



# The Evaluation of Properties of Chars Produced from Wastes of Different Origins

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## ABSTRACT

This paper presents a screening of primary char samples produced through the hydrothermal liquefaction of biomass. Currently, numerous studies demonstrate the potential of hydrothermal conversion char residues as sorbents. The relevance of this work lies in utilizing materials that are rarely used in other areas of production, such as aquatic vegetation, organic waste, algae, bark and wood waste, food waste, and waste from the agro-industrial complex. This study aims to evaluate the sorption capacity (for iodine, phenol, and methylene blue) of char sorbents obtained from various raw materials via hydrothermal liquefaction and to identify the most suitable raw materials. To assess the charcoals, their elemental composition and sorption capacities for methylene blue, iodine, and phenol were analyzed. The average yield of charcoal was 35%. The results indicate that the obtained chars demonstrated the highest sorption capacity for methylene blue (up to 239 mg.g<sup>-1</sup>), while phenol sorption was the lowest (not exceeding 19 mg.g<sup>-1</sup>). These findings suggest that the produced chars are promising raw materials for the production of sorbents.

## INTRODUCTION

Pollution is a longstanding global environmental challenge, primarily driven by anthropogenic activities. This study explores one of the methods to mitigate anthropogenic impacts – wastewater treatment with sorbents.

In recent years, sorbents have gained increasing popularity for wastewater treatment due to their ease of use and regenerability (Fouda-Mbanga et al. 2024). Samodolova et al. (2024) employed a charcoal sorbent obtained by pyrolysis of walnut shells to treat wastewater contaminated with heavy metal ions. The authors investigated the dynamic sorption of aluminum, chromium, copper, iron, magnesium, and zinc ions. Their results demonstrated that the sorbents effectively removed chromium and copper ions from the solution, regardless of the process temperature.

Kaewtrakulchai et al. (2024) used carbon sorbents obtained through the hydrothermal conversion of shrimp processing waste to treat wastewater contaminated with antibiotics (oxytetracycline). Their experimental data demonstrated a 100% purification efficiency of the antibiotic solution when a sorbent concentration of 2 g.L<sup>-1</sup> was applied for a sorption period of 10 min (with an initial antibiotic concentration of 300 mg.L<sup>-1</sup>).

Sorbents are also widely used in soil remediation. Wyszowska et al. (2023) conducted soil remediation experiments on diesel fuel and petroleum ether contamination using biochar, halloysite, and alginite. All samples demonstrated potential for soil remediation, with biochar showing the highest efficiency.

Although sorbents are effective in wastewater and soil treatment, they remain an expensive product. Andriyko et al. (2024) calculated the cost of bentonite-carbon

sorbent, which was produced using lignite, bentonite and a binder. The cost of raw materials alone amounted to \$78 per ton of sorbent. Even without considering the cost of the equipment, it is evident that sorbents are costly.

Efficient and relatively inexpensive sorbents can be obtained through the pyrolysis of dry biomass. Chen et al. (2024) conducted the pyrolysis of dried coffee grounds at 550°C for 1.5 h. Structure analysis using SEM revealed high porosity. The authors tested the sorption of heavy metal ions ( $\text{Pb}^{2+}$ ,  $\text{Ni}^{2+}$ ), achieving sorption capacities of 67.037  $\text{mg}\cdot\text{g}^{-1}$  for lead and 10.265  $\text{mg}\cdot\text{g}^{-1}$  for nickel.

Amosa (2015) carried out the pyrolysis of palm oil production waste at a temperature of 900 °C for 15 min. The resulting product exhibited a surface area of 886.2  $\text{m}^2\cdot\text{g}^{-1}$ , as measured by BET, and high porosity, confirmed by SEM. The sorbent demonstrated purification efficiencies of 90% for hydrogen sulfide and 95% for manganese ions.

Ifan et al. (2023) performed pyrolysis of 2 types of raw materials: wheat straw and excess sludge, as well as their mixture in the ratio of 1:1. The raw materials were dried, crushed, and sieved before undergoing pyrolysis at 550 °C for 3 h. At a sorbent dosage of 3  $\text{g}\cdot\text{L}^{-1}$  and above, the phosphate removal rate reached 100%. The used sorbents were used as fertilizer for mustard plant cultivation.

Unfortunately, the use of pyrolysis for waste treatment is not always effective. In most studies, the wet raw material requires prolonged drying (several days) before pyrolysis. Sylwan & Thorin (2023) used pyrolysis char derived from excess sludge to treat wastewater contaminated with heavy metals; however, the char demonstrated poor performance.

There are several methods for producing char sorbents. Güleç et al. (2022) compared three potential methods of obtaining char sorbents: hydrothermal conversion, torrefaction, and pyrolysis. Hydrothermal conversion is conducted at temperatures ranging from 100 to 320°C, with char yields ranging from 0 to 100%. Torrefaction is performed at 200-300°C with 20-95% char yield, while pyrolysis is carried out at 300-570°C, producing a 15-65% char yield.

Hydrothermal liquefaction is a process of thermochemical conversion of biomass to produce synthetic bio-oil as well as biochar. This process takes place in an aqueous environment and can be enhanced with the use of catalysts. One advantage of this method is the ability to control process parameters, making it more versatile (Sharma et al. 2024).

