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PHYSICOCHEMICAL CHARACTERISTICS OF ACTIVATED CARBONS FROM SAWDUST AND THEIR APPLICATION IN WATER PURIFICATION

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This paper investigates the production of activated carbon adsorbents based on wood sawdust (WSD) via carbonization and chemical activation with potassium hydroxide, and evaluates their potential for wastewater treatment. The aim of the study was to investigate the influence of the sawdust/KOH mass ratio and heat treatment conditions on the formation of the porous structure, physicochemical, and adsorption characteristics of the resulting materials. Chemical activation at 900°C was found to significantly enhance the micro- and mesoporous structure and increase the BET specific surface area from 38.9 to 776 m^2/g, with the total pore volume increasing to 0.385 cm^3/g. Raman spectroscopy data showed that the degree of graphitization of the activated carbons ranged from 19.3 to 27.4%, indicating the formation of a more ordered carbon matrix. SEM and elemental analysis results confirmed the formation of a developed porous structure and an increase in carbon content to 99.6%. Practical testing of activated carbon based on sawdust impregnated with KOH in a ratio of WSD/KOH 1:1 (AC-2) during the treatment of real wastewater showed high efficiency in removing organic pollutants, petroleum products and surfactants (up to 90–94%). These results confirm the potential of using activated carbons based on wood waste in water treatment and environmental protection technologies.

Keywords: adsorbent, waste, wood sawdust, activation, specific surface area.

АҒАШ ҮГІНДІЛЕРІНЕН АЛЫНҒАН БЕЛСЕНДІРІЛГЕН КӨМІРЛЕРДІҢ ФИЗИКА-ХИМИЯЛЫҚ СИПАТТАМАЛАРЫ ЖӘНЕ ОЛАРДЫ СУДЫ ТАЗАРТУДА ҚОЛДАНУ

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Бұл мақалада ағаш үгінділерге (АҮ) негізделген белсендірілген көміртекті адсорбенттерді өндіруді калий гидроксидімен көміртектеу және химиялық активтендіру арқылы зерттейді және олардың ағынды суларды тазарту әлеуетін бағалайды. Зерттеудің мақсаты үгінді/КОН массалық қатынасы мен термиялық өңдеу жағдайларының алынған материалдардың кеуекті құрылымының, физика-химиялық және адсорбциялық сипаттамаларының қалыптасуына әсерін зерттеу болды.900°C температурадағы химиялық активтендіру микро- және мезокеуекті құрылымды айтарлықтай жақсартып, БЭТ меншікті бетінің ауданын 38,9-дан 776 $м^2/г$-ға дейін арттыратыны, ал жалпы кеуек

көлемі 0,385 см³/г-ға дейін артатыны анықталды. Раман спектроскопиясының деректері белсендірілген көміртектердегі графиттену дәрежесі 19,3-тен 27,4%-ға дейін өзгергенін көрсетті, бұл реттелген көміртекті матрицаның пайда болуын көрсетеді. СЭМ және элементтік талдау нәтижелері дамыған кеуекті құрылымның пайда болғанын және көміртегі мөлшерінің 99,6%-ға дейін артқанын растады. Нақты ағынды суларды тазарту кезінде АУ/КОН 1:1 (АС-2) қатынасында КОН сіңірілген үгінді негізіндегі белсендірілген көмірді практикалық сынақтан өткізу органикалық ластаушы заттарды, мұнай өнімдерін және беттік белсенді заттарды (90–94%-ға дейін) жоюда жоғары тиімділікті көрсетті. Бұл нәтижелер ағаш қалдықтарына негізделген белсендірілген көмірлерді суды тазарту және қоршаған ортаны қорғау технологияларында қолдану мүмкіндігін растайды.

Түйін сөздер: адсорбент, қалдық, ағаш үгіндісі, активация, меншікті беттік аудан.

ФИЗИКО-ХИМИЧЕСКИЕ ХАРАКТЕРИСТИКИ АКТИВИРОВАННЫХ УГЛЕЙ ИЗ ДРЕВЕСНЫХ ОПИЛОК И ИХ ПРИМЕНЕНИЕ В ВОДООЧИСТКЕ

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В данной работе исследовано получение активированных углеродных адсорбентов на основе древесных опилок (ДО) методом карбонизации и химической активации гидроксидом калия, а также оценена возможность их применения для очистки сточных вод. Целью исследования являлось изучение влияния массового соотношения древесные опилки/КОН и условий термообработки на формирование пористой структуры, физико-химические и адсорбционные характеристики полученных материалов. Установлено, что химическая активация при температуре 900 °C приводит к существенному развитию микро- и мезопористой структуры и росту удельной поверхности по БЭТ с 38,9 до 776 м²/г, при увеличении общего объёма пор до 0,385 см³/г. По данным Рамановской спектроскопии степень графитизации активированных углей составляет 19,3–27,4 %, что свидетельствует о формировании более упорядоченной углеродной матрицы. Результаты СЭМ и элементного анализа подтвердили образование развитой пористой структуры и повышение содержания углерода до 99,6 %. Практическая апробация активированного угля на основе древесных опилок, пропитанного КОН в соотношении ДО/КОН 1:1 (АС-2), при очистке реальных сточных вод показала высокую эффективность удаления органических загрязнителей, нефтепродуктов и поверхностно-активных веществ (до 90–94 %). Полученные результаты подтверждают перспективность использования активированных углей на основе древесных отходов в технологиях водоочистки и охраны окружающей среды.

Ключевые слова: адсорбент, отход, древесные опилки, активация, удельная поверхность.

Introduction. Removing persistent and toxic contaminants from atmospheric and wastewater emissions is one of the most pressing environmental challenges [1–5]. Increasing anthropogenic impacts necessitate the development of highly effective methods for extracting harmful substances from gaseous and liquid media [4,5]. Among the various approaches, adsorption technology stands out for its versatility, enabling significant extraction and selectivity for a wide range of pollutants [2-5].

Carbon adsorbents obtained by activation are characterized by a large surface area and a complex

pore hierarchy, which explains their widespread use in purification processes [1-4]. Various forms of biomass, particularly wood waste (sawdust), are promising and cost-effective raw materials for the synthesis of such materials, as they are an inexpensive and renewable resource [1, 3, 4].

The adsorption process involves the concentration of adsorbate molecules at the phase boundary. Depending on the type of forces responsible for this retention, a distinction is made between physical sorption (due to van der Waals forces) and chemisorption (associated with the formation of chemical bonds) [6–10]. The branched porous system of activated carbons provides high specific surface areas, which is a key factor in the efficient absorption of particles of various sizes [6–9]. The presence of specific functional groups on the surface can significantly enhance the binding of certain contaminants through chemical interactions, which is reflected in the kinetic parameters and the type of adsorption isotherms [7, 8]. For the mathematical description of equilibrium in such systems, the Langmuir, Freundlich, and BET models are widely used, allowing for a quantitative assessment of the capacity and binding energy of the adsorbent [8, 9].

The technology for producing carbon adsorbents from biomass includes a pyrolysis (carbonization) stage followed by chemical or physical treatment to develop porosity (Fig.1). Chemical activation with potassium hydroxide (KOH) is recognized as one of the most effective methods for the targeted creation of a microporous structure with a high specific surface area [6, 8, 9]. During this stage, thermal decomposition of the main components of wood (cellulose and lignin) occurs, which initiates the formation of micropores and a significant increase in the internal surface area of the material [6-9]. Wood sawdust has proven itself as a feedstock for the production of adsorbents demonstrating high capacity and promising for use in water and gas purification systems [6-10].



