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TECHNOLOGICAL APPROACHES FOR PRODUCING ACTIVATED CARBON ADSORBENTS FROM PAULOWNIA TOMENTOSA BIOMASS: COMPARATIVE ANALYSIS OF STEAM AND MICROWAVE ACTIVATION METHODS

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Abstract. The development of sustainable and high-performance adsorbents from renewable biomass resources has become an important research direction in modern environmental and adsorption technologies. In this study, Paulownia tomentosa wood waste was investigated as a renewable precursor for the production of activated carbon adsorbents. Two activation approaches, namely conventional steam activation and non-conventional microwave activation, were comparatively evaluated in terms of technological efficiency, structural development, and adsorption performance. The proposed technology consists of biomass preparation, drying, size reduction, pyrolysis under an inert atmosphere, followed by either steam or microwave activation. The influence of activation conditions on pore development, carbonization degree, and adsorption characteristics was investigated. Structural and physicochemical properties of the obtained adsorbents were evaluated using adsorption methods, FTIR spectroscopy, SEM, TEM, EDS, and XRD analyses. The results demonstrated that both activation approaches produced highly porous carbon structures; however, microwave activation significantly reduced processing time and energy consumption while maintaining comparable adsorption properties. The obtained activated carbons exhibited a well-developed porous structure, oxygen-containing functional groups, and a highly carbonized matrix, making them promising candidates for adsorption applications. The developed technology provides a scientific basis for the utilization of Paulownia biomass as a low-cost renewable precursor for advanced sorption materials.

Keywords: Paulownia tomentosa, activated carbon, biomass valorization, steam activation, microwave activation, porous carbon materials, adsorption technology, sorption materials.

1. Introduction

The increasing demand for efficient adsorbents in environmental protection, water treatment, gas purification, and industrial separation processes has stimulated extensive research on renewable biomass-derived sorption materials. Activated carbons remain among the most widely used adsorbents owing to their high specific surface area, developed pore structure, chemical stability, and regeneration capability [1–3].

Traditionally, commercial activated carbons are produced from coal, peat, and wood precursors. However, growing environmental concerns and the need for sustainable resource utilization have encouraged the exploration of alternative biomass feedstocks [4,5]. Agricultural residues, forestry wastes, nut shells, fruit stones, rice husks, and lignocellulosic biomass have been extensively investigated as potential precursors for carbonaceous adsorbents [6–8].

Among renewable biomass resources, Paulownia tomentosa has attracted considerable attention due to its rapid growth rate, high annual biomass productivity, and favorable lignocellulosic composition. The wood contains significant amounts of cellulose, hemicellulose, and lignin, which provide suitable precursors for porous carbon formation during carbonization and activation processes [9–11].

Several studies have reported the preparation of activated carbons from Paulownia biomass and demonstrated their promising adsorption characteristics toward water vapor, volatile organic compounds, and gaseous pollutants [12–14]. Nevertheless, comparative investigations of conventional steam activation and microwave-assisted activation remain limited.

Therefore, the objective of this study was to develop and evaluate a technological approach for producing activated carbon adsorbents from Paulownia tomentosa biomass using steam and microwave activation methods and to compare their technological and structural characteristics.

2. Materials and Methods

2.1 Raw Material

Wood residues of Paulownia tomentosa were used as the precursor material. The biomass consisted of trunk, branch, and bark residues collected after wood processing operations.

2.2 Preparation Procedure

The technological process involved:

- drying of biomass at 105°C for 12–24 h;
- grinding and size reduction;
- pyrolysis under nitrogen atmosphere;
- activation using either steam or microwave treatment;
- cooling, washing, filtration, drying, and classification.

2.3 Steam Activation

Steam activation was performed at 800–900°C for 1–2 h using water vapor as the activating medium. The process was conducted under controlled temperature and gas flow conditions.

2.4 Microwave Activation

Microwave activation was carried out using microwave radiation at 700–800°C equivalent conditions with power levels ranging from 400 to 800 W for 10–30 min under an inert atmosphere.

2.5 Characterization

The obtained adsorbents were characterized using: BET surface area measurements; FTIR spectroscopy; SEM analysis; TEM analysis; EDS elemental analysis; XRD structural analysis.

3. Results and Discussion

3.1 Technological Comparison of Activation Methods

The proposed technological scheme demonstrates that both activation approaches produce activated carbon materials through similar carbonization stages. However, significant differences were observed in energy consumption and processing time.

Steam activation requires prolonged thermal treatment (1–2 h) and continuous steam generation, resulting in relatively high energy consumption. In contrast, microwave activation achieves rapid volumetric heating of the carbonized biomass, significantly reducing activation time to 10–30 min.

The reduction in processing time improves process productivity and decreases operational costs, making microwave activation attractive for industrial implementation.

3.2 Structural Development of Adsorbents

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Pyrolysis followed by activation resulted in the formation of a highly developed porous carbon structure. The release of volatile compounds and tar fractions contributed to pore formation, while activation enlarged and interconnected the pore network.