The use of char residue from hydrothermal liquefaction as a sorbent is currently gaining significant attention. Lu et al. (2021) performed hydrothermal liquefaction of algae, demonstrating the potential of this method for biomass

conversion. Aktas et al. (2024) produced coal from excess sludge through hydrothermal conversion. After activation and pelleting, the surface area increased to 791  $\text{m}^2\cdot\text{g}^{-1}$ , enhancing its sorption capacity.

Char sorbents produced by hydrothermal conversion have found widespread application in wastewater treatment. Yu et al. (2021) investigated the sorption of lead ions using a char sorbent derived from algae. The chars obtained were low-porous. FTIR showed the presence of active groups on the sorbent surface: C=O, C=C, and SiO. The degree of purification of the solution ranged from 20% to 100%, depending on the lead concentration. Marx & van der Merwe (2021) performed phenol sorption experiments, reporting extraction efficiencies ranging from 5% to 14%, depending on the sorbent dosage. Unactivated chars were characterized by poorly developed BET surface area: mesopores 1.54  $\text{m}^2\cdot\text{g}^{-1}$ , micropores 24.78  $\text{m}^2\cdot\text{g}^{-1}$ .

Kulikova et al. (2024) compared the life cycle impacts of algae processing using pyrolysis and hydrothermal liquefaction methods. A comparison of the impact of the methods on climate change showed that using wind power for hydrothermal conversion will reduce the environmental load compared to pyrolysis, highlighting the ecological benefits of hydrothermal processing.

Summarising the studied material, we came to some conclusions:

- 1) Most often, cellulose-containing raw materials or other structural polysaccharides are used for the production of chars, regardless of the method of their production. Less often, a mixture of organic wastes with cellulose-containing raw materials is used. This is due to the prospects of such raw materials for obtaining char sorbents, with high carbon content, and porosity of the initial material.
- 2) Chars obtained by pyrolysis are characterized by high porosity. Both SEM and BET analyses show this. For example, Amosa (2015) obtained chars that exhibited a surface area of 886.2  $\text{m}^2\cdot\text{g}^{-1}$ , as measured by BET. At the same time, coals obtained by HTL exhibit low porosity. Marx and van der Merwe (2021) obtained chars characterized by a low BET surface area: mesopores 1.54  $\text{m}^2\cdot\text{g}^{-1}$ , micropores 24.78  $\text{m}^2\cdot\text{g}^{-1}$ . The surface of such chars is characterized by the presence of active centers (C=O, C=C, SiO groups). This proves chemisorption as the main sorption mechanism of such coals.
- 3) Hydrothermal conversion is a cheap, ecologically favourable and promising method of producing coal sorbents from various types of raw materials.

Many studies have demonstrated that hydrothermal conversion is a universal method for producing char sorbents, making it suitable for various raw materials, including wet biomass. However, the question remains as to which raw materials are most effective for the production of sorbents by hydrothermal conversion.

This study aims to evaluate the sorption capacity (for iodine, phenol, and methylene blue) of char sorbents obtained from various raw materials by hydrothermal liquefaction and to identify the most suitable raw materials.

## MATERIALS AND METHODS

The experiment was performed 3 times. The error of the experiment should not exceed 10%. For each sample, the chars were produced three times. A series of experiments was performed in each of the 3 chars. This allowed levelling out the influence of uncontrollable factors that could occur in the process of char production.

### Materials

Dichloromethane, phenol, iodine, methylene blue, potassium bromate, potassium bromide, hydrochloric acid, potassium iodide, and sodium thiosulfate were of ACS purity grade and purchased from Diaem (Moscow, Russia). Water was distilled on an evaporative distiller immediately before the experiments.

### Objects of Research

The objects of research include raw materials that are not commonly utilized in traditional methods. All materials were categorized into the following groups:

1. Plant biomass: *Phragmites australis*, *Scirpus lacustris*, *Typha angustifolia*, and *Miscanthus*
2. Organic waste: Excess sludge
3. Baltic Sea algae: *Furcellaria*
4. Bark wood waste: Pine bark
5. Food waste: Apple waste and coffee waste
6. Agro-industrial complex waste: Cow manure and wheat straw

The plant biomass used in the study is widely distributed in the Kaliningrad region. Aquatic vegetation contributes to the purification of nutrients in water bodies, provided that it is collected in a timely manner (Kulikova et al. 2023). The organic composition of aquatic vegetation is rich in cellulose, hemicellulose, and pectin (Beyzi et al. 2023). The plant samples used in this study were collected from the Curonian Bay area in the Kaliningrad region, Russia. Fig. 1 presents the appearance of the plants used.

Countries near the Baltic Sea produce approximately 4.0 million tons of sewage sludge per year (dry matter) (Kacprzak et al. 2017). Most of this sludge is disposed of in landfills, reducing the amount of usable land (Xu et al. 2021). Excess sludge primarily consists of minerals (Mulopo 2024). In this study, sludge samples were collected from the water treatment plant in Sovetsk, Kaliningrad region, Russia. The sludge appeared as a black, wet substance (Fig. 1). For the experiment, the sludge was dried for 24 h at 80°C.