Fig.1 - Production of activated carbon from biomass

The degree of processing, determined by the KOH/biomass mass ratio, has a significant impact on the morphology and performance characteristics of the final product, such as specific surface area, microporous volume, yield, and mineral content (ash content) [6-10]. Increasing the proportion of the activating agent intensifies its interaction with the carbon framework, promoting the formation of a developed pore network and, as a consequence, an increase in the specific surface area [7-9]. Thus, optimization of this parameter is of paramount importance for the creation of adsorbents with improved sorption properties and stability under conditions of repeated use [6-10].

Carbon materials obtained from sawdust by KOH activation are effectively used to remove a variety of organic and inorganic contaminants from aqueous solutions, including heavy metal ions, synthetic dyes, and other dissolved compounds [10-15]. Chemical activation not only increases porosity but also promotes the formation of functional groups on the surface capable of specific interaction with target contaminants [6, 10, 14]. The use of such adsorbents improves water quality, and their resistance to degradation allows for multiple sorption-desorption (regeneration) cycles [16-18].

Materials and methods. Experimental studies were carried out at the Institute of Coal Chemistry and Technology (Astana). Wood sawdust was used as the starting material. The characteristics of the

feedstock (in mass percent): A^d - 17.49 W^r - 68.34; V^d - 9.61 C^{td} - 61.96 O^{td} - 38.04. The main objective of the study was to obtain activated carbon sorbents based on biomass by carbonization and chemical activation, as well as a comprehensive study of their physicochemical and adsorption characteristics for subsequent use in wastewater treatment. The scheme of wood sawdust processing by the activation method is shown in Figure 2.

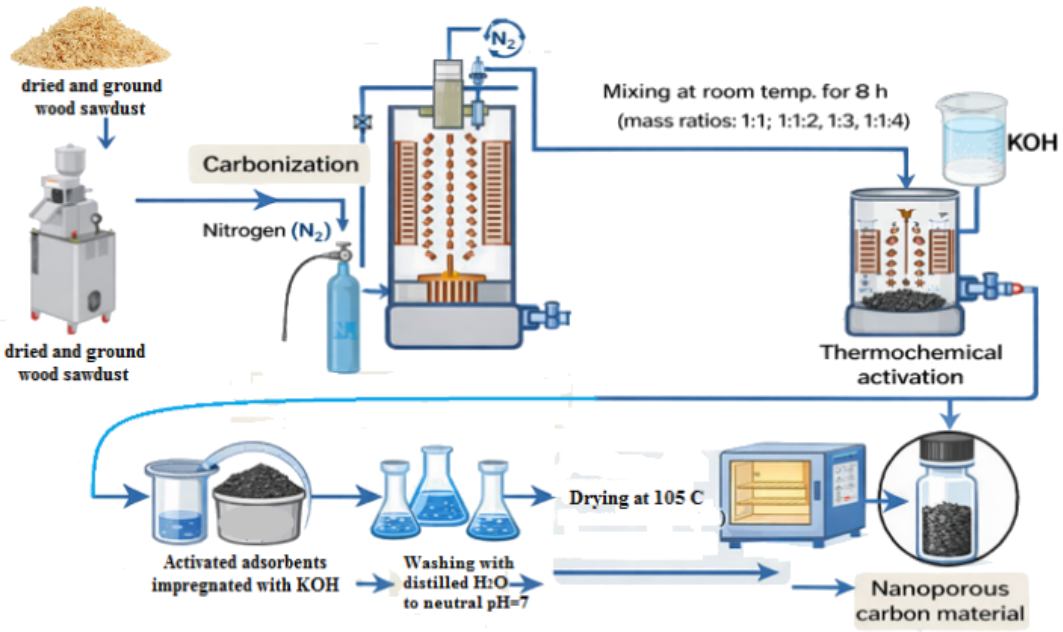


Figure 2 - Sawdust processing diagram

Wood sawdust was pre-crushed and dried to a constant weight. Carbonization was carried out in a BR-12NRT rotary tube furnace in a nitrogen atmosphere at a temperature of 550 °C for 60 minutes at a heating rate of 5 °C/min. After carbonization, the resulting material was thoroughly mixed with potassium hydroxide (KOH) powder in weight ratios of 1:1, 1:2, 1:3, and 1:4 and kept at room temperature for 8 hours. Next, thermochemical activation was carried out in a nitrogen atmosphere up to 900 °C at a heating rate of 5 °C/min with a 1-hour hold at 900 °C. Physical activation with water vapor was carried out at a temperature of 700–900 °C. After activation was complete, the samples were washed with distilled water to a neutral pH of 7 to remove residual reagents, then dried at 105 °C to a constant weight. As a result, a carbon material with a developed nanoporous structure was obtained.

The study utilized activated carbon (AC) synthesis methods, as well as a set of techniques for assessing their physicochemical and adsorption properties. Specifically, moisture content, ash content, volatile matter, aqueous extract pH, bulk density, methyl orange adsorption activity, total pore volume using the water absorption method, elemental analysis, and specific surface area determination using the BET method were determined. The potential of AC for wastewater treatment was also assessed.

The following laboratory equipment was used to perform the experiments: a BR-12NRT rotary tube furnace, a Thermostep Eltra thermogravimetric analyzer, a Chromas GC gas chromatograph, a Shaker-Incubator ES-20/60 incubator-shaker, a PD-303 spectrophotometer, a pH meter, a centrifuge, an ultrasonic bath, and others. Raman spectroscopy and Fourier transform infrared spectroscopy (FTIR) were used to study the chemical structure and degree of ordering of the carbon matrix, which made it possible to identify the types of carbon bonds, surface functional groups, and the degree

of graphitization of the materials. The elemental composition, morphology, and particle size of the samples were analyzed using energy-dispersive X-ray spectroscopy (EDX) on a Quanta 3D 200i scanning electron microscope.

In this work, the following abbreviations were used to designate the studied samples of activated carbons: AC-1: activated carbon based on wood sawdust, 900°C; AC-2: activated carbon based on wood sawdust impregnated with KOH, WSD/KOH=1:1, 900°C; AC-3: activated carbon based on wood sawdust impregnated with KOH, WSD/KOH=1:2, 900°C; AC-4: activated carbon based on wood sawdust impregnated with KOH, WSD/KOH=1:3, 900°C; AC-5: activated carbon based on wood sawdust impregnated with KOH, WSD/KOH=1:4, 900°C.

Results and discussion. During biomass carbonization, volatile matter is intensively removed, leading to the formation of a primary porous structure and an increase in the carbon content, resulting in biochar. Subsequent activation, carried out by physical or chemical methods, promotes further development and deepening of the material' s porous structure. The resulting activated carbon is characterized by a high specific surface area (BET) and significant adsorption capacity. Table 1 presents the material balance for the sawdust activation process.

Table 1 - Material balance of the wood sawdust activation process

№	Name of adsorbents	Incoming products		Outgoing products		
		Raw materials, %	Water, %	Porous carbon, %	Liquid product, %	Gas, %
1	Carbonization of wood sawdust at 550 °C	44.44	55.56	53.15	25.50	21.35
2	AC-1	44.44	55.56	55.48	24.12	20.40
3	AC-2	44.44	55.56	41.45	26.00	32.55
4	AC-3	54.55	45.45	46.98	29.50	23.52
5	AC-4	54.55	45.45	39.92	33.84	26.24
6	AC-5	54.55	45.45	37.69	33.50	2.81

A material balance of the process showed that the sawdust carbonization stage produces porous carbon with a yield of approximately 53%, with a significant portion of the mass being converted into liquid and gaseous products. For the AC-1 sample, obtained without a chemical activator, a slight increase in the yield of the solid product was observed, which is due to the stabilization of the carbon structure during high-temperature treatment.

