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INVESTIGATION OF THE ADSORPTION PROPERTIES OF ACTIVATED CARBON DERIVED FROM FRUIT PITS

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Annotation: This study investigates the adsorption properties of activated carbon derived from fruit pit waste, specifically walnut, apricot, and peach pits. Activation was conducted at 800–850°C using both thermal and thermochemical methods, including steam treatment and chemical agents such as 10% $ZnCl_2$ and H_2SO_4 solutions. Benzene vapor was used as the adsorbate to evaluate the adsorption efficiency of the produced carbon adsorbents. Key parameters such as monolayer capacity (α_m), saturation volume (Vs), specific surface area (S), micropore volume (W_0), and mesopore volume (Wme) were calculated using BET theory and micropore volume filling equations.
The results revealed that thermochemical activation significantly enhances the structural and adsorption characteristics compared to thermal activation. For instance, FC-WP-136 showed a 3.2-fold increase in pore volume under thermochemical conditions, with surface area reaching up to 1397.11 m²/g. Adsorption isotherms were classified as Type I, indicating microporous structures with high initial benzene uptake. The average pore radius was found to decrease with increased microporosity.
These findings demonstrate the effectiveness of utilizing agricultural waste as a raw material for producing high-performance, selective carbon adsorbents. The study supports the development of cost-effective, import-substituting technologies for environmental purification and industrial applications.

Key words: Activated carbon, Fruit pit waste, Thermochemical activation, Benzene adsorption, Specific surface area, Micropore structure, BET analysis.

Introduction: Nowadays, the rapid development of industrial and agricultural sectors in our Republic and across the globe, along with the expanding application fields of activated carbon, has led to an increasing demand for selective adsorbents. One of the urgent challenges is the development of efficient, import-substituting technologies based on local raw materials. In this context, the production of low-cost activated carbon from domestic resources remains a topical issue.
The third priority area of the Action Strategy for the Further Development of the Republic of Uzbekistan outlines important tasks aimed at the development of high-tech industrial processing sectors, primarily through the deep processing of local raw materials into high-quality end products. In this regard, scientific research into the production of selective carbon-based adsorbents from local raw materials—specifically, fruit pits—and the determination of

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their adsorption properties is of great importance. There is also a pressing need to develop energy-efficient technologies for the production of selective carbon adsorbents.

Literature review: Several methods are used to enhance the adsorption properties of carbon-based adsorbents. These include thermal activation, steam activation, and chemical activation techniques. Upon activation, the specific surface area of carbon adsorbents can reach up to 1000 m^2/g, significantly improving their adsorption efficiency. [1; 340-p].

In our country, scientific studies have mainly focused on the adsorption of organic compounds onto natural mineral compounds such as bentonites [2; p. 68], and on the adsorption of both organic and inorganic substances onto synthetic zeolites [3; p. 64, 4; p. 64, 5; p. 48, 6; p. 48]. However, the effect of thermal treatment temperatures on the adsorption capacity of carbon adsorbents derived from fruit pits has not been thoroughly investigated. Therefore, it is essential to conduct a fundamental study on the adsorption of organic vapor molecules onto carbon-based adsorbents activated by thermal and steam treatment at various temperatures.

Methodology: Studying the effect of different thermal treatment temperatures on the adsorption capacity of carbon-based adsorbents, including those derived from fruit pits, is of great importance in adsorption processes. For this purpose, carbon adsorbents were prepared from waste fruit pits of walnut, apricot, peach, and bitter almond trees grown in the territory of Uzbekistan. The activation was carried out thermally at 400–500°C and using steam at 800–850°C for 3 hours.

The adsorption of benzene vapors on the obtained carbon adsorbents was investigated.

Before being used as the adsorbate, benzene was purified and dried under vacuum conditions. To ensure the vapor pressure matched the tabulated values for pure benzene, it was first cooled and then heated to remove dissolved gases. After this preparation, adsorption measurements were carried out.