*Furcellaria* is a red algae found in the Baltic Sea. From late fall to early spring, biomass is deposited onto the shore, creating an unfavorable appearance on the beaches. Along with the algae, oil and plastic contaminants that accumulate in the algae thickets are also washed ashore (Gorbunova & Esyukova 2020). *Furcellaria* contains alginates, fucoidan, laminarin, and other compounds (Olsson et al. 2020). In this study, the algae were collected from the shores of the Baltic Sea (Kaliningrad region, Russia). *Furcellaria* has a branched structure and is black in color (Fig. 1).

Bark waste is a by-product of wood product manufacturing and is most frequently burned for energy production (Cesprini et al. 2020). Bark waste is rich in lignin, hemicellulose, and cellulose (Alonso-Esteban et al. 2022). In this study, common pine bark collected from the Kaliningrad region of Russia was used. The bark samples ranged in size from 2 cm<sup>2</sup> to 10 cm<sup>2</sup> and were brown in color (Fig. 1).

Food waste, a by-product of the food industry, was also used in this study. Coffee waste was obtained from the operation of a coffee machine, while apple waste was obtained in the production of apple juice. The main components of apple waste are fiber and pectin (Li et al. 2024). Local apples from the Kaliningrad region were used. The food waste samples were dried before the experiments (Fig. 1). The food waste was dried in a drying oven at 70-80 degrees centigrade for several hours until free moisture was removed.

Among agro-industrial wastes, cow manure (classified as IV type of hazard) and wheat straw (classified as V type of hazard) were used in this study. Wheat straw primarily contains cellulose and lignin (Yuan et al. 2024). Both straw and manure samples were collected from farms in the Kaliningrad region. Fig. 1 demonstrates the appearance of the raw materials.

### Determination of Raw Material and Char Compositions

Ash content was determined according to GOST 26226-95: "Fodder, mixed fodder, mixed fodder raw materials. Methods of determination of crude ash" and GOST R 55661-2013: "Solid mineral fuel, Ash content determination".

Water content was determined according to GOST R 57059-2016 "Fodder, mixed fodder, mixed



Fig. 1: Objects of the research.

fodder raw materials. Express method of moisture determination”.

Carbon content was determined using a Vario EL Cube elemental analyzer (Elementar Analysensysteme GmbH, Langenselbold, Germany). The CHNS analysis was based on the area of the chromatographic peaks of  $N_2$ ,  $CO_2$ ,  $H_2O$ , and  $SO_2$ .

### Char Production

To produce chars, the raw materials were dried to adjust the hydromodulus. Plant-based raw materials were additionally cut into 3-5 cm long sticks.

The prepared raw materials were loaded into a hydrothermal liquefaction reactor, with adjustable parameters for temperature and speed of rotation of the magnetic stirrer (Fig. 2). An anchor and distilled water were added. The hydromodule was 1:10. The process of hydrothermal liquefaction was conducted under the following conditions:

- Temperature: 260°C



Fig. 2: Reactor for hydrothermal liquefaction.

- Pressure: 5–6 MPa
- Duration: 20 min

After the hydrothermal liquefaction process, the reactor was cooled. The contents were filtered, and the reactor vessel and solid residue were washed with dichloromethane to ensure complete extraction of the oil. The char was then dried at 104°C for 2 h.

### Evaluation of Sorption Capacity

Sorption capacity was determined using methylene blue, following GOST 4453-74: “Active Absorbing Powder Charcoal. Specifications”. The iodine sorption capacity was measured by calculating the difference in iodine concentration in the solution before and after sorption (30 min) (Evsina 2012). The phenol sorption capacity was evaluated by

measuring the difference in phenol concentration after 5 h of sorption (Tukhvatullina et al. 2015).

Sorption of the above compounds is a standard method for evaluating sorbent properties. Sorption of iodine shows the adsorption capacity of the char. Sorption of methylene blue is characterised by the presence of mesopores on the surface of the char. Sorption of these compounds is an indirect indicator of porosity. Phenol sorption is used to evaluate the efficacy against organic compounds.

## RESULTS AND DISCUSSION

### Elemental Composition of Raw Materials

For the initial evaluation of the selected material, the elemental composition was analyzed. Since the target product of this study is char sorbents, the key element of interest

Table 1: Elemental composition of raw materials (dried).

