 0.61	0.61 – 0.45	0.45 – 0.30	0.30 – 0.25	0.23 – 0.17	0.17 – 0.10	< 0.1	Total
Content, % wt.	0.3 ± 0.04	0.4 ± 0.07	1.0 ± 0.18	2.5 ± 0.01	0.6 ± 0.03	6.8 ± 0.1	5.5 ± 0.06	82.7 ± 0.23	100

According to the results shown in Table 2, the largest proportion of carbonised material after grinding (82.7 % by weight) is made up of particles less than 0.1 mm in size. Such a high content of the fine fraction indicates the efficiency of the grinding process and contributes to an increase in the specific surface area of biochar, which is a critical factor for its further use, in particular in the processes of immobilization of biologically active substances.

One of the key aspects of using biochar as a matrix for immobilizing biologically active substances is its ability to modify mineral metabolism, in particular by changing the pH of the medium. This property is due to the presence of both acidic and basic functional groups in biochar, which gives them ion exchange activity. Sources of acidic functional groups can be pectin, hemicellulose, lignin, as well as residual protein components, which, being ampholytes, also exhibit basic properties due to amino acid residues.

The scientific literature [27] notes the ambiguity of the effect of biochar on the bioavailability of micro- and macronutrients. Some researchers point to the potential ability of biochar to irreversibly bind calcium, iron and other trace elements, which can disrupt mineral balance. Others, on the contrary, argue that these elements are subsequently released as a result of microbial degradation of residual polysaccharides (in particular, pectin and hemicelluloses) and become available to microorganisms.

Based on the assumption that the ion-exchange function of biochar is important for the immobilization of biologically active components, we studied its acid-base and ion-exchange properties. For this purpose, the potentiometric titration method was used. The objects of analysis were: rice husk (feedstock), Biochar-300, Biochar-500 and Biochar-MX (obtained by microwave irradiation).

Typical potentiometric titration curves are shown in Figs. 1 and 3. Their appearance reflects the total contribution of all ionized groups and allows us to classify the studied biochars as polyfunctional ion exchangers. For quantitative analysis, differentiated curve shapes were used (Figs. 2 and 4), which provide a more accurate identification of titration jump points. The pK values of the ionic groups were determined according to the Henderson-Hasselbach equation adapted for polyelectrolytes.

Table 3 shows the values of the maximum cation exchange capacity (CEC) of raw materials and biochar. The obtained results show that biochar has lower values of CEC compared to the feedstock (1...3 meq/g), and for biochar this indicator ranges from 0.89...1.15 meq/g. This indicates a reduced ion exchange capacity of biochar and, accordingly, a lower potential for influencing the mineral balance in the microbial environment.

The integral ion exchange capacity of raw materials depends on the content of functional groups with different pK values, which are significantly affected by the local chemical environment. As can be seen from Table 3, the acidic functional groups of biochar have pKa in the range of 7.1...10.7, which gives grounds to classify them as weakly acidic. This further confirms the polyelectrolyte character of biochar with the potential to regulate the acid-base balance in the processes of immobilization of biologically active substances.

For the purpose of comparison, it is advisable to cite the known pK values of some organic functional groups: acetic acid has a pK of ≈ 4.76; a typical polyelectrolyte, pectin, is characterized by a pK range of 3...5; phenolic hydroxyl groups have a pK in the range of 9...10; the sulfhydryl group of the amino acid cysteine is about 8.3; the guanidine group of arginine is about 12.5.

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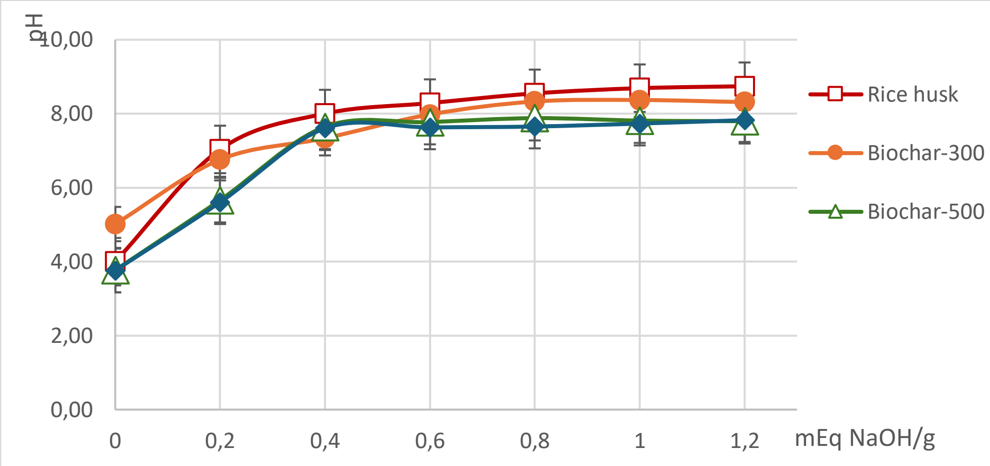