The use of KOH as an activating agent (AC-2–AC-5) leads to a decrease in the yield of porous carbon and an increase in the proportion of liquid and gaseous products. With an increase in the sawdust/KOH mass ratio, the processes of chemical activation and gasification of the carbon matrix intensify. This promotes the development of the porous structure of the activated carbon, but is accompanied by a decrease in the yield of the solid product. The composition of the gas released during the activation of adsorbents is presented in Table 2.

The gas phase during the carbonization and activation of sawdust is predominantly H_2 and N_2. With increasing temperature and the use of KOH, the content of CO, CO_2, and CH_4 increases, indicating intensification of gasification processes and chemical etching of the carbon

matrix. These changes confirm the development of the porous structure of activated carbons during high-temperature activation. Table 3 shows the physicochemical properties of the adsorbents.

Table 2 - Composition of the gas released during the activation of adsorbents

№	Temperature	Concentration of gases released during activation, %					
		H2	O2	N2	CO2	CO	CH4
Carbonization of wood sawdust at 550 °C							
1	200	34.65	18.96	46.39	-	-	-
2	300	37.49	11.66	50.85	-	-	-
3	400	29.89	12.52	50.10	5.21	2.28	-
4	500	31.32	11.74	49.60	5.63	1.71	-
5	600	35.84	11.65	49.78	2.67	0.06	-
6	700	34.65	18.96	46.39	-	-	-
7	800	37.49	11.66	50.85	-	-	-
8	900	29.89	12.52	50.10	5.21	2.28	-
AC-1							
1	200	32.39	18.86	48.75	-	-	-
2	300	19.37	7.69	72.94	-	-	-
3	400	29.11	19.52	51.34	0.03	-	-
4	500	27.16	18.95	51.04	1.49	-	1.36
5	600	26.85	19.42	52.05	0.71	0.24	0.73
6	700	32.59	15.89	46.92	0.83	2.51	1.26
7	800	48.06	12.36	32.03	0.97	5.05	1.53
8	900	46.82	12.27	35.44	0.63	4.74	0.73
AC-2							
1	200	23.21	21.21	55.45	0.13	-	-
2	300	25.53	19.72	54.23	0.58	-	-
3	400	29.31	14.03	55.71	0.95	-	-
4	500	31.25	15.65	52.77	0.33	-	-
5	600	32.62	18.50	55.75	0.30	1.63	0.12
6	700	25.84	16.28	55.38	0.40	2.09	0.09
7	800	27.45	14.08	53.82	1.15	2.15	1.35
8	900	26.78	18.52	52.31	0.87	1.52	-
AC-3							
1	200	20.44	25.11	54.45	-	-	-

2	300	25.41	25.85	48.74	-	-	-
3	400	39.18	16.03	44.73	0.06	-	-
4	500	32.10	18.84	48.20	0.65	-	0.21
5	600	28.23	15.04	54.81	0.84	-	1.08
6	700	32.03	12.36	48.06	0.97	5.05	1.53
7	800	33.26	12.65	47.27	0.86	4.98	1.84
8	900	35.54	12.27	46.82	0.63	4.74	-
AC-4							
1	200	29.86	19.63	50.51	-	-	-
2	300	15.33	20.30	64.37	-	-	-
3	400	22.02	19.84	58.14	-	-	-
4	500	19.78	20.65	56.36	0.05	3.16	-
5	600	26.14	20.52	53.28	0.06	-	-
6	700	22.92	18.97	49.16	8.95	-	-
7	800	28.52	20.06	45.51	5.09	0.61	0.21
8	900	27.48	21.33	49.08	1.54	0.30	0.27
AC-5							
1	200	32.81	18.61	48.03	0.55	-	-
2	300	32.44	17.24	50.32	-	-	-
3	400	31.32	19.18	49.51	0.08	-	-
4	500	31.14	19.41	49.19	0.26	-	-
5	600	31.74	19.00	49.15	0.11	-	-
6	700	46.14	11.49	33.01	2.57	3.02	6.77
7	800	29.21	19.23	48.40	1.17	0.42	1.57
8	900	33.46	16.44	42.60	2.46	0.58	4.46

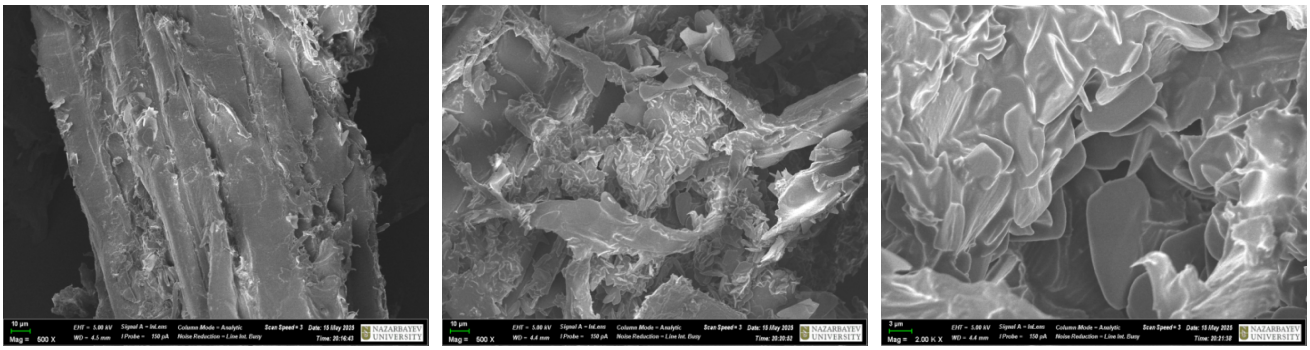
Table 3 - Physicochemical properties of adsorbents

Name of the adsorbent	**W^rt,%**	**A^r,%**	**V^d, %**	**VΣ (water), cm^3/g**	**rbulk, g/cm^3**	**pHa-queous extract**	***Am.o.*, mg/g**	**Am.b., mg/g**	**Aiodine, %**	**C, %**	**S, %**
AC-1	11.6485	10.6394	39.8985	1.34	0.36	6.42	20	55.5	33.02	35.6849	0.1289
AC-2	14.9856	17.4080	29.5104	0.47	0.43	8.13	16	43.5	36.83	49.6151	0.5081
AC-3	47.2916	9.7137	30.1872	0.55	0.39	7.94	16	51.5	35.56	48.552	0.4754
AC-4	27.0063	52.9835	37.1542	0.93	0.33	7.68	17	46.5	39.37	49.7723	0.5592
AC-5	40.7749	11.6485	25.9925	0.67	0.35	7.25	19	42.5	43.18	49.7936	0.5460

Sample AC-1, obtained without chemical activation, is characterized by a low BET specific surface area (38.9 m²/g) and comparatively low iodine adsorption activity (33.0%), indicating a poorly developed porous structure. The addition of KOH leads to a sharp increase in porosity and adsorption properties: for AC-2 and AC-3, the specific surface area increases to 390.22 and 314.36 m²/g, respectively, and the carbon content rises to 49.6 and 48.6%.