Sample	Ash, %	Carbon, %	Hydrogen, %	Nitrogen, %	Sulphur, %	Oxygen, %	Moisture content, %
<i>Phragmites australis</i>	4.68±0.40	44.75±0.10	6.897±0.080	0.57±0.02	0.100±0.006	38.79±1.10	4.21±0.10
<i>Scirpus lacustris L.</i>	5.45±0.50	42.89±0.07	6.896±0.097	0.73±0.00	0.357±0.000	37.08±1.40	6.60±0.10
<i>Typha angustifolia L.</i>	5.18±0.50	43.93±0.06	6.757±0.085	0.80±0.03	0.221±0.007	37.21±2.10	5.90±0.10
<i>Miscanthus</i>	8.87±0.30	43.27±0.22	6.620±0.017	0.42±0.01	0.070±0.000	36.85±0.90	3.90±0.10
Sewage sludge	29.51±0.07	31.97±0.20	6.340±0.011	5.60±0.07	0.954±0.002	12.13±2.30	13.50±0.10
<i>Furcellaria</i>	19.51±0.01	33.90±0.16	6.277±0.000	4.77±0.01	3.631±0.001	24.81±0.60	7.10±0.10
Pine bark	2.43±0.20	52.08±0.09	7.133±0.011	0.33±0.07	0.073±0.008	30.65±0.70	7.30±0.10
Coffee waste	1.66±0.10	50.06±0.05	8.509±0.007	2.22±0.05	0.195±0.008	30.86±1.50	6.50±0.10
Apple waste	1.43±0.01	40.78±0.09	7.921±00.46	0.33±0.00	0.051±0.000	43.89±1.60	5.60±0.10
Cow manure	12.1±0.16	43.51±0.05	6.459±0.080	1.66±0.04	0.211±0.007	31.36±2.00	4.70±0.10
Wheat straw	8.52±0.10	44.2±0.33	6.112±0.070	0.79±0.07	0.019±0.016	34.76±±0.69	5.60±0.10

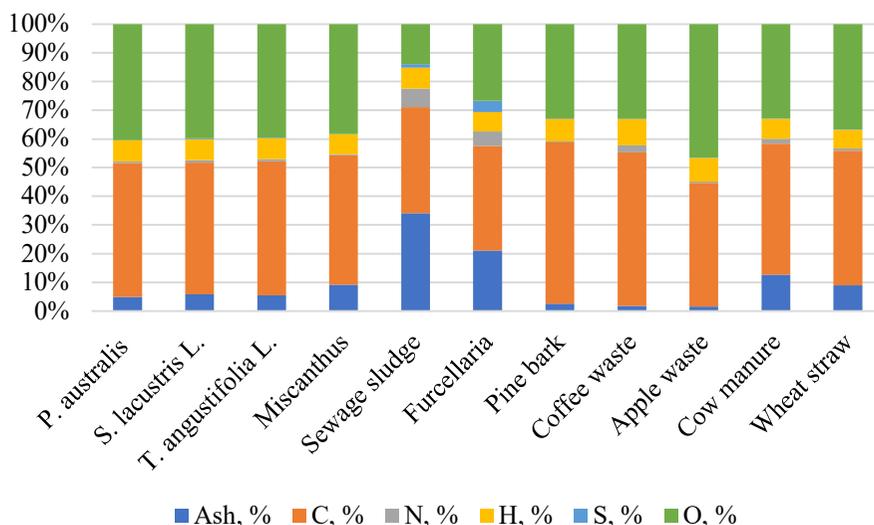


Fig. 3: Elemental composition of raw materials.

Table 2: Hydrochar yield.

Raw materials	Yield, %
Phragmites australis	39±2
Scirpus lacustris L.	31±1
Typha angustifolia L.	42±3
Miscanthus	44±2
Sewage sludge	32±2
Furcellaria	35±3
Pine bark	59±3
Coffee waste	36±2
Apple waste	31±1
Cow manure	44±2
Wheat straw	32±4

for the study is carbon. At high ash content, char has poor sorption properties (Nature Technology 2022); therefore,

the ash content of the selected materials should be low ash content. Table 1 summarizes the elemental composition of the dried raw materials.

For visual clarity, the elemental composition is presented in Fig. 3. Elemental composition of raw materials showed that the most promising raw materials for obtaining char sorbents are food waste, bark waste and aquatic vegetation. The highest carbon content was observed in pine bark (52%), making it the most suitable raw material for sorbent production.

### Characterization of Produced Chars

An important economic parameter in char production is the product yield. Table 2 shows the yield of chars obtained from different raw materials through hydrothermal liquefaction.

The average char yield across all raw materials was approximately 38%. The highest char yield was obtained

