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SCIENTIFIC REQUIREMENTS FOR ADSORBENTS USED IN THE PREPARATION OF SORPTION MATERIALS

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Abstract. The development of high-performance adsorption materials remains one of the most important challenges in environmental protection, water treatment, gas purification, and resource recovery technologies. The efficiency of adsorption processes is largely determined by the physicochemical properties of adsorbents, including their porous structure, specific surface area, mechanical stability, chemical resistance, and surface functional groups. Therefore, establishing scientifically grounded requirements for adsorbent materials is essential for designing efficient sorption systems and improving the performance of adsorption-based technologies. This paper analyzes the fundamental requirements imposed on adsorbents used in modern sorption processes. Particular attention is given to structural parameters such as micropore and mesopore distribution, pore volume, specific surface area, adsorption capacity, selectivity, regeneration ability, thermal stability, and mechanical strength. The influence of surface chemistry and oxygen-containing functional groups on adsorption performance is also discussed. In addition, the relationships between pore structure, adsorption mechanisms, and adsorbent efficiency are examined from both physicochemical and colloid-chemical perspectives. The study demonstrates that the development of advanced sorption materials requires an integrated approach combining optimized porous architecture, surface functionality, and operational stability. The results may serve as a scientific basis for the design, selection, and application of high-performance adsorbents derived from both conventional and renewable raw materials.

Keywords: adsorbent, adsorption materials, adsorption capacity, porous structure, micropores, mesopores, specific surface area, functional groups, adsorption selectivity, sorption technology, activated carbon, adsorption efficiency.

Introduction

The increasing number of industrial enterprises and the expansion of existing production facilities have led to a growing demand for adsorbent materials. In particular, the medical, food-processing, petroleum and gas, and textile industries require large quantities of highly efficient adsorbents for purification, separation, and environmental protection processes. However, a significant proportion of the sorption materials currently used in industrial applications are still imported, including BAU-A grade activated carbon produced in the Russian Federation. Therefore, the development of import-substituting adsorbents based on locally available raw materials has become an important scientific

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and technological challenge. In recent years, considerable efforts have been made in Uzbekistan to establish the production of adsorbents from indigenous resources and industrial by-products through the implementation of advanced and economically viable technologies.

At present, within the framework of national localization and import-substitution programs, special attention is being paid to the production of adsorbents from locally available raw materials in order to reduce dependence on imported products and strengthen the national economy. The development of domestic adsorbent production not only contributes to economic sustainability but also promotes the efficient utilization of renewable resources and industrial waste streams [1–6].

Today, contamination of atmospheric air, water resources, and soil caused by various anthropogenic activities has become one of the most pressing global environmental issues. Adsorption technologies play a crucial role in addressing these challenges due to their high efficiency, operational simplicity, and wide applicability. Consequently, the demand for advanced adsorbents with superior adsorption performance continues to increase worldwide. In this context, the development of cost-effective, environmentally friendly, and highly efficient adsorbents derived from local raw materials represents an important scientific and practical task [7–9].

Modern research has demonstrated that a wide range of carbonaceous precursors can be utilized for the preparation of adsorbents, including coal, peat, agricultural residues, wood waste, fruit stones, nut shells, rice husks, cotton stalks, and various other biomass resources. Biomass-based precursors are particularly attractive because of their renewability, low cost, abundance, and environmental sustainability. The cellulose, hemicellulose, and lignin constituents present in biomass serve as important structural precursors for the formation of highly developed porous carbon frameworks during carbonization and activation processes.

As a result, the scientific substantiation of the requirements imposed on adsorbents and the selection of suitable biomass feedstocks for the production of high-performance sorption materials have become key issues in contemporary adsorption science and technology.

The primary requirements for a raw material to be considered suitable for adsorbent production are as follows:

- A high carbon content should be present in the raw material.
- The material should possess a strong ability to develop micro- and mesoporous structures during activation.
- It should exhibit high mechanical strength.
- High thermal and chemical stability are required.
- The raw material should provide a high product yield during the activation process.
- It should be a locally available and renewable resource.
- The material should be economically viable and cost-effective.
- The possibility of large-scale industrial processing should be ensured.

The performance of adsorbents is primarily governed by their specific surface area, pore structure, and surface functional groups. Therefore, the higher the content of organic constituents in the precursor material, the greater the probability of forming a highly developed porous structure during activation. Such materials exhibit excellent adsorption performance toward gaseous pollutants, including H_2S, CO_2, SO_2, and NO_x, as well as a wide range of organic and inorganic contaminants.

Under the conditions of Uzbekistan, Paulownia tomentosa, which has recently been cultivated extensively within localization and afforestation programs, represents one of the most promising renewable feedstocks for adsorbent production. Its rapid growth rate, high annual biomass yield, and the substantial accumulation of wood, branch, and bark residues provide significant opportunities for

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efficient resource utilization. Furthermore, the biomass of Paulownia contains considerable amounts of cellulose, hemicellulose, and lignin, which serve as essential precursors for the formation of well-developed micro- and mesoporous structures during carbonization and activation processes.

