ISSN 2181-8622

Manufacturing technology problems

Scientific and Technical Journal Namangan Institute of Engineering and Technology

Volume 10
Issue 3
2025

ADSORPTION ISOTHERM OF HYDROGEN SULFIDE ON AN ACTIVATED ADSORBENT DERIVED FROM HYBRID PAULOWNIA TOMENTOSA WOOD

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Abstract: This study presents the results of investigating the adsorption isotherms of hydrogen sulfide on a carbonaceous adsorbent derived from *Paulownia tomentosa* (woolly paulownia) wood using the steam–gas activation method. The thermodynamic and structural parameters of the sorbent were examined, which determine its high sorption capacity and chemical stability during interaction with H_2S. Steam–gas activation of *Paulownia tomentosa* charcoal was carried out at controlled temperatures (700–850 °C) using water vapor as the activating agent. The resulting adsorbent exhibited a well-developed microporous structure and a high specific surface area (up to 1100 m²/g). The adsorption isotherms of H_2S at 303 K were studied using microcalorimetry and static adsorption methods. It was found that the adsorption process is of a physico-chemical nature, indicating a predominantly monomolecular mechanism of interaction. Analysis of the linear portion of the adsorption isotherm showed that the number of active sites on the adsorbent surface is **0.54 mmol/g.** This value reflects the high activity of the microporous structure and the presence of polar functional groups on the sorbent surface. Furthermore, the results indicate that the interaction between the adsorbate and the adsorbent occurs through the formation of a complex in a **3:1 ratio ($3H_2S:C$)** at the active sites. Such an interaction pattern suggests a monomolecular adsorption mechanism of H_2S and confirms the high selectivity, stability, and efficiency of the carbonaceous adsorbent in gas purification processes. The obtained results demonstrate that steam-activated carbon derived from *Paulownia tomentosa* is a promising sorbent for hydrogen sulfide removal from gas streams, offering high capacity, stability, and environmental safety. This work opens opportunities for further optimization of activation conditions and surface modification to enhance the efficiency of natural and industrial gas purification.

Keywords: adsorption, adsorbent, isotherm, pressure, relative pressure, mechanism, hydrogen sulfide.

Introduction. The modern environmental and resource-energy paradigm imposes increasingly stringent demands on technologies for the purification of polluted media — air, wastewater, and industrial gases. One of the key directions in such technologies is the development of adsorption-active materials characterized by high sorption capacity, stability, and economic feasibility. Particularly promising in this regard are adsorbents derived from biomass and wood-based raw materials, as they combine the advantages of resource availability, low cost, and potentially high efficiency [1].

As a raw material for producing such an adsorbent, the wood of *Paulownia tomentosa* (also known as the woolly paulownia) is of particular interest. This is a fast-growing tree capable of thriving on relatively poor soils, which makes it potentially attractive from the standpoint of sustainable raw material supply [2]. A number of studies have examined the use of *Paulownia tomentosa* wood as a raw material for producing activated carbon or sorbents with high adsorption capacity. For instance, Alam et al. described a technology for obtaining activated carbon from *Paulownia tomentosa* wood for the removal of dyes from wastewater [3].

Paulownia tomentosa wood appears to be a promising raw material for adsorbents for several reasons. First, this tree species is characterized by a high growth rate, relatively low soil requirements, and the ability to thrive under conditions unfavorable for many other species, which makes it a resource with strong potential for sustainable utilization [2]. Second, the wood and its by-products (such as sawdust and wood chips) can be available in significant quantities with the development of plantation cultivation, thereby reducing the cost of raw materials. Third, *Paulownia tomentosa* wood can be converted into a carbonaceous material-activated carbon or carbonized sorbent-with a well-developed porous structure, which is essential for achieving high adsorption efficiency.

The literature emphasizes that the production of adsorbents from wood remains a relevant research direction: "The composition and properties, micro- and macroporous structure, and physicochemical characteristics of adsorbents obtained from local wood, as well as from *Paulownia* as a raw material for adsorbent production, have been studied" [4]. Thus, the selection of *Paulownia tomentosa* as a raw material base for adsorbent production is justified from both resource and technological standpoints.