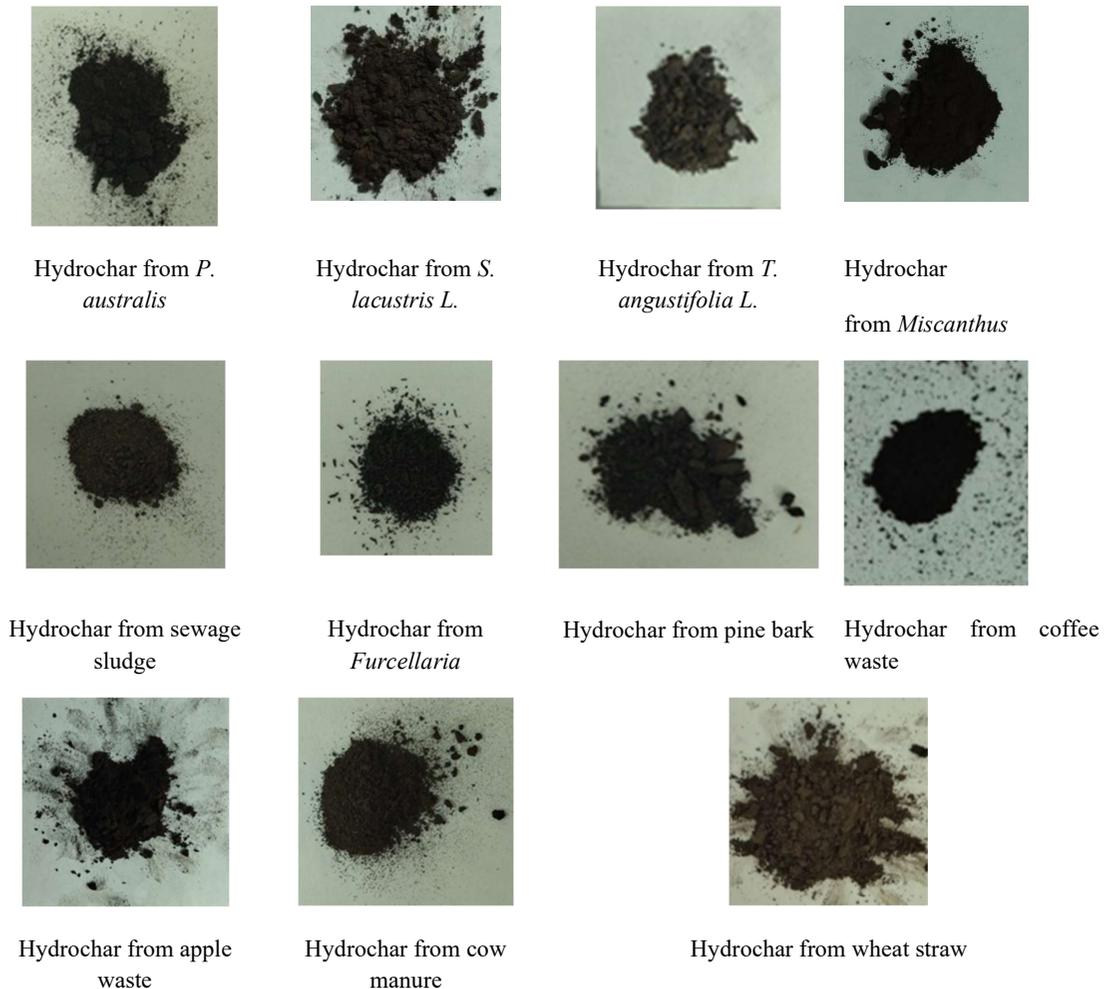


Fig. 4: Hydrochars.

Table 3: Elemental composition of hydrochars.

Material	Ash, %	Carbon, %	Hydrogen, %	Nitrogen, %	Sulphur, %	Oxygen, %
<i>Phragmites australis</i>	11.80±0.06	58.01±0.10	5.431±0.076	0.64±0.04	0.049±0.001	22.67±0.12
<i>Scirpus lacustris</i> L.	4.28±0.02	65.08±0.57	6.063±0.046	2.26±0.03	0.161±0.001	19.36±0.23
<i>Typha angustifolia</i> L.	6.54±0.09	59.00±0.05	6.632±0.046	3.21±0.01	0.216±0.001	21.80±0.17
Miscanthus	5.84±0.00	62.52±0.56	5.880±0.018	0.53±0.02	0.064±0.000	23.97±0.23
Sewage sludge	62.85±0.58	22.85±0.58	2.930±0.032	2.53±0.02	0.610±0.001	6.34±0.15
Furcellaria	33.99±2.71	40.45±0.80	4.034±0.037	4.01±0.01	3.373±0.004	11.54±0.16
Pine bark	3.14±0.50	63.68±0.07	5.021±0.035	0.60±0.04	0.043±0.000	24.82±0.24
Coffee waste	1.91±0.10	71.11±0.23	8.373±0.058	2.94±0.02	0.133±0.001	14.63±0.14
Apple waste	1.42±0.00	68.57±0.56	5.815±0.038	0.81±0.03	0.040±0.000	22.05±0.16
Cow manure	18.26±0.10	53.96±0.76	5.965±0.024	1.92±0.04	0.354±0.001	18.44±0.24
Wheat straw	7.30±0.04	61.98±0.44	5.731±0.043	1.29±0.07	0.023±0.028	23.68±0.62

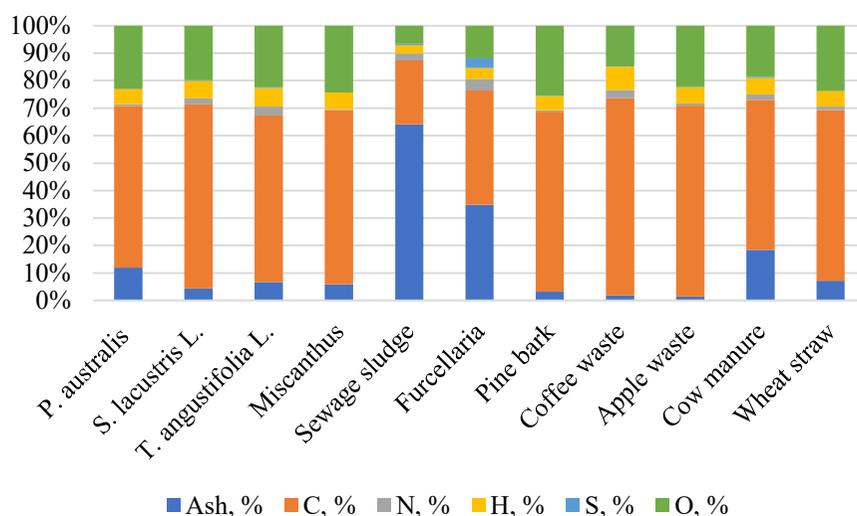


Fig. 5: Elemental composition of hydrochars.

from pine bark (59%), while the lowest yield was from *Typha angustifolia* L. (31%). Fig. 4 depicts the chars produced using the hydrothermal liquefaction method.