Fig. 1. Integral curves of potentiometric titration

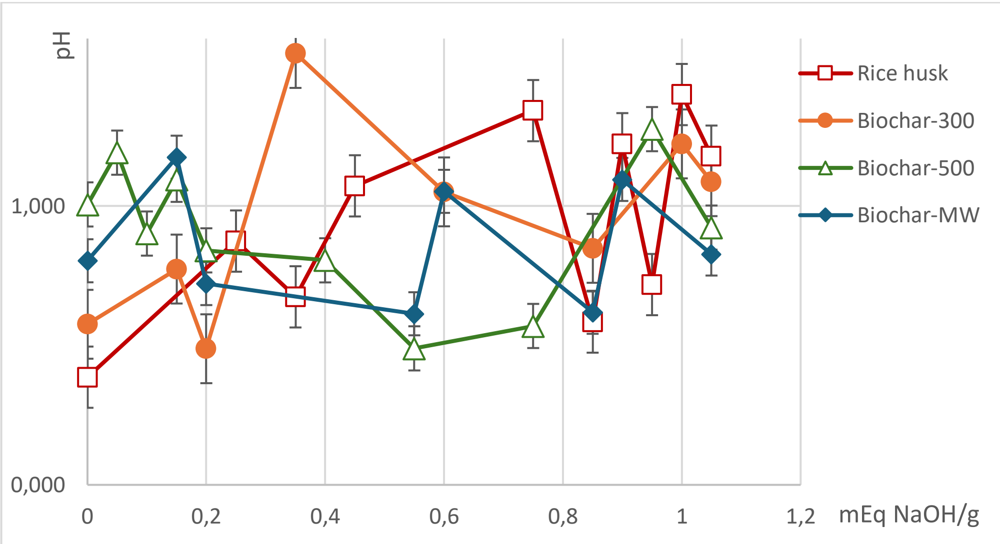

Fig. 2. Differential curves of potentiometric titration

Obviously, it is quite difficult to classify the acidic groupings of biochar, which may include all the above types of functional groups, as well as a number of others, unambiguously. In this regard, determining the nature of ionic groups in biochar requires a significant amount of assumptions and contextual interpretation of the titration results.

In particular, the groups with the lowest pKa values (7.1...7.5) can be preliminarily associated with the carboxyl functions of uronic acid residues inherent in pectins and hemicelluloses. Groups with pKa > 8.0 can be associated with phenolic hydroxyl structures of lignin or R-groups of some amino acids of protein origin.

It is worth noting that the determination of the acid-base properties of biochar should be carried out individually for each type of sample, taking into account the method of its preparation. For example, biochar obtained at a temperature of 300 °C (biochar-300) is characterized by functional groups with a pKa in the range of 9.6...10.7, which most likely correspond to phenolic hydroxyl groups. A similar pKa spectrum is observed for the feedstock, which, however, contains a much larger amount of polyphenolic components, which determines its pronounced acidic properties.

Table 3

Characterisation of the acid and cation exchange properties of the studied samples

Sample	The pKa value	Functional group content, meq/g	Maximum capacity of exchange, meq/g
Rice husk	7.1	0.2 ± 0.3	1.0
	8.0	0.1 ± 0.3	
	9.9	0.7 ± 0.9	
	7.3	0.1 ± 0.3	0.9
	9.8	0.8 ± 0.9	
Biochar-MX	7.4	0.1 ± 0.1	1.0

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Continuation of the table 3

	7.9	0.1 ± 0.2	
	9.2	0.8 ± 1.2	
Biochar-300	8.4	0.1 ± 0.2	0.9
	9.6	0.1 ± 0.3	
	10.7	0.7 ± 0.9	
Biochar-500	7.2	0.2 ± 0.3	1.3
	7.8	0.4 ± 0.7	
	9.4	0.7 ± 0.7	

Table 4 shows the results of the study of the ability of biochar to bind cations of two metals - calcium and lead. Calcium was chosen because this element is most often mentioned in the context of a possible negative effect of biochar on mineral metabolism, in particular due to a hypothetical decrease in its bioavailability. Therefore, a comparison of the calcium binding capacity of biochar and the feedstock (rice husk) is of particular scientific value.

The lead model was chosen for the purpose of preliminary evaluation of biochar efficiency as a sorbent for binding heavy metals that may be contained in wastewater. Determining the level of lead ion sorption allows us to draw conclusions about the potential of biochar to participate in detoxification processes, which is especially relevant in the context of using biochar in technologies for the treatment of polluted water bodies.