Carbonaceous materials derived from Paulownia wood and bark are characterized by a high specific surface area, favorable adsorption properties, and good regeneration capability. In addition, the availability of this biomass as a local renewable resource contributes to reducing the production costs of adsorbents and creates opportunities for the development of import-substituting sorption materials. Consequently, Paulownia-based biomass can be regarded as a highly promising precursor for the production of advanced adsorbents intended for environmental protection, gas purification, water treatment, and various industrial adsorption applications.

Consequently, the selection of a suitable precursor for adsorbent production should be based on several key criteria, including its chemical composition, physical characteristics, activation potential, availability, and economic feasibility. Among the various biomass resources, Paulownia tomentosa residues represent a highly promising renewable feedstock that satisfies these requirements. Owing to its favorable chemical composition and structural characteristics, this biomass can serve as an effective precursor for the production of high-performance activated adsorbents. The development of advanced adsorbent materials derived from Paulownia waste and their application in environmental remediation, water purification, gas treatment, and sustainable resource utilization are of considerable scientific significance and practical importance.

The selection of a suitable precursor is one of the most critical stages in the synthesis of adsorbent materials. In this process, several key factors must be considered, including renewability of the feedstock, biomass productivity, chemical composition, pore-forming potential, availability, and economic feasibility. From this perspective, Paulownia tomentosa biomass represents a highly promising raw material for the production of advanced adsorbents. Owing to its rapid growth rate, substantial annual biomass yield, and favorable lignocellulosic composition, Paulownia has attracted increasing attention as a sustainable precursor for the development of high-performance carbon-based sorption materials.

The selection of an appropriate precursor is a critical step in the synthesis of adsorbent materials, as the performance of the final product largely depends on the intrinsic properties of the raw feedstock. Key selection criteria include renewability, biomass productivity, chemical composition, pore-forming capability, availability, and economic viability. From this perspective, Paulownia tomentosa biomass has emerged as a particularly promising precursor for the development of advanced adsorbent materials.

Among the various species of Paulownia, Paulownia tomentosa is distinguished by its exceptionally rapid growth rate and high biomass productivity. Its ability to generate substantial quantities of wood and foliage within a relatively short growth cycle makes it an attractive renewable resource for the production of carbon-based sorbents. These characteristics not only ensure a sustainable supply of raw material but also enhance its value as an environmentally benign and economically feasible feedstock for adsorption technologies [10].

The suitability of a raw material for adsorbent production is largely determined by its chemical composition. According to data reported in the literature, Paulownia tomentosa wood contains approximately 45–50% cellulose, 20–25% hemicellulose, and 18–22% lignin. These lignocellulosic constituents play a crucial role in the formation of highly porous carbon structures during carbonization and activation processes. In addition, the biomass contains 2–5% mineral matter, including calcium, potassium, magnesium, and silicon, which may significantly influence the

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development of pore structure and the physicochemical characteristics of the resulting adsorbents during activation [11–12].

The mineral composition of biomass also plays a significant role in determining the physicochemical properties of the resulting adsorbents. According to published studies, carbonaceous sorbents derived from Paulownia tomentosa biomass exhibit a specific surface area in the range of 1100–1500 $m^2\ g^{-1}$, while their total pore volume typically varies between 0.6 and 0.9 $cm^3\ g^{-1}$. Such structural characteristics indicate the formation of a highly developed porous network with a substantial number of accessible adsorption sites. Consequently, these materials demonstrate considerable potential for the adsorption of gaseous pollutants, particularly hydrogen sulfide (H_2S) and other low-molecular-weight compounds, owing to their enhanced surface accessibility and pore architecture [13–14].

The adsorption performance of carbon-based materials is determined not only by their pore structure but also by the nature and abundance of surface functional groups. Oxygen-containing functionalities formed during the activation process, including hydroxyl (–OH), carboxyl (–COOH), and carbonyl (C=O) groups, play a crucial role in governing the interactions between the adsorbent surface and adsorbate molecules. These functional sites can serve as active centers for adsorption through hydrogen bonding, acid–base interactions, and electrostatic forces. In particular, the presence of such surface functionalities has been reported to enhance the affinity of activated carbon materials toward hydrogen sulfide (H_2S), thereby improving adsorption efficiency and overall sorption performance [10].

One of the key advantages of Paulownia tomentosa biomass lies in its renewable nature, environmental sustainability, and economic viability. Owing to its exceptionally rapid growth rate and ability to generate large quantities of biomass within a relatively short cultivation period, Paulownia represents a reliable and continuously available feedstock for the production of carbon-based adsorbents. Furthermore, its widespread local availability enhances resource accessibility and reduces production costs, making it an attractive precursor for the sustainable manufacture of high-performance sorption materials.