The technological process of producing an adsorbent from wood includes several stages: raw material preparation (drying and crushing), carbonization (thermal treatment in an inert or controlled atmosphere), subsequent activation (either physical-using steam or gas-or chemical-using acid or alkali), and final processing (washing, drying, and fractionation). An analysis of the literature makes it possible to identify characteristic technological parameters and specific features associated with the use of *Paulownia tomentosa* wood in such processes.

In the study by Alam et al., the following procedure was described: the wood is ground and subjected to activation (chemical and/or physical) to obtain activated carbon, which is subsequently used in adsorption experiments [3]. In particular, this work demonstrated that the adsorbent derived from *Paulownia tomentosa* effectively removed dyes ("acid red 4" and "methylene blue") from aqueous solutions. The effects of pH, contact time, initial concentration, adsorbent dosage, and temperature were investigated [3].

Furthermore, in a study using wood from a hybrid *Paulownia tomentosa* species, the adsorption isotherm and differential enthalpy of hydrogen sulfide adsorption on the resulting carbonaceous sorbent were examined [5]. These findings indicate that *Paulownia tomentosa* wood can be utilized not only for water purification but also for gas-phase adsorption applications.

It is worth noting several important technological aspects:

1. **Carbonization** must ensure the removal of volatile components and the formation of a stable carbon matrix.
2. **Activation** (e.g., steam or chemical) develops the porous structure and increases the specific surface area, which is critical for adsorption capacity. Studies on other types of wood-based materials have shown that heating rate, activating agent flow rate, and residence time have a significant effect on porosity, product yield, and adsorption performance [6].
3. After activation, **post-treatment-**including washing, drying, and possibly surface modification (e.g., functionalization)-is important to enhance selectivity, adsorption kinetics, and capacity.

Although studies on the use of activated carbons derived from *Paulownia tomentosa* wood remain limited, significant findings already demonstrate the potential of this material. In the work by **Alam et al.**, activated carbon from *Paulownia tomentosa* was applied for the removal of two dyes-**Acid Red 4** and **Methylene Blue-**from aqueous solutions. A rapid equilibrium stage (~5 min) was observed, and the adsorption kinetics were best described by the **pseudo-second-order model.** The equilibrium data fit well with the **Langmuir isotherm model** [3]. Thermodynamic analysis revealed that the activation energy and enthalpy of adsorption differed for the two dyes: for Acid Red 4: E_a=30.57 kJ/mol, ΔH=24.88 kJ/mol, ΔS=-2843.32 J/mol·K; for Methylene Blue: E_a=3.712 kJ/mol, ΔH=1.1927 kJ/mol, ΔS=-0.329 J/mol·K [3]. These differences indicate that the adsorption mechanism depends on the adsorbate properties (charge, molecular structure) and environmental factors (such as pH).

In another study on the adsorption of **hydrogen sulfide (H_2S)** using a sorbent obtained from hybrid *Paulownia tomentosa* wood, both the adsorption isotherms and differential enthalpy were investigated. The recorded adsorption capacity reached approximately **0.25 mmol·g^{-1}** [5]. These data demonstrate that *Paulownia tomentosa* wood can be used not only for **aqueous purification** but also for **gas-phase adsorption**.

A general review of **green adsorbents** emphasizes that biomass-derived materials (including wood-based sorbents) are promising due to their **low cost, renewability**, and **ease of modification** [1].

Advantages, Limitations, and Prospects:

1. Advantages. The raw material is readily available due to the fast-growing nature of Paulownia tomentosa; it enables the production of carbon-based adsorbents with high porosity and substantial adsorption capacity. Its applications are versatile-covering both water purification and gas treatment. Moreover, local production is feasible in regions where plantation cultivation of Paulownia tomentosa is expanding (for example, the conditions in Uzbekistan are potentially suitable).

2. Limitations. Currently, there is a limited number of studies specifically focused on Paulownia tomentosa wood. Further data are needed regarding process scaling, stability, regeneration, and economic viability. Technological parameters-such as the optimal activation conditions (temperature, activating agents, time)-strongly influence product yield, porosity, and adsorbent strength. Additional evaluation of long-term durability, regeneration efficiency, and competitiveness with commercial materials is also required, along with life-cycle (LCA) and cost analyses for Paulownia-based adsorbents.