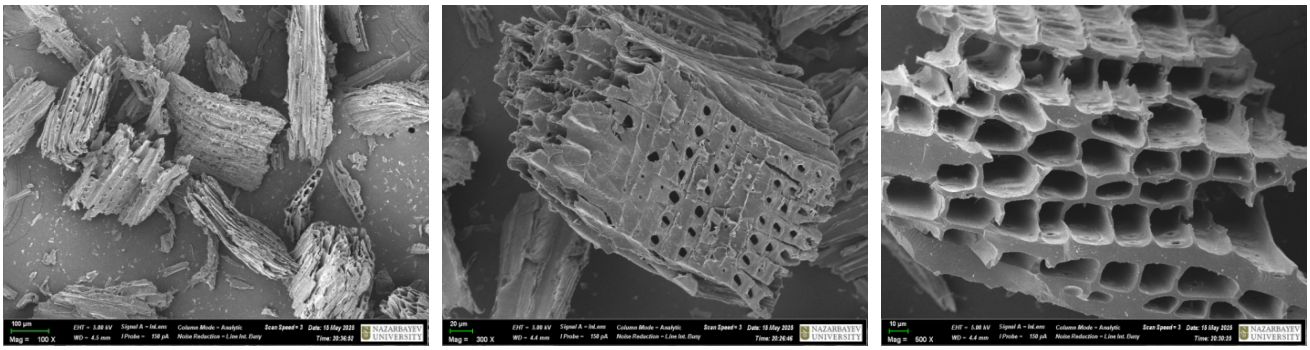
The maximum adsorption characteristics are observed for sample AC-5, for which S_{BET} reaches 776.0 m²/g and iodine adsorption activity is 43.2%, which is due to the intense chemical etching of the carbon matrix with a high KOH content. Moreover, the pH of the aqueous extracts of all samples is in the slightly alkaline-neutral range (6.4–8.1), confirming the practical application of the resulting adsorbents for water purification.

Figure 3 shows an SEM image of the original sawdust before processing. The natural structure of the wood is visible, with dense, relatively smooth surfaces and fragments of cell walls. The pores are not yet open, and the texture is more solid and compact. This morphology is characteristic of unprocessed biomaterial, which preserves the natural structure of the cellulose-lignin complex, providing mechanical strength and low porosity to the material.



a **b** **c**

Fig.3 - Micrograph of the original sawdust: a,b-x500; c-x2 000



a **b** **c**

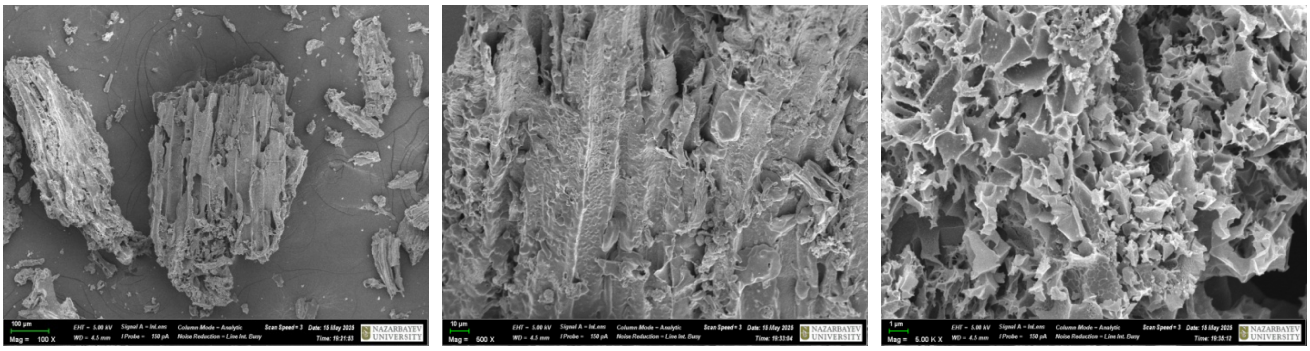
Fig.4 - SEM image of the adsorbent AC-1: a-x100; b-x300; c-x500

Figure 4 shows an SEM image of activated sawdust obtained after alkaline treatment and thermal activation. Compared to the original material (Fig.3), a significant change in surface morphology is observed: the structure becomes loose, with a distinct system of pores of varying sizes. The appearance of micropores and mesopores indicates the destruction and combustion of the

organic matrix under the action of the activator, which contributes to an increase in the specific surface area. The surface acquires a spongy, heterogeneous structure characteristic of carbon adsorbents, confirming the successful formation of a developed porous network during the activation process.

Figure 4 shows large, regular, honeycomb-like cellular channels. These are the vascular elements of the wood, which become clearly visible after activation. Activation removes some organic matter and opens the pores, increasing the specific surface area. The porous structure creates favorable conditions for adsorption.

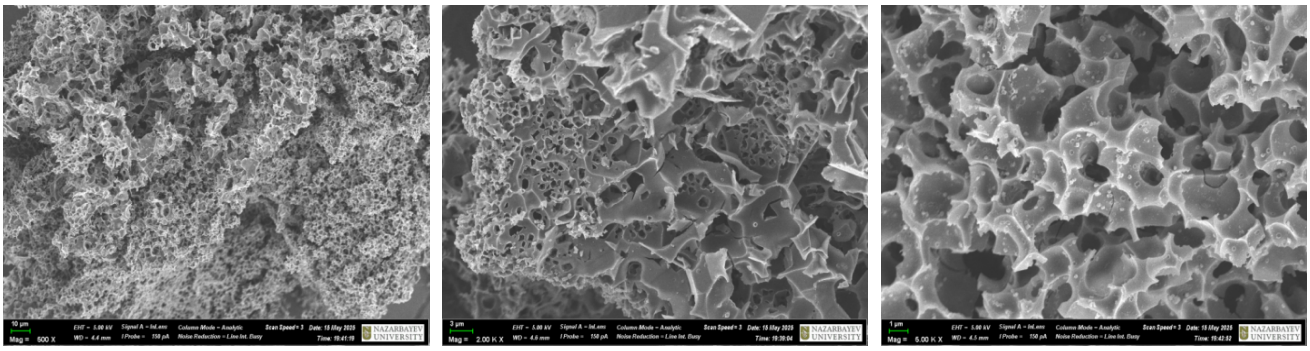
This structural modification increases the specific surface area and makes active sorption sites more accessible, significantly enhancing the adsorption properties of the material. Thus, activation of rice husk results in the formation of a structurally developed porous adsorbent, promising for use in water and gas purification processes.



a **b** **c**

Fig.5 - SEM image of the adsorbent AC-2: a-x100; b-x500; c-x5 000

When sawdust is treated with potassium hydroxide in a 1:1 ratio, intense etching of the walls and the formation of micro- and mesopores occurs. As a result, the activated material acquires a well-developed surface area and becomes a highly porous carbon adsorbent (Figure 5).