Table 4

Characteristics of calcium and lead ion binding

Sample	Sorption of Pb^{2+}		Sorption of Ca^{2+}	
	mg/g	% of the initial weight	mg/g	% of the initial weight
Rice husk	22.5 ± 0.4	57.4 ± 1.1	2.1 ± 0.2	36.1 ± 4.5
Biochar-MX	19.6 ± 0.3	50.1 ± 0.9	0.3 ± 0.2	4.8 ± 3.8
Biochar-300	21.5 ± 0.4	56.9 ± 1.1	1.5 ± 0.3	29.1 ± 4.6
Biochar-500	7.3 ± 0.5	19.6 ± 1.3	0.2 ± 0.1	2.2 ± 1.6

The results of the analysis indicate that calcium ions (Ca^{2+}) are least efficiently bound by biochar-500 compared to biochar-300 and biochar obtained by microwave irradiation. The probable reason for this is the reduced content of phenolic compounds in biochar-500, which limits the number of active sites for calcium coordination.

Although the binding of lead ions is generally higher, its efficiency in Biochar-500 is lower compared to other samples. Given that biochar-500 is usually considered as a potential sorbent for heavy metals, the results indicate the need to consider not only the overall sorption capacity but also the specific composition of functional groups.

The values of anion exchange capacity for the studied biochar samples are in the range of 0.7–1.2 meq/g (Table 5). The exception is biochar-500, which is characterized by the lowest value of this indicator. This is probably due to the low content of protein components, which are the source of the main functional groups for anion exchange.

The number of ionogenic groups capable of anion exchange varies from 0.1 mEq/g in Biochar-500 to 1.2 mEq/g in Biochar-MX. The highest pKb values among the studied samples were found in biochar-500 (pKb = 7.5), biochar-MX (pKb = 7.3) and biochar-300 (pKb = 7.0). Other anion-exchange groups demonstrate pKb values in the range of 4.9–6.3, which allows them to be classified as weakly basic.

Table 5

Characterization of basic and ion-exchange properties of biochar and raw materials

Sample	The value of pKb	Content of groups of basic nature, meq/g	Maximum exchange capacity, meq/g
Rice husk	6.0	0.2 ± 0.3	0.8
	4.9	0.6 ± 0.8	
Biochar-300	7.0	0.2 ± 0.3	0.7
	5.2	0.5 ± 0.7	
Biochar-500	7.5	0.1 ± 0.2	0.1
Biochar-MX	7.3	0.4 ± 0.6	1.2
	6.9	0.3 ± 0.4	
	6.3	0.5 ± 0.7	

The anion-exchange properties of biochar are closely related to its ability to influence the acid-base balance of the medium, in particular, to reduce acidity by increasing the pH value when in contact with the substrate. This ability of biochar of various origins is illustrated by the data presented in Figs. 3 and 4. According to the results obtained, the ion exchange activity of most samples is much more pronounced in alkaline media than in acidic ones, which indicates the presence of weakly basic functional groups in the biochar structure.

All the biochar samples studied demonstrate the ability to significantly change the pH of the medium, but the highest buffering activity is exhibited by the biochar obtained by microwave irradiation (biochar-MX). This indicates a higher concentration of basic ionic groups capable of anion exchange and potentially greater efficiency of such biochar in stabilising the acid-base regime in the processes of immobilization and functioning of immobilized biologically active drugs.