3. Future prospects. Further development should aim at optimizing activation processes tailored to specific pollutants (heavy metals, organic dyes, gases) and studying surface functionalization methods (e.g., introduction of active groups or metal modification) to enhance selectivity and capacity. Pilot-scale experiments and comparative studies with commercial activated carbons are essential. Additionally, assessing production and environmental performance within a regional framework (e.g., Central Asia, including Uzbekistan) is important. Integrating the use of Paulownia tomentosa into a renewable raw-material system-covering tree cultivation, wood processing, adsorbent production, and a closed-loop utilization cycle-represents a promising direction.

In summary, Paulownia tomentosa wood is a promising raw material for adsorbent production owing to its rapid growth, availability, and technological potential. Existing studies have demonstrated positive results for dye solution and gas purification, but for industrial application, further optimization, scale-up, regeneration studies, and economic assessments are required. Overall, this research direction is highly relevant and aligns with modern trends in green and sustainable purification technologies.

Thus, Paulownia tomentosa wood represents a promising raw material for the production of adsorbents due to its rapid growth rate, availability, and technological potential. Existing studies demonstrate positive results in the purification of dye solutions and gas media; however, for industrial application, further research is required on process optimization, scale-up, adsorbent regeneration, and economic feasibility. Overall, this direction is highly relevant and aligns with the modern trends of green and sustainable purification technologies.

Methods and Materials. The adsorption isotherms of hydrogen sulfide (H_2S) were measured using an experimental system consisting of a universal high-vacuum adsorption unit coupled with a Tian–Calvet-type differential automated microcalorimeter (model DAC-1-1A). This system provides high measurement accuracy (within the low-pressure range down to 10^{-4} torr) and excellent signal stability. The adsorption-calorimetric method applied in this study makes it possible to obtain the molar thermodynamic characteristics of adsorption and to elucidate in detail the mechanisms of interaction within adsorbent–adsorbate and adsorbate–adsorbate systems. Dosing of the adsorbate and the performance of adsorption measurements were carried out using a high-vacuum apparatus that allows gas introduction by both gas-volume and volume-liquid methods. Equilibrium pressures in the range of $10^{-5} \div 0.8$ torr were measured with a diaphragm baratron of type B627, whereas for pressures $P > 0.8$ torr a mercury U-tube manometer was employed. The use of the adsorption-calorimetric method enables comprehensive investigation of nanostructured, microporous, and mesoporous adsorbents, provides detailed characterization of their active surface, and allows determination of the key thermodynamic parameters and mechanisms governing the adsorption processes [7-13].

In this study, a carbonaceous adsorbent derived from the wood of the hybrid tree Paulownia tomentosa was used as the research material. This type of wood was selected due to its high biomass growth rate, low ash content, and favorable physicochemical properties, which allow for the production of sorbents with a well-developed porous structure. The process of obtaining the adsorbent involved two successive activation stages. In the first stage, the raw wood material underwent thermal treatment (carbonization) under controlled heating in an inert atmosphere. This stage ensured the removal of volatile organic compounds, the formation of a carbon matrix, and the initial development of a microporous structure. In the second stage, a conventional steam–gas activation was applied, during which the carbonized material was exposed to water vapor at temperatures between 750 °C and 850 °C. Steam acted as the activating agent, inducing partial oxidation of the carbon surface, increasing the specific surface area, and promoting the formation of an extensive microporous network. This activation method facilitates the development of pores of various sizes (micro-, meso-, and macropores), which significantly enhances the sorption capacity of the adsorbent. The resulting carbon material is characterized by a high specific surface area (up to 1000-1100 m^2/g), low ash content, and a stable structure. These properties make it an effective adsorbent for hydrogen sulfide (H_2S) removal from gas mixtures. Elemental analysis confirmed a predominant carbon content (>85%) and the presence of oxygen-containing functional groups that contribute to the chemisorption of hydrogen sulfide. Thus, the carbon sorbent based on *Paulownia tomentosa* wood represents an environmentally friendly and technologically accessible material with high performance characteristics, making it a promising candidate for further studies in the fields of gas purification and adsorption thermodynamics.