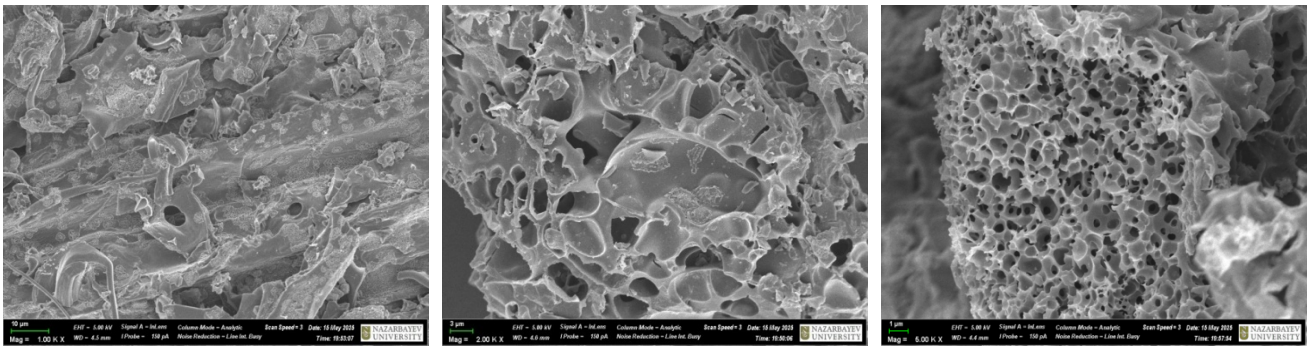


a **b** **c**

Fig.6 - SEM image of the adsorbent AC-3: a-x500; b-x2 000; c-x5 000

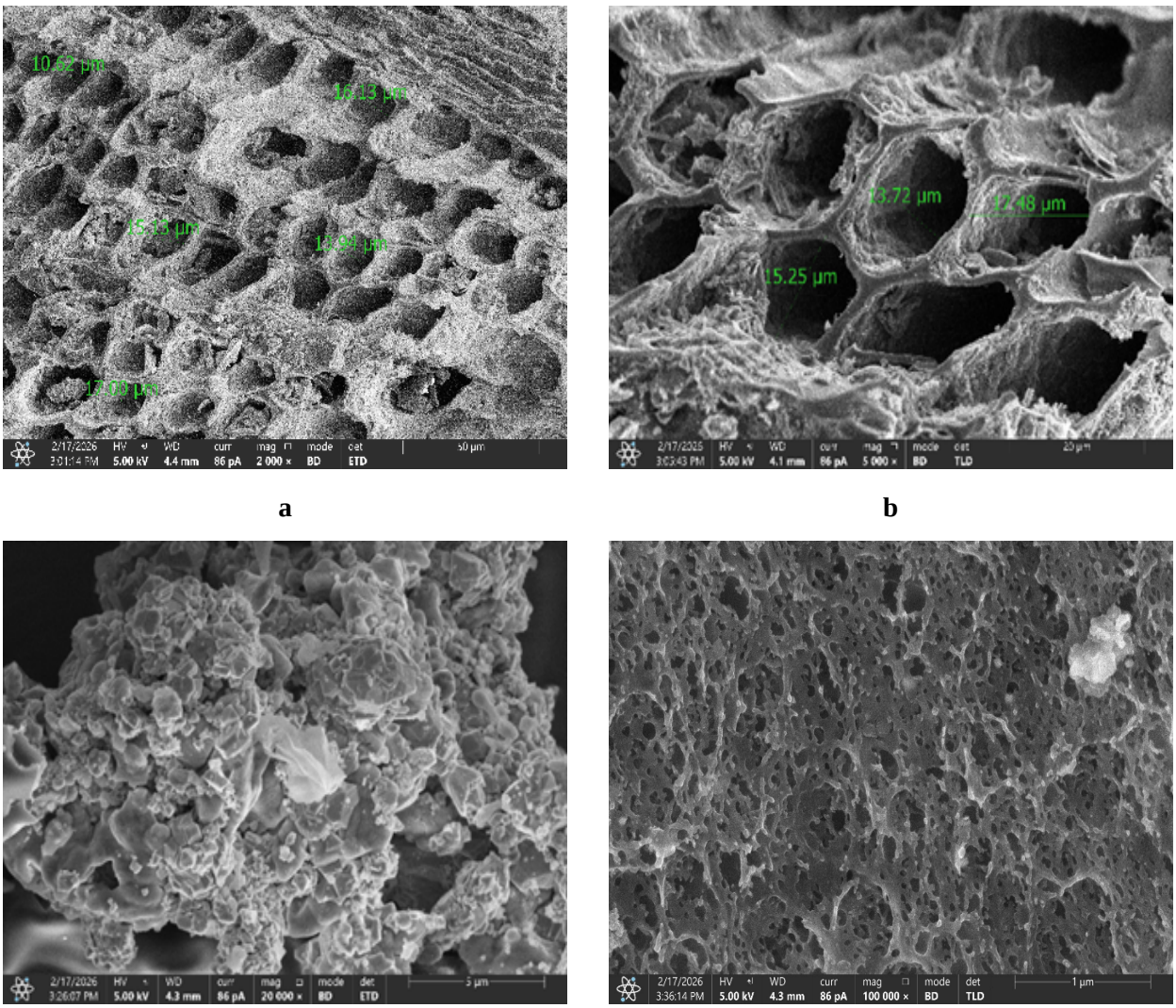
The SEM image reveals a highly developed porous structure. The surface is characterized by a large number of damaged areas and through pores, indicating intensive exposure to the activator. The material appears looser, with numerous micro- and mesopores, which contributes to an increased

specific surface area and enhanced adsorption capacity. However, excessive activation can lead to partial destruction of the matrix (Figure 6).



a **b** **c**

Fig.7 - SEM image of the adsorbent AC-4: a-x1 000; b-x2 000; c-x5 000



a **b**

c **d**

Fig.8 - SEM image of the adsorbent AC-5: a-x2 000; b-x5 000; c-x20 000; d-x100 000

The overall structure retains a more coherent framework compared to variant 1/2. The pores are more evenly distributed, with both small and medium pores visible, but their number is smaller. The surface is less disrupted, indicating a gentler effect of the activator (Figure 7).

Figure 8 shows SEM images of the AC-5 adsorbent at various magnifications. The material is characterized by a developed porous structure with a system of interconnected pores and pronounced surface roughness. Hierarchical porosity is observed, including macro- and mesopores, as well as small surface defects formed during chemical activation. This morphology ensures efficient mass transfer and adsorbate access to active sites. SEM analysis confirms that the AC-5 adsorbent has a developed porous architecture with a high degree of structural heterogeneity, which, combined with an increased degree of graphitization, creates favorable conditions for the efficient adsorption and diffusion of molecules within the material.

The elemental composition of the samples is presented in Table 4.

Table 4 - Results of elemental analysis of samples

Name of the adsorbent	Elemental composition, wt.%										
	C	O	Na	Mg	Al	Si	K	Ca	Fe	Cl	Cu
Raw wood sawdust	68.45	31.55	-	-	-	-	-	-	-	-	-
AC-1	99.63	-	-	-	-	-	0.11	0.26	-	-	-
AC-2	83.10	14.60	0.15	0.11	0.07	0.33	1.43	-	-	0.08	0,05
AC-3	88.40	10.90	0.07	0.07	-	0.21	0.31	-	-	-	-
AC-4	50.30	37.80	0.48	-	0.14	0.04	10.7	-	0.47	-	-
AC-5	85.90	11.10	-	0.10	-	0.10	0.10	1.00	1.40	0.10	-

Elemental analysis revealed that carbonization and chemical activation of wood biomass significantly alter its composition. The original sawdust contained 68.45% carbon and 31.55% oxygen, while the resulting adsorbents were characterized by increased carbon content: AC-1 – 99.63%, AC-2 – 83.10%, AC-3 – 88.40%, and AC-5 – 85.90%, while the oxygen content decreased. The adsorbents retained mineral components (Na, Mg, Al, Si, K, Ca, Fe, etc.), which were most pronounced in samples AC-2, AC-4, and AC-5. Thus, the AC-5 adsorbent contains Mg (0.10%), Si (0.10%), K (0.10%), Ca (1.00%), Fe (1.40%), and Cl (0.10%), indicating the formation of a functionally active surface. The obtained data confirm that carbonization and chemical activation effectively modify biomass, ensuring the formation of a developed carbon matrix and the production of highly effective carbon adsorbents.