Results: As seen from the adsorption isotherms of benzene vapors (Figure 1), carbon adsorbents derived from fruit pit waste and activated at 800–850°C using 10% aqueous $ZnCl_2$ solution (thermochemical activation) demonstrated varying adsorption behaviors. Benzene adsorption was studied on the adsorbents labeled **AU-UK-74.5-800-850**, **AU-UK-136-800-850**, and **AU-ZHU-136-800-850**. The imported **JACOBI-brand activated carbon** exhibited a lower initial adsorption capacity compared to the two experimental adsorbents, particularly **AU-ZHU-136 800-850**, indicating the competitive performance of locally produced carbon materials.

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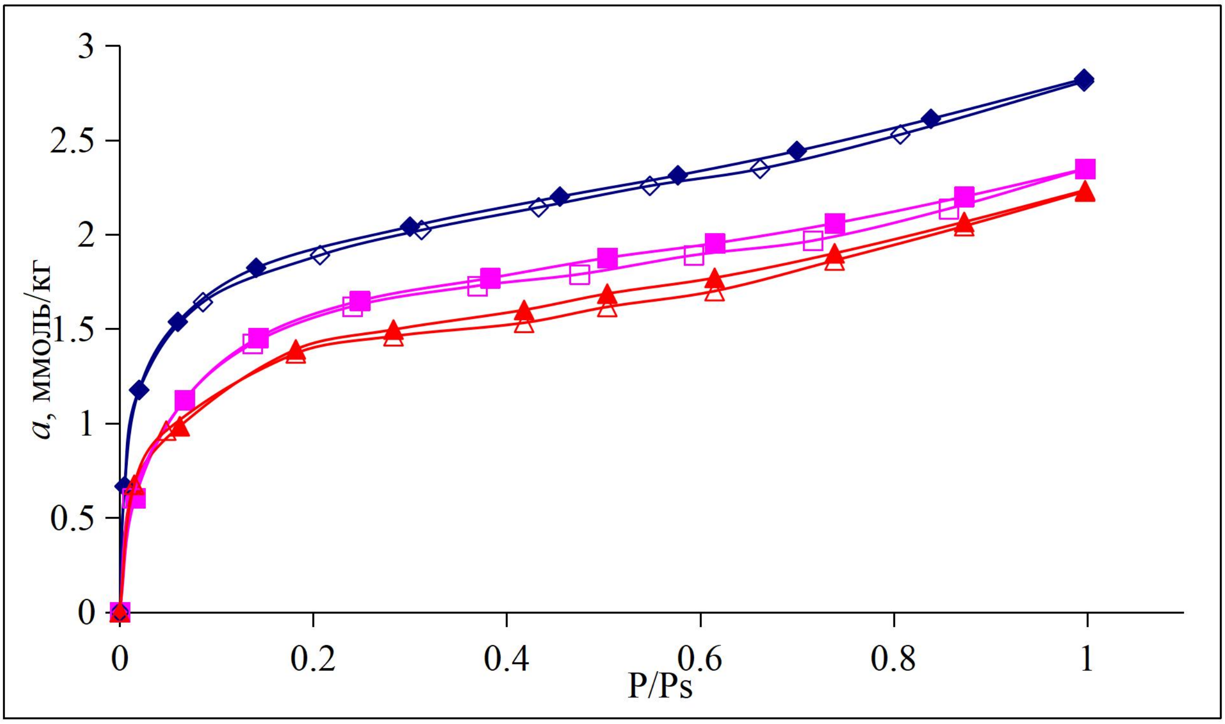

Figure 1: Adsorption isotherms of benzene vapor on carbon adsorbents obtained from fruit pit waste by thermochemical activation at 800–850°C:
(1) AU-UK-136, (2) AU-YUK-74.5, (3) AU-ZHU-136.