Results. The adsorption isotherm of hydrogen sulfide on a traditionally activated carbon adsorbent obtained from hybrid *Paulownia tomentosa* wood is shown in **Figure 1.** Minor saturation of the adsorption volume is observed at an adsorption amount of **0.02 mmol/g** at the equilibrium relative pressure **P/Ps=6·10⁻⁵** (corresponding to **P=1.06 torr**)-*Figure 1a*. Here, **Ps=17932 torr** represents the saturation pressure of hydrogen sulfide at **303 K**. Due to the relatively high vapor pressure of hydrogen sulfide, the experiment was carried out up to **670 torr.** The adsorption isotherm reaches a value of **1.75 mmol/g** at the relative pressure **P/Ps=0.0374** (or **P=670 torr).**

Figure 1a presents the adsorption isotherm of hydrogen sulfide on a carbon adsorbent derived from *Paulownia tomentosa* wood plotted as a function of **P/Ps**.

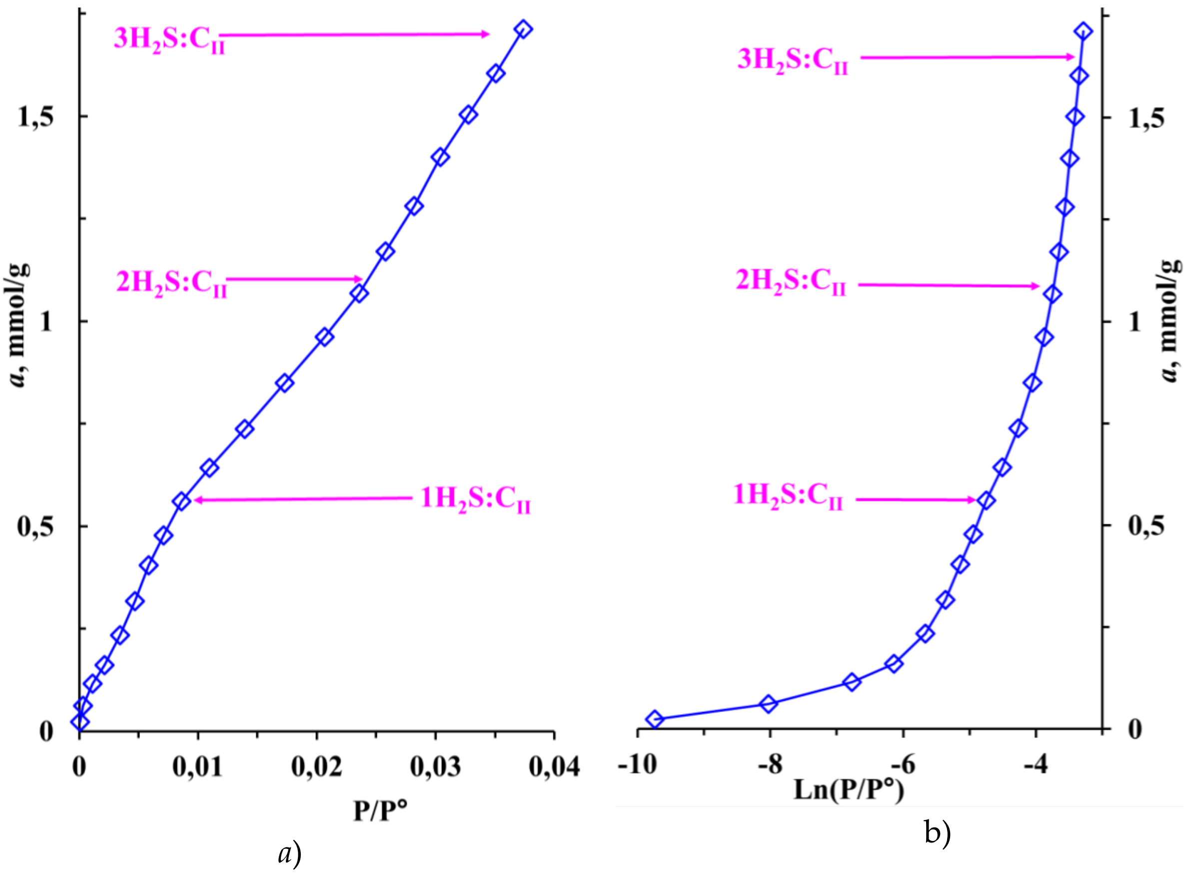

Fig. 1. Adsorption isotherms of H_2S molecules on a traditionally activated carbon adsorbent derived from *Paulownia tomentosa* wood at 303 K. a) in relative pressure coordinates, b) in logarithmic coordinates

The curve exhibits a typical shape for **microporous carbon materials**, reflecting the stepwise filling of active surface sites and micropores. In the low-pressure region (**P/Ps<0.01**), a sharp increase in adsorption is observed, indicating the presence of **high-energy adsorption centers** and **strong interactions** between H_2S molecules and the adsorbent surface. In the medium-pressure range, the process slows down due to the gradual filling of micropores, and with a further increase in pressure, the curve levels off into a **plateau**, indicating the attainment of **quasi-saturation**.