Figure 9 shows the Raman spectra of five adsorbents (AC-1, AC-2, AC-3, AC-4, AC-5). All spectra clearly exhibit two characteristic bands: D (1350 cm ^{1}), corresponding to defective and amorphous carbon, and G (1580 cm ^{1}), reflecting the presence of an ordered graphite structure. Comparison of the ID/IG intensity ratio shows that AC-1 and AC-2 are characterized by higher values, indicating a low degree of graphitization and a significant content of defective carbon. For AC-3 and AC-4, the ID/IG ratio decreases, indicating the formation of a more ordered carbon structure. The spectra of AC-3 and AC-4 also exhibit weak bands in the region of 2700 cm ^{1} (2D), indicating the presence of graphite-like regions. Graphitization analysis revealed the following values: AC-1 – 19.3%, AC-2 – 27.4%, AC-3 – 25.0%, AC-4 – 25.9%, and AC-5 – 34.4%. Adsorbent AC-5 is characterized by the

highest degree of graphitization and the lowest ID/IG ratio, indicating a significant reduction in the proportion of defective carbon and an increase in the size of graphite domains. A more pronounced 2D band confirms the formation of a highly organized carbon structure. Thus, Raman analysis demonstrates that optimization of carbonization and chemical activation conditions contributes to a reduction in defects, an increase in the degree of graphitization, and the formation of a porous carbon matrix with improved structural and adsorption characteristics.

The adsorption characteristics of the adsorbents are presented in Figure 10 and Table 5.

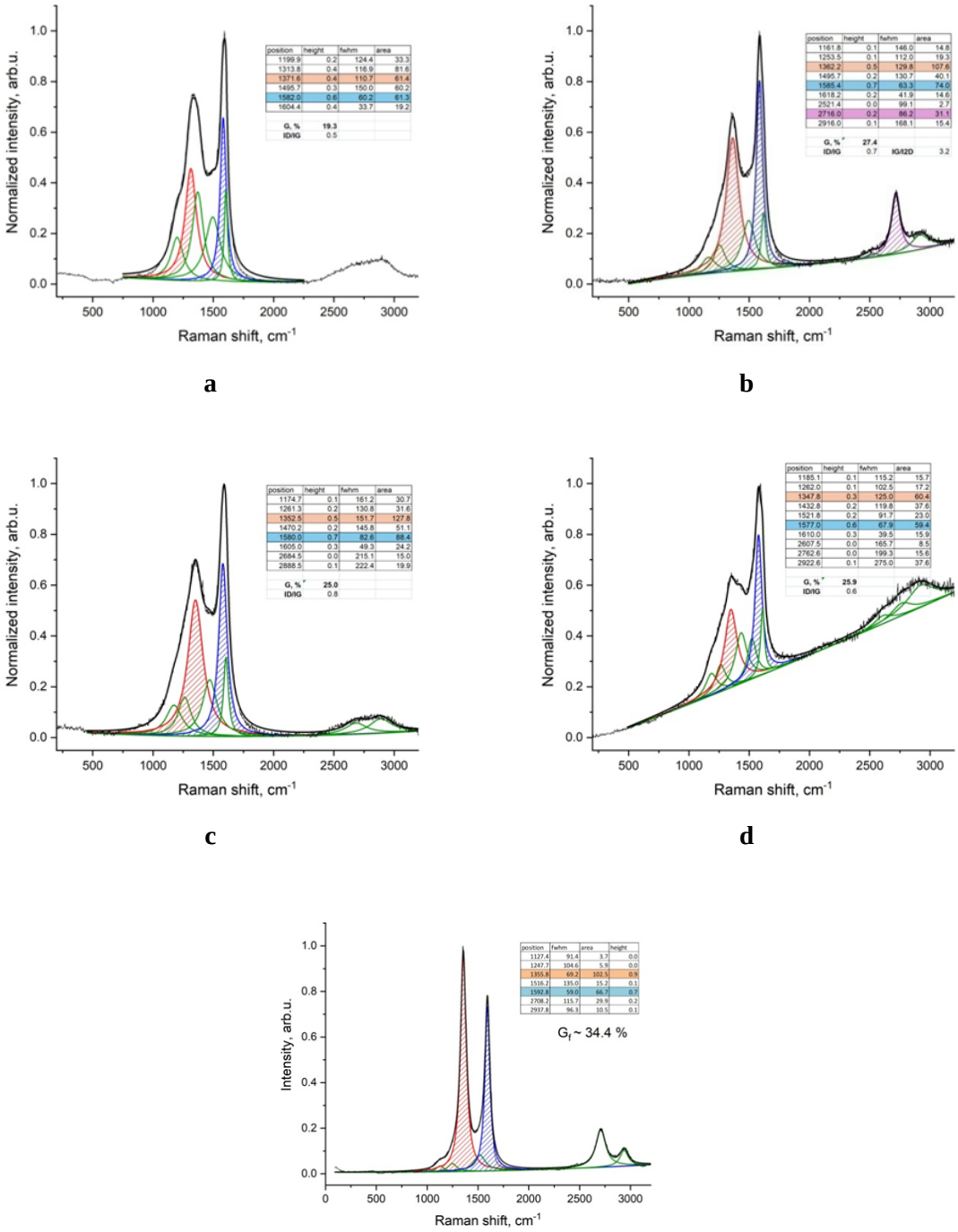
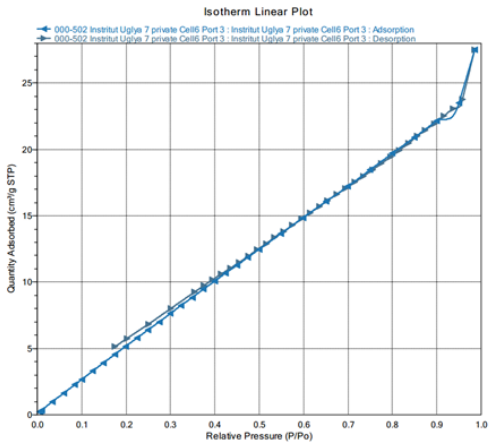


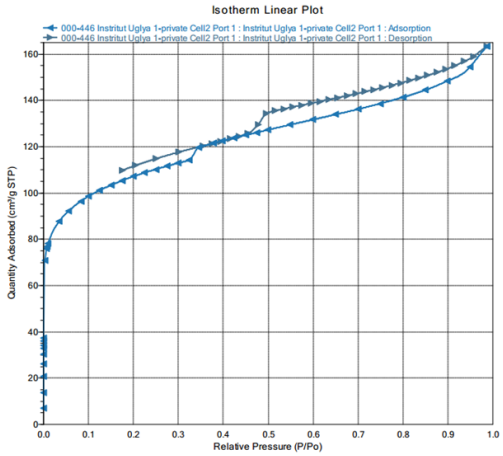
Fig.9 - Raman spectrum of adsorbents: a-AC-1; b-AC-2; c-AC-3; d-AC-4; e-AC-5