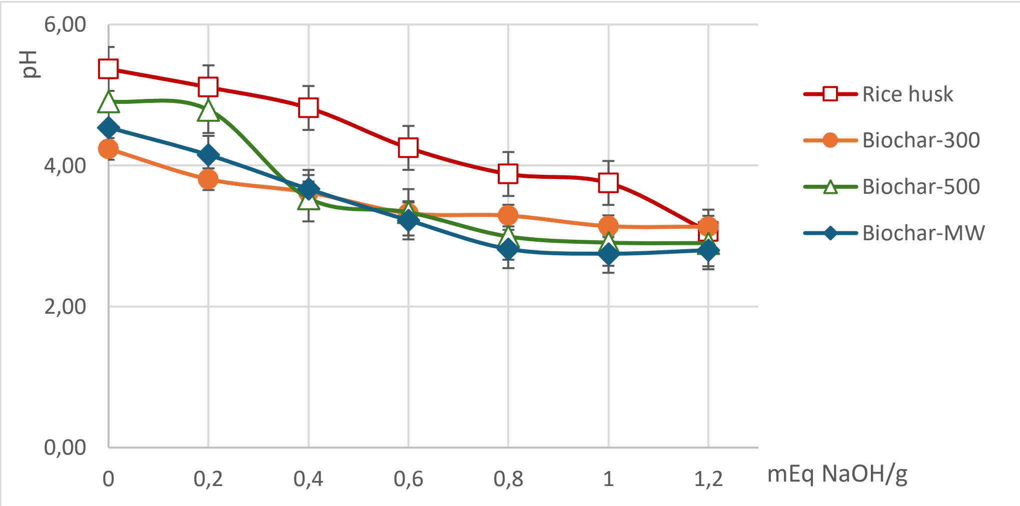

Fig. 3. Integral curves of potentiometric titration

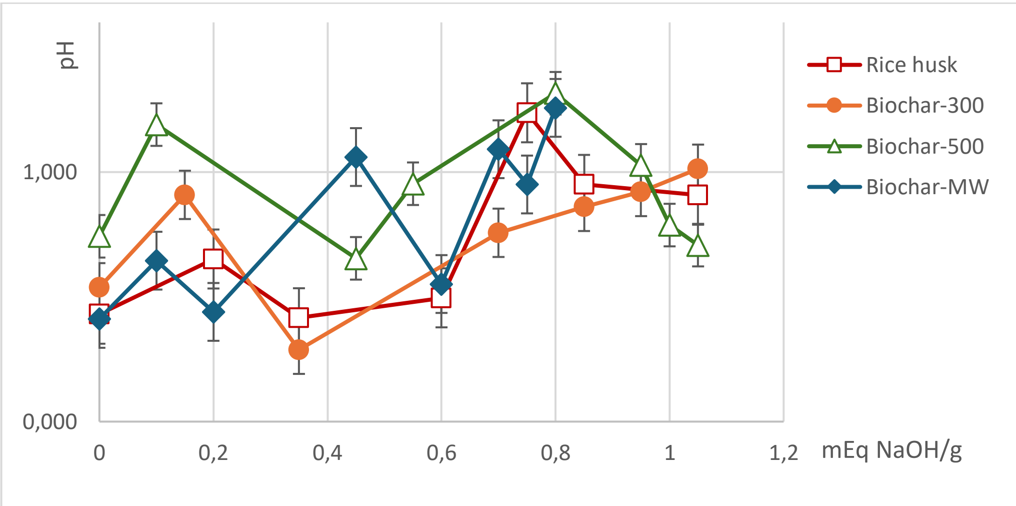

Fig. 4. Differential curves for potentiometric titration

At pH 7–8, biochars, acting as weak acids, can cause a pH shift to the acidic side and also bind ammonia, which, according to some assumptions, is one of the factors that affect pH changes during the immobilization process and the functioning of immobilized drugs. Given these facts, it can be assumed that Biochar-MX and Biochar-300 have the greatest impact on pH changes. The increase in pH when interacting with raw materials is more pronounced, while biochar-500 has the least effect.

Thus, due to their ampholytic properties, biochars not only act as acceptors of metal ions, but also serve as a softened pH regulator.

The polymeric composition and surface structure of biochar largely determine their functional characteristics, which was the basis for a detailed study of these parameters.

Table 6 shows the results of the analysis of the average pore radius (r, 10^{-10} m) and specific surface area (Ssp, m^2/g).

Table 6

Structural characteristics of the sample surface

Sample	Structural characteristics of the surface	
	$r*10^{10}$	Ssp, m^2/g sample
Biochar-500	24.80	164.21
Biochar-300	27.01	132.77
Biochar-MX	26.99	152.19
Rice husk	26.98	130.07

According to the data presented in Table 6, during the experimental comparative analysis of the structural characteristics of the surface of biochar and rice husk as a feedstock, it was found that the specific surface of biochar significantly exceeds the corresponding indicator of the feedstock. This indicates the effectiveness of the applied methods of raw material modification aimed at improving the functional properties of the material. With an increase in the pyrolysis temperature, the specific pore surface increases, but the best parameters of the developed surface are demonstrated by the biochar obtained by microwave pyrolysis, which emphasises the prospects of this method for obtaining high-quality biochar with enhanced functional characteristics for use in the immobilization of biologically active substances and in environmental technologies.

Conclusions

Thus, the studies conducted allow us to conclude that as the pyrolysis temperature increases, the lignin and ash content increases; the microwave method preserves more cellulose; most of the carbonized material (≈ 83 %) consists of small particles < 0.1 mm; biochar has a lower cation exchange capacity than raw materials, but retains its multifunctional ion exchange properties; biochar acts as a weak acid and ampholyte, capable of regulating pH and binding ammonia; Biochar-500 is most effective for removing Pb^{2+} ions, while other samples are better at binding Ca^{2+}. Biochar simultaneously sorbs metal ions and stabilizes pH, making it promising for environmental protection technologies.

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