The specific surface areas (S) of the carbon materials obtained from fruit pit waste by thermochemical activation at 800–850°C were found to be as follows: **AU-UK-136** – 1397.11 m²/g, **AU-YUK-74.5** – 1294.33 m²/g, and **AU-ZHU-136** – 985.09 m²/g. The saturation pore volumes (Vs) of these samples were determined as: **AU-UK-136** – 0.2514057 cm³/g, **AU-YUK-74.5** – 0.2059116 cm³/g, and **AU-ZHU-136** – 0.1962319 cm³/g.

The adsorption of benzene vapors on carbon adsorbents activated by steam at 800–850°C was also investigated (Figure 2).

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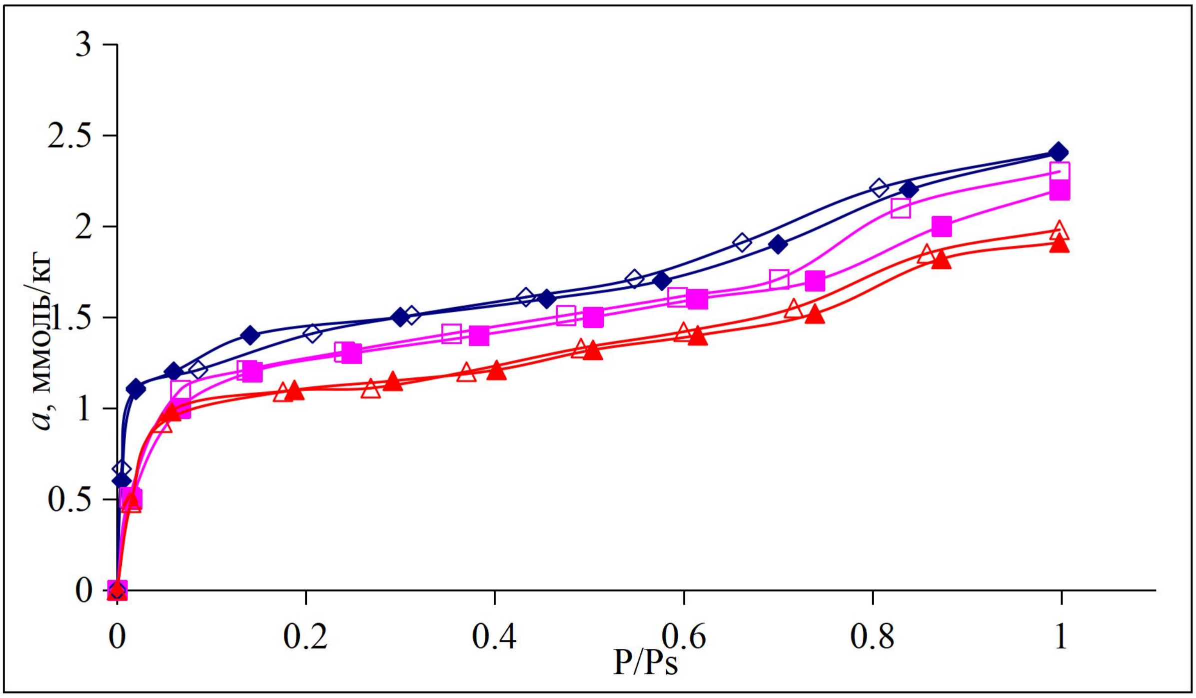

Figure 2: Adsorption isotherms of benzene vapor on carbon adsorbents derived from fruit pit waste and thermally activated at 800–850°C:
(1) AU-UK, (2) AU-YUK, (3) AU-ZHU

From the adsorption isotherms obtained in the studied systems, it was found that the amount of benzene adsorbed on carbon adsorbents thermally activated with steam at 800–850°C was lower compared to those thermochemically activated at the same temperature range. Specifically, benzene adsorption was lower by a factor of **1.28** for **AU-YUK-74.5**, **1.3** for **AU-UK-136**, and **1.26** for **AU-ZHU-136**.

Such an increase in adsorption capacity observed in thermochemically activated samples indicates that structural modifications occurred in the carbon adsorbents, even when the activation temperatures were kept the same (800–850°C).