Table 5 - Adsorption characteristics of adsorbents

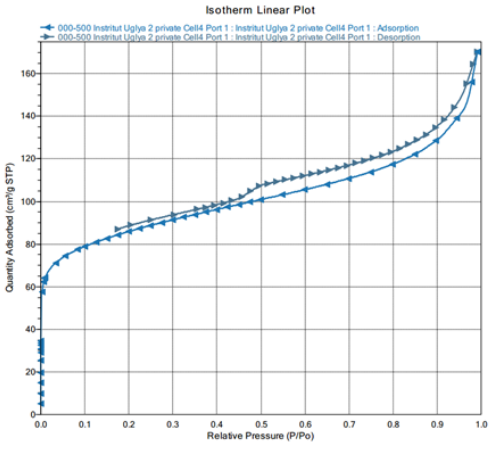
Characteristics	Adsorbents				
	AC-1	**AC-2**	**AC-3**	**AC-4**	**AC-5**
Surface area at a single point at p/p0 = 0.20000 (m^2/g)	36.90	372.50	85.89	400.00	499.00
BET surface area (m^2/g)	38.88	390.22	314.36	568.00	610.11
Langmuir surface area (m^2/g)	59.60	420.10	485.00	610.00	640.00
t-Plot Micropore area (m^2/g)	0.00	210.80	245.13	420.00	499.34
Total pore volume at p/p0 = 0.99000 (cm^3/g)	0.042	0.253	0.170	0.4532	0.3852
Average pore diameter (4V/A) (nm)	4.20	2.60	2.17	3.00	2.52
BJH Adsorption Average pore diameter (nm)	3.60	5.13	3.20	3.12	3.80
Micropore volume (cm^3/g)	-	0.087	0.064	0.182	0.076
Average pore diameter (nm)	-	1.60	0.62	0.68	0.78



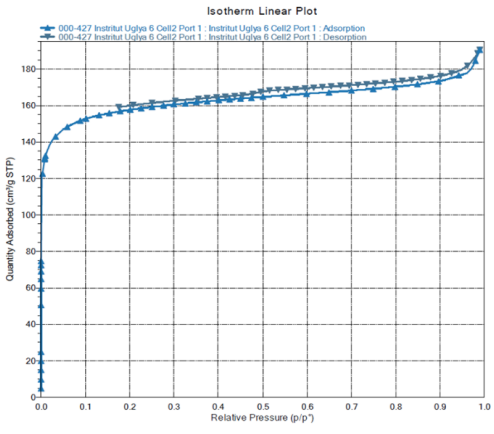
a



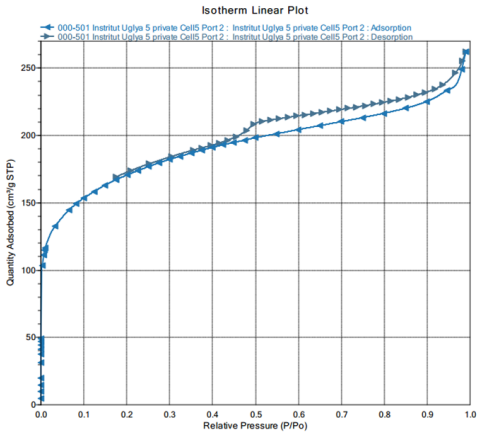
b



c



d



e

Fig.10 - Graph of adsorbent isotherms: a-AC-1; b-AC-2; c-AC-3; d-AC-4; e-AC-5

The types of adsorption–desorption isotherms are presented in Figure 11.

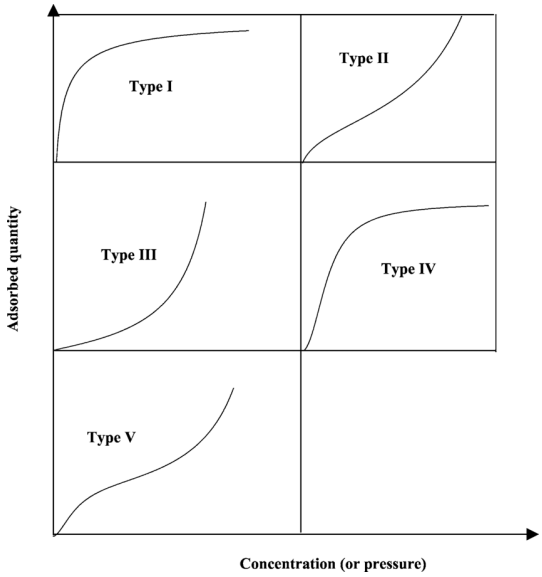
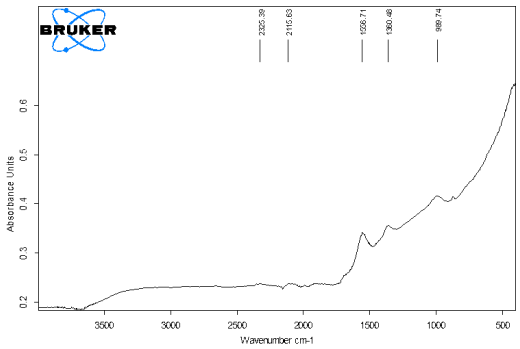
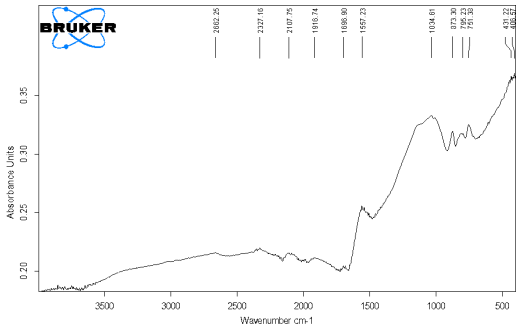
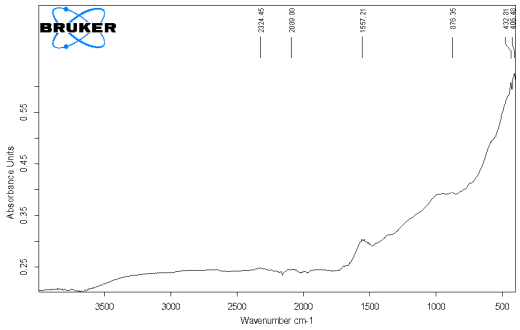


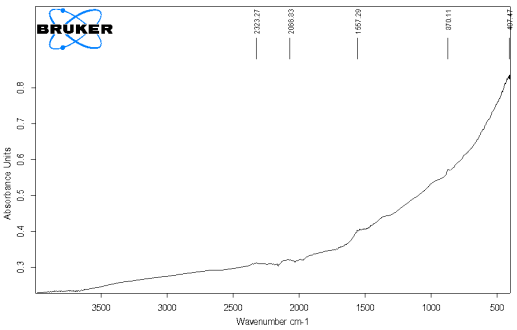
Fig.11 - Types of adsorption-desorption isotherms

The results of texture analysis show that the AC-1 adsorbent is characterized by type II isotherms, a low specific surface area (≈40 m²/g), and a small pore volume, indicating a poorly developed porous structure with a predominance of meso- and macropores. Analysis of the presented adsorption-desorption isotherm shows that the AC-4 adsorbent belongs to type I according to the IUPAC classification. This is confirmed by a sharp increase in the volume of adsorbed nitrogen in the region of low relative pressures ($p/p_0 < 0.1$), indicating intensive filling of micropores. With a further increase in pressure, the curve gradually reaches a plateau, which is typical of materials with a limited pore volume. The absence of a pronounced hysteresis loop indicates an insignificant proportion of mesopores. Thus, the studied adsorbent is predominantly a microporous material with a developed specific surface area. Adsorbents AC-2, AC-3, and AC-5 belong to type V isotherms and are characterized by a high specific surface area (314–610 m²/g) and a significant contribution of micropores. The most developed microporous structure is observed in AC-5, as evidenced by the

highest values of SBET and pore volume. These adsorbents possess increased adsorption capacity and are more promising for practical applications.