FTIR analyses confirmed the formation of oxygen-containing functional groups including hydroxyl, carbonyl, and carboxyl functionalities. These groups serve as active adsorption sites and contribute to adsorption performance. TEM and SEM analyses revealed a heterogeneous porous morphology characterized by carbon aggregates, porous domains, and partially ordered carbon structures. EDS results confirmed the predominance of carbon with minor amounts of oxygen and mineral elements. XRD patterns indicated predominantly amorphous carbon structures with limited ordering, which is typical for biomass-derived activated carbons. Figure 1 illustrates the technological scheme for the production of activated carbon adsorbents from Paulownia tomentosa biomass. The process consists of several sequential stages, including raw material preparation, pyrolysis, activation, cooling, washing, drying, and final product recovery. In the first stage, Paulownia wood residues are mechanically ground to obtain a uniform particle size distribution. The material is subsequently dried at 105°C for 12–24 hours to remove excess moisture. Moisture reduction is essential for improving the efficiency of the subsequent carbonization and activation processes. The dried biomass is then subjected to thermal treatment in a pyrolysis reactor under an inert gas atmosphere. Pyrolysis is performed at 500–600°C for 1–2 hours, resulting in the release of volatile organic compounds and the formation of a carbon-rich char. This stage serves as the foundation for the development of the adsorbent structure.

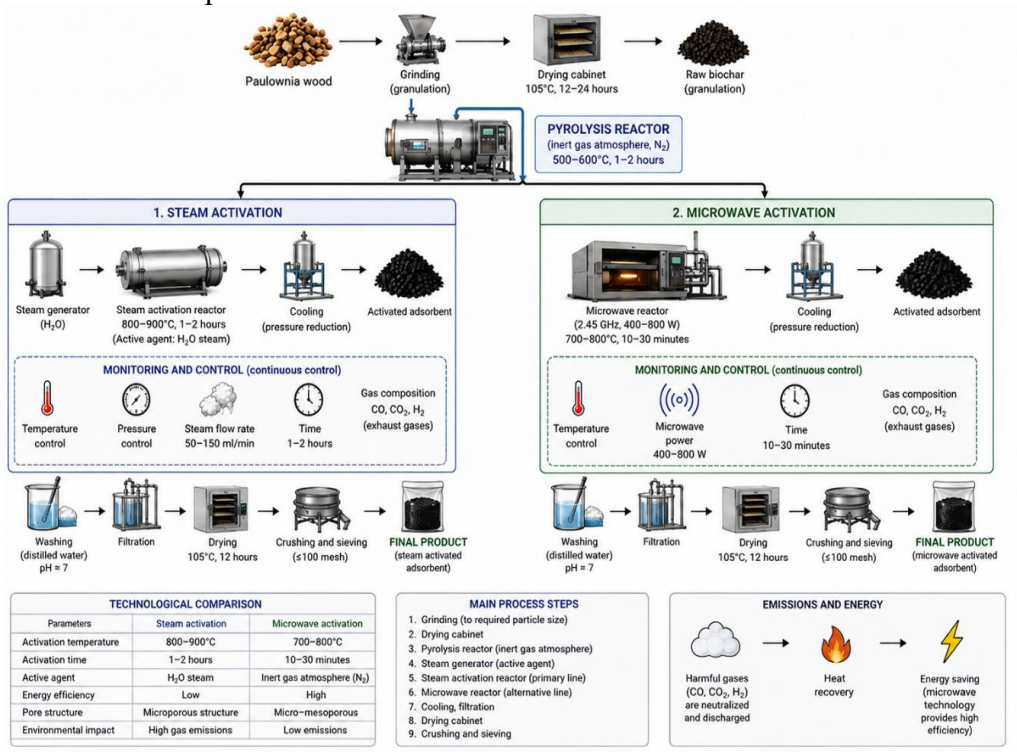


Figure 1. Technological flow diagram for the production of activated carbon adsorbents from Paulownia tomentosa biomass using steam and microwave activation methods.

The obtained char is activated using two different technological approaches. The first approach is conventional steam activation, carried out at 800–900°C for 1–2 hours in the presence of water vapor. Steam reacts with the carbon matrix, opens previously inaccessible pores, and promotes the

formation of a well-developed microporous structure, leading to the production of highly efficient activated adsorbents.

The second approach involves microwave-assisted activation. In this method, the carbonized material is treated in a microwave reactor at a power of 400–800 W under conditions corresponding to 700–800°C for 10–30 minutes. Microwave heating provides volumetric energy transfer throughout the material, significantly accelerating the activation process while reducing energy consumption.

For both activation methods, critical process parameters such as temperature, pressure, activating medium flow rate, and treatment time are continuously monitored. In addition, the composition of the evolved gases (CO, CO_2, and H_2) is controlled throughout the process.

Following activation, the products are cooled, washed with distilled water, filtered, and dried. The dried material is subsequently crushed and sieved to obtain a uniform adsorbent fraction suitable for practical applications.

The technological comparison demonstrates that steam activation promotes the development of a highly microporous structure, whereas microwave activation substantially reduces processing time and energy consumption. Therefore, both technologies can be considered effective approaches for the production of high-performance carbon adsorbents from Paulownia tomentosa biomass.

3.3 Advantages of Microwave Activation

The comparative analysis showed that microwave activation offers:

- reduced processing time;
- lower energy demand;
- improved process controllability;
- simplified technological implementation.

These advantages support its application as a promising alternative to conventional steam activation.

4. Conclusions

Activated carbon adsorbents were successfully produced from Paulownia tomentosa biomass using both conventional steam activation and microwave-assisted activation technologies.

The developed technological approach demonstrated the feasibility of converting renewable wood residues into high-value sorption materials. Structural analyses confirmed the formation of highly porous carbon matrices enriched with adsorption-active functional groups.

Microwave activation significantly reduced activation time and energy consumption while maintaining favorable structural properties, indicating its potential as an efficient and sustainable activation method.

The results confirm that Paulownia tomentosa biomass represents a promising renewable precursor for the production of advanced activated carbon adsorbents suitable for environmental and industrial adsorption applications.

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