Furthermore, the adsorption of benzene vapors was studied for carbon adsorbents derived from fruit pit waste and activated with 10% aqueous $\mathbf{H_2SO_4}$ vapor at 800–850°C (Figure 3).

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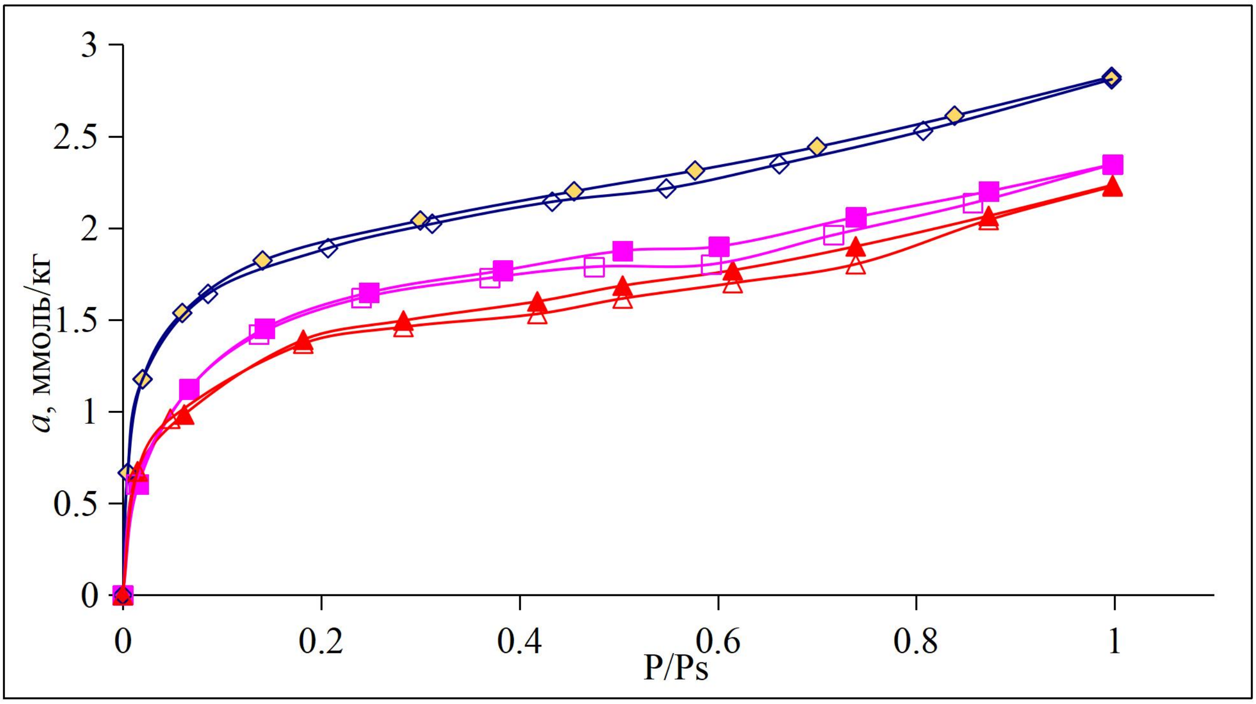

Figure 3: Adsorption isotherms of benzene vapor on carbon adsorbents derived from fruit pit waste and activated at 800–850°C using 10% H_2SO_4 vapor (thermochemical activation):
(1) AU-UK, (2) AU-YUK, (3) AU-ZHU

According to the adsorption isotherms obtained in the studied systems, the amount of benzene adsorbed on carbon adsorbents activated with 10% H_2SO_4 solution at 800–850°C was found to be lower than that of adsorbents thermochemically activated without sulfuric acid under the same conditions.