From the graph data, it was established that the total number of active sites of the adsorbent is 0.56 mmol/g, which corresponds to a well-developed microporous structure and a high hydrogen sulfide adsorption capacity. This value is consistent with the typical characteristics of activated carbon materials obtained by the steam–gas activation method at temperatures of 750–850 °C.

The graph reveals three characteristic stages, corresponding to different stoichiometric ratios of adsorbed molecules to carbon centers:

1. $1H_2S:C_{II}$ - primary monolayer physical adsorption on active sites;
2. $2H_2S:C_{II}$ - formation of associated H_2S molecular pairs inside micropores due to hydrogen bonding and dipole–dipole interactions;
3. $3H_2S:C_{II}$ - multilayer filling or clustering of hydrogen sulfide molecules within confined microporous spaces.

This sequential increase in the stoichiometric coefficient (1→2→3) reflects a transition from predominantly physical adsorption to physicochemical adsorption, involving associative interactions between H_2S molecules.

Figure 1b presents the adsorption isotherm of hydrogen sulfide on the carbon adsorbent derived from Paulownia tomentosa wood by thermal and steam–gas activation. The dependence of the adsorbed amount on the logarithm of the relative pressure Ln(P/Ps) exhibits a typical curve corresponding to physicochemical sorption on microporous carbon materials.

An exponential relationship between adsorption capacity and pressure is clearly visible, indicating the presence of a developed system of active micropores capable of supporting multi-stage interactions of H_2S molecules with the adsorbent surface. At low Ln(P/Ps) values, the process is characterized by a slow increase in adsorption capacity, corresponding to the filling of the most energetically favorable active sites. With increasing pressure, a more intensive gas uptake is observed, associated with the involvement of less active micropores.

Analysis of the isotherm shows that the adsorption centers reach saturation at a=0.56 mmol/g, reflecting the total capacity of the active micropores. Three conditional stages of interaction can be distinguished on the curve, corresponding to stoichiometric ratios of $1H_2S:C_{II}$, $2H_2S:C_{II}$, and $3H_2S:C_{II}$. These regions represent the successive attachment of H_2S molecules to the active sites of the carbon matrix, which may result from both physical adsorption and the formation of weak donor–acceptor bonds between sulfur-containing molecules and oxygen-bearing functional groups on the carbon surface.

Thus, the obtained data confirm that the steam–gas activated carbon adsorbent possesses high sorption capacity and a well-developed microporous structure. The shape of the isotherm indicates a physicochemical interaction mechanism between H_2S and the surface and can be satisfactorily described by the Dubinin–Radushkevich equation, which suggests a predominantly monomolecular adsorption mechanism.

The high sorption capacity and the presence of stable active sites make this carbon material a promising candidate for the purification of gas streams from hydrogen sulfide.

Conclusion. The adsorption of hydrogen sulfide molecules at 303 K was studied on a carbonaceous adsorbent derived from Paulownia tomentosa wood by thermal and steam–gas activation methods. The adsorption isotherm was determined in the range from low saturation regions up to a pressure of 670 torr, and the adsorption mechanism was established. It was found that the number of active sites of the adsorbent is 0.56 mmol/g, and that hydrogen sulfide molecules in the micropores of the adsorbent form a $3H_2S$:C adsorption mechanism. The isotherm demonstrates that the carbon adsorbent derived from *Paulownia tomentosa* exhibits pronounced microporosity and a high sorption capacity toward H_2S. The adsorption mechanism is stepwise (1–$3H_2S$:C) and is governed by the sequential filling of active sites and micropores, accompanied by the formation of associated molecular complexes within the adsorbent structure. The experimental adsorption–calorimetric research results make it possible to develop theoretical concepts of chemical and physical adsorption on carbonaceous adsorbents, as well as to obtain the main thermodynamic functions of the studied systems required for the calculation of sorption process technologies and equipment in practical applications.

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