### Elemental Composition of Hydrochars

To assess the potential of using chars as sorbents, elemental analysis was performed on the produced hydrochars. Table 3 and Fig. 5 summarize the elemental composition of the hydrochars.

For all samples, except apple waste, miscanthus, and reed, the ash content increased after hydrothermal conversion. The carbon content of most samples increased, except for char derived from excess sludge, which showed reduced carbon content. Hydrochars produced from furcellaria and sewage sludge had carbon content below 50%, making them less suitable as sorbents. In contrast, chars derived from food waste and aquatic vegetation exhibited carbon content exceeding 60%, indicating high sorption potential.

### Sorption Capacity of Hydrochars

The primary objective of this study was to evaluate the potential of chars in purifying wastewater by sorbing contaminants. The sorption capacity of hydrochars for methylene blue, phenol, and iodine was assessed. The results are presented in Table 4 and Fig. 6.

The best values of methylene blue sorption were achieved using hydrochar from apple waste (238.7 mg.g<sup>-1</sup>), followed by coffee waste (171.0 mg.g<sup>-1</sup>), and wheat straw (100 mg.g<sup>-1</sup>). In contrast, *Typha angustifolia* L. char demonstrated the lowest sorption capacity for methylene blue (3.0 mg.g<sup>-1</sup>), making it the least effective sorbent.

Furcellaria (41.9 mg.g<sup>-1</sup>), coffee waste (32.2 mg.g<sup>-1</sup>), and *Typha angustifolia* L. (29.7 mg.g<sup>-1</sup>) hydrochars showed high sorption properties for iodine. Conversely, the lowest values of iodine sorption capacity are demonstrated by chars from bark waste (5.1 mg.g<sup>-1</sup>) and miscanthus (4.8 mg.g<sup>-1</sup>).

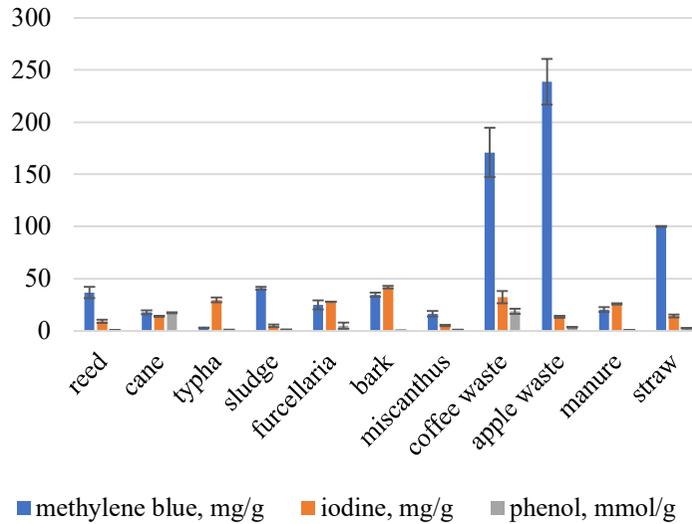


Fig. 6: Sorption capacity of hydrochars.

Table 4: Sorption capacity of hydrochars.

Material of hydrochar	Sorption capacity for methylene blue, mg.g <sup>-1</sup>	Iodine sorption capacity, mg.g <sup>-1</sup>	Sorption capacity for phenol, mg.g <sup>-1</sup>
<i>Phragmites australis</i>	36.7±5.3	9.1±1.5	0.5±0.1
<i>Scirpus lacustris L.</i>	17.8±2.0	13.8±0.5	17.3±0.6
<i>Typha angustifolia L.</i>	3.0±0.1	29.7±2.4	1.0±0.1
<i>Miscanthus</i>	40.8±1.5	4.8±1.3	5.0±3.0
Sewage sludge	24.9±4.3	27.7±0.2	0.1±0.0
<i>Furcellaria</i>	34.6±2.0	41.9±1.2	1.0±0.1
Pine bark	16.4±2.7	5.1±0.1	1.0±0.1
Coffee waste	171.0±23.7	32.2±5.9	18.7±2.4
Apple waste	238.7±21.9	13.4±0.9	3.4±0.1
Cow manure	20.4±2.3	25.6±0.6	0.7±0.1
Wheat straw	100.0±0.4	14.2±1.3	2.4±0.1

The highest value of sorption capacity for phenol was achieved in chars obtained from reed (17.3 mg.g<sup>-1</sup>) and coffee waste (14.9 mg.g<sup>-1</sup>). While the chars derived from sludge (0.1 mg.g<sup>-1</sup>) showed the lowest sorption capacity for phenol, indicating poor performance for this contaminant.