Specifically, the adsorption capacity decreased by a factor of **1.32** for **AU-YUK 74.5**, **1.25** for **AU-UK-136**, and **1.36** for **AU-ZHU-136**. This decrease in adsorption performance confirms that structural differences occur in carbon adsorbents thermally and thermochemically activated at identical temperatures (800–850°C), influencing their surface and pore characteristics.

As observed from the adsorption isotherms of the presented systems, the amount of adsorbed benzene increased sharply from a relative pressure of **P/Ps = 0** up to approximately **P/Ps ≈ 0.4**, after which the increase became more gradual, approaching saturation.The steep rise in the isotherms at low relative pressures (**P/Ps ≈ 0.4**) indicates that benzene vapors are initially adsorbed on surfaces with high adsorption potential, which is characteristic of microporous structures.

Discussion: In the studied systems, a steep slope in the adsorption isotherms was observed at low relative pressures (P/Ps = 0.1–0.2), indicating significant uptake of benzene vapor at initial stages. The adsorption isotherms of these samples with benzene vapor were found to correspond to **Type I** in the classification of adsorption isotherms proposed by **Brunauer**. Type I isotherms are characteristic of **microporous adsorbents**, which exhibit a sharp rise followed by a near-vertical trend approaching the **P/Ps = 1** axis, forming an almost right angle.

The **specific surface area (S)** of the adsorbents was calculated using the **Brunauer–Emmett–Teller (BET)** theory. In this approach, a linear relationship is obtained by plotting **P/Ps/[a(1 – P/Ps)]** on the ordinate versus **P/Ps** on the abscissa.

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The specific surface area of the adsorbents was calculated using the following formula:

$S = a_m \cdot N \cdot \omega_0$ (3.1)

- **S** – specific surface area (m²/g)
- $\mathbf{a_m}$ – amount adsorbed in a monomolecular layer (mol/kg)
- $\mathbf{N_A}$ – Avogadro's number
- **ω** – surface area occupied by a single molecule (nm²)

Based on the adsorption isotherms of benzene vapor on the carbon adsorbents, several key parameters were calculated, including the **monolayer adsorption capacity** ($\boldsymbol{\alpha_m}$), **saturation volume (Vs)** (or **total adsorption capacity, αs**), and the **specific surface area (S)**.
The obtained results are summarized in **Table 1**.

Table 1.

Structural and Sorption Characteristics of Fruit Pit–Based Carbon Adsorbents Activated by Thermal and Steam Methods According to Benzene Vapor Adsorption:
FC-WP, FC-AP, FC-WP-136, FC-WP-Ar-136, FC-WP-74.5, FC-WP-Ar-74.5, FC-WP-111, FC-PP-78, FC-PP-98

Adsorbent	Activation Temperature, °C	Monolayer Capacity, a_m, mol/kg	Specific Surface Area, $S \cdot 10^{-3}$, m²/kg	Saturation Adsorption Capacity, a_s, mol/kg
FC-WP-136	800° C	1,06	255	2,64
	800° C+ Water Vapor	2,0	482	3,86
FC-WP-74,5	800° C	1,01	243	2,52
	800° C+ Water Vapor	1,82	438	3,8
FC-WP-111	800° C	0,7	169	2,1
	800° C+ Water Vapor	1,54	371	3,4
FC-PP-78	800° C	0,69	166	2,2
	800° C+ Water Vapor	1,48	357	3,2
FC-PP-98	800° C	0,74	178	2,3
	800° C+ Water Vapor	1,46	352	3,1

In all studied adsorbents, it was found that when the activation temperature was kept constant, both thermochemical and steam activation methods yielded different results. Specifically, thermochemical activation led to higher values of specific surface area (S) and saturation capacity (α_s) compared to steam activation.
As shown in Table 1 [7; pp. 25–32], in the case of activated carbons derived from fruit pit shells, the specific surface area of thermochemically activated adsorbents was significantly greater than that of steam-activated ones. Under such activation conditions, the release of volatile gases and tars from the carbon structure facilitates the formation of additional porosity within the

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adsorbent matrix.