The high cellulose and lignin contents of Paulownia tomentosa biomass, together with its ability to develop a well-defined porous structure and a surface enriched with functional groups, make it a promising precursor for the production of advanced sorption materials. These characteristics enable the resulting carbon-based adsorbents to effectively adsorb not only hydrogen sulfide (H_2S), but also water vapor (H_2O), benzene (C_6H_6), ethanol (C_2H_5OH), carbon dioxide (CO_2), and a variety of other adsorbates. In recent years, carbonaceous materials prepared from different parts of the Paulownia tree, including wood residues, stems, and bark, have been extensively investigated for the adsorption of water vapor, volatile organic compounds, and carbon dioxide. The reported results indicate that these materials possess a highly developed porous structure and favorable surface chemistry, suggesting significant potential for H_2S adsorption and other gas purification applications.

One of the significant advantages of adsorbents derived from Paulownia tomentosa waste biomass is their excellent long-term operational stability and regeneration capability. According to cyclic adsorption–desorption studies reported in the literature, these sorbents are capable of retaining approximately 80–85% of their initial adsorption capacity even after five to six regeneration cycles. Such behavior indicates a high degree of structural stability and resistance to performance degradation during repeated use.

The ability to maintain adsorption efficiency over multiple regeneration cycles is a critical parameter for practical applications, as it directly affects the economic feasibility and operational sustainability of adsorption-based technologies. Compared with conventional carbonaceous adsorbents,

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Paulownia-derived sorbents exhibit competitive and, in some cases, superior regeneration performance, highlighting their potential for long-term industrial utilization.

Nevertheless, a comprehensive assessment of their long-term adsorption behavior under extended cyclic operating conditions requires further investigation. Additional studies focusing on adsorption kinetics, structural stability, and regeneration efficiency over a larger number of cycles would provide a deeper understanding of the durability and practical applicability of these materials in large-scale adsorption processes.

The adsorption performance of carbon materials derived from Paulownia tomentosa can be further enhanced through appropriate chemical modification strategies (Figure 1). According to published studies, activated sorbents prepared from Paulownia tomentosa wood have exhibited a Brunauer–Emmett–Teller (BET) specific surface area of up to 1350 $m^2\ g^{-1}$ and a total pore volume of approximately 0.72 $cm^3\ g^{-1}$.



Figure 1. Potential pathways for the production of adsorbents from Paulownia tomentosa wood waste

Under these structural conditions, an H_2S adsorption capacity of up to 92 mg g^{-1} has been reported [15]. These findings demonstrate the significant potential of Paulownia biomass as a precursor for the synthesis of high-performance carbon adsorbents with well-developed porous structures and enhanced adsorption characteristics.

In general, the selection of suitable precursor materials for adsorbent production requires compliance with a number of fundamental criteria that determine their applicability and performance in adsorption processes. The principal requirements and evaluation parameters commonly used for assessing potential adsorbent feedstocks are summarized in Table 1.

Table 1.

Requirements and selection criteria for assessing the suitability of raw materials as adsorbent precursors

№	Adsorbent Performance Requirements and Their Evaluation Criteria	
1	High Carbon Content	A carbon content of ≥70% is essential for the formation of active adsorption sites.
2	Pore-Forming Capability	Micropore formation should occur during pyrolysis through the release of volatile gases and the removal of tar

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		components from the precursor material.
3	Resistance to Activation Processes	The structural integrity of the material should be maintained during both chemical activation (e.g., KOH, H_3PO_4) and physical activation (e.g., steam or CO_2)
4	Surface Energy and Functional Groups	The presence of oxygen-containing functional groups, such as hydroxyl (–OH), carboxyl (–COOH), and carbonyl (C=O), after activation enhances the density of active adsorption sites and improves adsorption performance.
5	Effect of Moisture Content and Thermal Conditions	After drying at 105°C, the moisture content should not exceed 5%. Excessive moisture may hinder pore development and reduce the efficiency of the activation process
6	Ash Content and Harmful Impurities	A low concentration of undesirable impurities in the precursor material is essential for the production of high-quality adsorbents. The presence of chlorine-, sulfur-, fluorine-containing compounds and excessive metal salts may adversely affect the adsorbent structure and lead to deactivation of active adsorption sites.
7	Thermal Stability ($\Delta m < 10$ % at 1000°C)	The adsorbent structure should maintain its stability under high-temperature conditions.

The use of precursor materials that satisfy the above-mentioned requirements enables the synthesis of highly efficient carbon-based sorption materials. The selection of an appropriate feedstock is primarily governed by several key factors, including its chemical composition, pore-forming potential, renewability, availability, and economic feasibility. In the present study, the trunk wood, branches, and bark residues of the hybrid Paulownia tomentosa tree were selected as the precursor materials for adsorbent production. This biomass was chosen due to its compliance with the fundamental requirements for adsorbent synthesis, particularly its high content of organic constituents and its ability to generate a well-developed porous structure during carbonization and activation processes. Taking these characteristics into consideration, different morphological parts of the Paulownia tree were utilized as renewable feedstocks for the preparation of carbonaceous sorption materials with enhanced adsorption performance.

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