### Relationship Between Carbon Content and Sorption Capacity

According to the obtained data, the regular correlation between carbon content in chars and their phenol sorption is traced. Fig. 7 shows the dependence of the sorption capacity of chars on their carbon content. The determination coefficient is equal to 0.9971. The model is correct. For objectivity of the results, only chars derived from aquatic vegetation were included in the figure to ensure the comparison of similar raw materials.

The relationship between carbon content and phenol sorption is exponential – with increasing carbon content in the raw material, a sharp increase in phenol sorption capacity is observed. The sorption capacity for phenol reaches 10 mg.g<sup>-1</sup> at a carbon content of 64%, which is several tens of times higher than the sorption capacity at 58-60% carbon content. This suggests that chars with a higher carbon fraction exhibit superior adsorption efficiency for phenolic compounds.

A similar trend was reported in the study by Anisuzzaman et al. (2015), which studied the sorption of 2,4-dichlorophenol (a phenolic compound). Their study demonstrated that as the carbon content of the sorbent increased, the degree of pollutant removal also increased. This is most likely due to the presence of CEC bonds on the surface of the char.

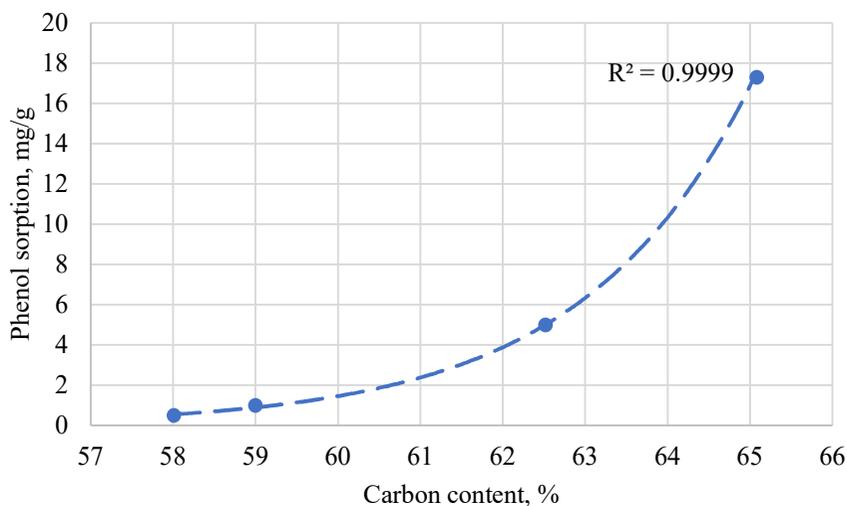


Fig. 7: Relationship between carbon content and phenol sorption.

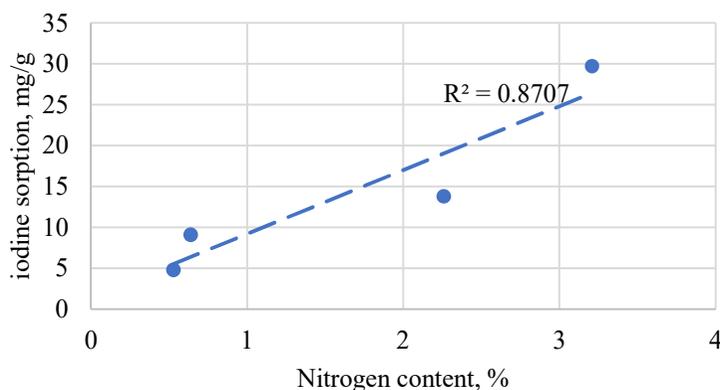


Fig. 8: Relationship between nitrogen content and iodine sorption.

### Iodine Sorption and Its Dependence on Nitrogen Content

No clear correlation was observed between carbon content and the sorption capacity for methylene blue or iodine. This is likely due to the chemisorption mechanism involved in the adsorption of these substances, which is influenced by the presence of functional groups rather than carbon content alone. The study by Aktas et al. (2024) investigated the surface of carbon sorbents using FT-IR analysis and identified the presence of carboxyl, hydroxyl, ketone, and nitro groups, which can enhance the sorption of certain substances. Chemisorption occurs mainly through a donor-acceptor mechanism. Hydrogen donors include carboxyl and hydroxyl groups. Hydrogen acceptors include keto group, nitro group and hydroxyl group (the latter acts as both acceptor and donor).

Iodine chemisorption occurs due to functional donor groups (Krivosheev et al. 2016). These include carboxyl

and hydroxyl groups and amino groups. Iodine may also be absorbed by metals (e.g., silver) and unsaturated bonds. Fig. 8 shows that as the nitrogen content increases, the iodine sorption capacity increases. The dependence is linear, i.e., the sorption capacity is directly proportional to the nitrogen content in the char. The determination coefficient is equal to 0,8707. The resulting model satisfies the real data. In the case of these chars, it is assumed that iodine sorption occurs primarily through nitro groups. This means that the main type of iodine sorption is chemisorption.