In particular, for the sample steam-activated at 800°C (SACFPW – Steam-Activated Carbon from Fruit Pit Waste), the structural and sorption characteristics were found to be superior compared to other adsorbents. Compared to FPC-800 (fruit pit carbon activated thermochemically), the specific surface area (S) increased by a factor of 1.9, and the saturation capacity (αs) increased by 1.5 times [8; pp. 275–277].

This behavior is attributed to the chemical interaction between amorphous carbon and steam at high temperatures (800°C), which results in the formation of additional micropores and cracks within the carbon structure.

Based on the adsorption isotherms of benzene vapors and the Micropore Volume Filling Theory (MVFT) equation, the micropore volume (W_0), saturation adsorption volume (Vs), and mesopore volume (Wme) of the adsorbents were calculated using the following formula:

$W_{me} = V_s - W_0$

$$r_{del} = \frac{2 \ V_s \ 10^4}{S}$$

The average pore radius was calculated using a standard formula.

It was found that thermochemical activation led to an increase in both the micropore volume (W_0) and the adsorption volume at saturation, compared to thermal activation alone.Furthermore, a decrease in the average pore radius was observed.

This reduction in average pore size is attributed to the fact that thermochemical activation resulted in a greater proportion of micropores relative to mesopores, indicating a shift in the pore structure toward finer porosity.

The corresponding results are presented in Table 2.

Table 2.

Pore Volume Characteristics of Wood-Based Chars Activated by Thermal and Steam Methods According to Benzene Vapor Adsorption:

Adsorbent	Activation Temperature, °C	$W_0 \cdot 10^3$	$W_{me} \cdot 10^3$	Average Pore Radius, r_{ave}, Å
FC-WP-136	800° C	0,213	0,022	18,4
	800° C+ Water Vapor	0,295	0,048	14,2
FC-WP-74,5	800° C	0,204	0,020	18,4
	800° C+ Water Vapor	0,295	0,043	15,4
FC-WP-111	800° C	0,151	0,036	22,1
	800° C+ Water Vapor	0,269	0,034	16,3
FC-PP-78	800° C	0,170	0,026	23,6
	800° C+ Water Vapor	0,257	0,028	16,0
FC-PP-98	800° C	0,170	0,035	23,0
	800° C+ Water Vapor	0,251	0,025	15,7

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For FC-WP-136, thermal activation by heating up to 800°C resulted in nearly a 2-fold increase in pore volume, while thermochemical activation at the same temperature led to a 3.2-fold increase [9; pp. 156–158]. The mesopore volume as a percentage of the total adsorption volume (Vs) was 23.5% for FC-WP-136-800, 11% for FC-WP-74.5-800, 9.4% for FC-WP-111-800, 19.6% for FC-PP-78-800, and 20.5% for FC-PP-98-800 [10; pp. 277–278; 11; pp. 11367–11371].

Conclusion: In this study, activated carbon adsorbents were successfully synthesized from fruit pit waste using both thermal and thermochemical activation methods at 800–850°C. The structural and adsorption properties of the adsorbents were evaluated using benzene vapor as the adsorbate. Thermochemical activation, especially with $ZnCl_2$ and H_2SO_4, significantly improved key characteristics such as specific surface area, micropore volume, and adsorption capacity compared to conventional steam activation.

The adsorption isotherms followed Type I behavior, confirming the formation of predominantly microporous structures. Notably, the sample FC-WP-136 exhibited the highest specific surface area (1397.11 m^2/g) and superior benzene vapor uptake, with pore volume increasing by up to 3.2 times over non-activated samples. The results also showed a decrease in average pore radius, indicating enhanced microporosity.

Overall, the findings demonstrate that fruit pit waste can serve as an effective, low-cost raw material for producing high-performance carbon adsorbents. These materials show strong potential for use in selective adsorption, environmental cleanup, and industrial gas purification processes. The study contributes to the development of sustainable and import-substituting technologies based on locally available biomass resources.

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