Table 6 - IR spectra of the obtained samples

№	Name of samples	Interpretation
1	AC-2 	2350–2320 cm ¹ – weak bands, possibly CO_2 or C≡N (low intensity, background absorption) 2120–2110 cm ¹ – ≡C–C≡ or –N=C=O vibrations 1600–1550 cm ¹ – bending vibrations of aromatic rings or N–H groups 1400–1350 cm ¹ – C–N or SO_2 vibrations 1000–990 cm ¹ – aromatic substitutions, possible C–H deformations
2	AC-3 	2660–2665 cm ¹ – C–H stretching vibrations (aldehydes, carboxylic acids) 2330–2325 cm ¹ – CO_2 or isocyanate bands (weak intensity, background absorption) 2110–2105 cm ¹ – C≡C or –N=C=O triple bonds 1920–1915 cm ¹ – Combination vibrations of aromatic compounds 1700–1695 cm ¹ – C=O carbonyl group stretching vibrations 1560–1555 cm ¹ – Bending vibrations of aromatic rings or N–H 1040–1030 cm ¹ – C–O or S=O stretching vibrations 875–750 cm ¹ – Deformation vibrations of aromatic rings 430–405 cm ¹ – metal-oxygen bonds
3	AC-4 	2330–2320 cm ¹ – possible vibrations of CO_2 or isocyanate groups (–N=C=O, weak intensity) 2090–2085 cm ¹ – triple bonds (–C≡C–, –N=C=O) 1560–1555 cm ¹ – bending vibrations of aromatic rings or N–H 880–870 cm ¹ – =C–H deformations, characteristic of colored polymers 435–405 cm ¹ – metal–oxygen vibrations (Si–O, Al–O), indicate the presence of an inorganic filler

4	AC-5 	2325–2320 cm ¹ – possible vibrations of CO_2 or isocyanate groups (–N=C=O, weak intensity) 2070–2065 cm ¹ – triple bonds (–C≡C–, –N=C=O) 1560–1555 cm ¹ – bending vibrations of aromatic rings or N–H 875–865 cm ¹ – =C–H deformations, characteristic of colored polymers

IR spectroscopic studies of the resulting adsorbents were conducted at the Research Institute of Ecology and Sustainable Use of Bioresources of Al-Farabi Kazakh National University using a Bruker Alpha II laboratory IR spectroscopic instrument. The results are presented in Table 6.

Of the adsorbents obtained, AC-2 was selected for wastewater treatment because it possesses an optimal combination of a developed porous structure and surface functional activity sufficient for the effective binding of pollutants. An additional advantage of AC-2 is its cost-effectiveness and environmental safety: the adsorbent is based on sawdust impregnated with KOH in a 1:1 ratio, ensuring the availability of raw materials, low cost, and the absence of toxic components in the material.

Wastewater collected from the wastewater treatment plant of the Astana Su Arnasy State Enterprise (Astana) was used for testing. Chemical analysis of the samples was conducted in the enterprise' s accredited analytical laboratory. Based on the analysis results, purification rates for key indicators were calculated and compared with current wastewater quality standards. Table 7 presents the results of the chemical analysis of wastewater from the Astana Su Arnasy State Enterprise before and after treatment with the activated adsorbent AC-2. Figure 12 shows the wastewater treatment sample used in this study.



Figure 12 – Wastewater treatment sample

After treatment with the AC-2 adsorbent, a significant reduction in most pollutants was observed. For example, BOD decreased from 200.0 to 35.0 mgO/dm³, corresponding to 82.5% purification efficiency, and COD decreased from 444.0 to 123.0 mgO/dm³ (72.3%), demonstrating the high adsorption capacity of AC-2 for organic compounds. Suspended solids decreased by 30.9%, indicating partial removal of colloidal and suspended particles.

Metals and inorganic components also showed varying degrees of removal: iron decreased from 2.35 to 0.65 mg/dm³ (73.3%), and phosphates by 17.7%. The adsorbent demonstrated the highest efficiency for surfactants and petroleum products, with removal rates of 94.4% and 90.4%, respectively, confirming the potential of AC-2 for wastewater treatment of surfactants and hydrocarbon contaminants.

Table 7 – Results of chemical analysis of wastewater from Astana Su Arnasy before and after treatment with activated adsorbents AC-2

Name of indicators	*Standards according to regulatory documents (after biological treatment)*	Actual conc. before cleaning	Actual conc. after purification	Degree of purification, %
			AC-2	AC-2
pH	*6-9*	7.87	8.11	8.11
BOD (biological oxygen demand), mgO/dm^3	≤ 15	200.0	35.0	82.5
COD (chemical oxygen demand), mgO/dm^3	≤30	444.0	123.0	72.3
Suspended solids, mg/dm^3	≤ 15	139.0	96.0	30.9
Sulfates, mg/dm^3	≤ 500 *(average standard according to SNiP and SanPiN for wastewater)*	198.0	222.0	-
Ammonium nitrogen, mg/dm^3	≤2.0	46.38	33.58	27.6
Nitrites, mg/dm^3	≤ 0.08	0.073	0.34	-
Nitrates, mg/dm^3	≤ 40	0.66	0.34	48.5
Iron, mg/dm^3	≤ 0.3	2.35	0.65	73.3
Phosphates, mg/dm^3	≤2.0	13.05	10.75	17.7
Surfactants, mg/dm^3	≤ 0.5	6.81	0.38	94.42
Petroleum products, mg/dm^3	≤0.3	27.87	2.68	90.4

Some parameters, such as sulfates, ammonium nitrogen, and nitrites, showed either a slight decrease or even an increase in concentration after treatment (for example, nitrites increased from 0.073 to 0.34 mg/dm³). This may be due to the conversion of some compounds into other forms as a result of a chemical reaction with the adsorbent or a change in the pH of the medium, which after treatment was 8.11, remaining within acceptable limits (6-9).

Overall, the use of the AC-2 adsorbent demonstrated high efficiency in removing organic contaminants, petroleum products, and surfactants, as well as a partial reduction in the concentration

of inorganic components. These results confirm the feasibility of using the obtained activated carbon for wastewater treatment, especially with high concentrations of organics and petroleum products.

Conclusion. The study demonstrated that wood sawdust is an effective and affordable raw material for producing activated carbon adsorbents. It was found that the combination of carbonization at 550°C and chemical activation with KOH at 900°C resulted in the formation of a developed porous structure and a significant increase in the specific surface area of the material.

Increasing the KOH/biomass ratio intensifies the chemical etching of the carbon matrix, reduces the yield of the solid product, and simultaneously increases the specific surface area and micropore volume. The maximum textural characteristics were recorded for sample AC-5, but the optimal combination of porous structure, surface functional activity, and product yield was characteristic of adsorbent AC-2. SEM, elemental analysis, Raman spectroscopy, and IR spectroscopy confirmed the formation of a carbon framework with developed micro- and mesoporosity, the presence of surface functional groups, and an increased degree of graphitization. Practical testing of the AC-2 adsorbent in wastewater treatment demonstrated high efficiency in removing organic pollutants, petroleum products, and surfactants (up to 90–94%).

Thus, the resulting sawdust-based activated carbons are promising adsorbents for use in wastewater treatment technologies and can be considered an environmentally and economically viable alternative to industrial carbon sorbents.

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