The produced sorbents actually have a poorly developed porous structure. This was proved in the previous work (Muravieva et al. 2025). The value of specific surface area by BET did not exceed  $20 \text{ m}^2 \cdot \text{g}^{-1}$  even after activation, and the total pore volume did not exceed  $0.2 \text{ cm}^3 \cdot \text{g}^{-1}$ . This is much lower than that of porous materials. However, high sorption values for different substances were observed for the obtained sorbents. The only explanation for this phenomenon is chemisorption.

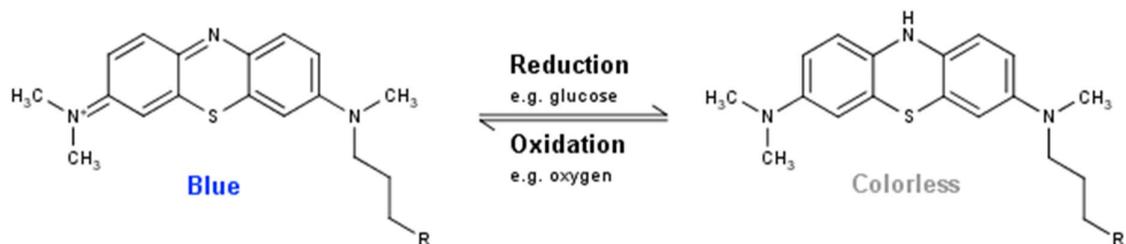


Fig. 9: Mechanism of methylene blue reduction.

### Methylene Blue Sorption Mechanism

Balykin et al. (2004) studied the sorption process of methylene blue. The authors proved that the main sorption of methylene blue is due to chemisorption by a donor-acceptor mechanism, i.e., the main type of sorption of methylene blue is chemisorption. In addition, the authors also concluded that during the sorption process, methylene blue undergoes reduction to its leucoform (colorless form) on the surface of the sorbent. Fig. 9 shows the mechanism of reduction of methylene blue to its colorless form. It can be inferred that hydroxyl groups play a significant role in the reduction of methylene blue from solution.

### CONCLUSIONS

A method was proposed for processing wastes from various industries and other types of biomass to produce carbon sorbents for wastewater treatment. The key findings of the study are as follows:

1. The elemental composition analysis of raw materials revealed that bark and coffee waste (with carbon content more than 50%) are the most suitable for producing char sorbents. In contrast, the least amount of carbon is found in excess sludge and furcellaria (about 30%), making them less effective for sorbent production. For elemental analysis, the raw material was ground, dried the removal of free moisture (some water stayed in the raw material).
2. Following hydrothermal liquefaction, the highest carbon content was achieved in chars derived from apple waste (71%) and coffee waste (69%), while excess sludge char exhibited the lowest carbon content (32%). Notably, the carbon content in excess sludge decreased after hydrothermal processing.
3. Chars from coffee waste ( $171 \text{ mg.g}^{-1}$ ), apple waste ( $239 \text{ mg.g}^{-1}$ ), and straw ( $100 \text{ mg.g}^{-1}$ ) demonstrated the best sorption capacity for methylene blue, while *Typha angustifolia* L. char showed the lowest sorption ( $3 \text{ mg.g}^{-1}$ ).
4. Furcellaria char exhibited the highest iodine sorption

capacity ( $42 \text{ mg.g}^{-1}$ ), whereas bark and miscanthus chars had the lowest ( $5 \text{ mg.g}^{-1}$ ).

5. Phenol sorption was generally low, with the best results obtained from coffee waste char ( $18.7 \text{ mg.g}^{-1}$ ) and reed char ( $17.3 \text{ mg.g}^{-1}$ ). The worst phenol sorption was observed in excess sludge char ( $0.1 \text{ mg.g}^{-1}$ ).
6. Phenol sorption showed a direct correlation with carbon content. The sorption of the other substances studied also depends on the carbon content, but the functional groups on the surface of the sorbent have a significant influence.
7. According to the results, the best raw material for the production of char sorbents is coffee waste. It is characterized by high carbon content (50.06%), low ash content (1.66%). The char yield was 36%, which is higher than that of some raw materials. Sorption capacity for methylene blue was  $171.0 \text{ mg.g}^{-1}$ , phenol  $18.7 \text{ mg.g}^{-1}$ , iodine  $32.2 \text{ mg.g}^{-1}$ . The sorption values are high and exceed the values of these indicators for other samples.

Based on the experimental results, it can be noted that the chemical composition of the feedstock influences the properties of the produced sorbents. High carbon content (mainly in the form of structural polysaccharides) promotes high sorption properties. First of all, it affects the sorption of phenol (probably due to the presence of unsaturated carbon-carbon bonds). The presence of nitrogen on the charcoal surface promotes better sorption of iodine (due to nitrogen-containing groups).

The assumed mechanism of coal sorption is chemisorption. This fact requires further work on the activation of sorbents and the search for their further application in wastewater treatment.

Overall, the produced char sorbents demonstrated moderate sorption properties. However, with further activation, they can be used for the treatment of wastewater containing dyes, halogens, and other pollutants.

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