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MATERIAL BALANCE AND TECHNO-ECONOMIC EFFICIENCY OF SORBENT MATERIAL PRODUCTION TECHNOLOGY

D.J. Jumayeva DSc
R.O. Akhrorova PhD
K.Sh. Zaripboev
B.H. Haydarov
I.A.Ergasheva
G.Juldasbayeva
Institute of General and Inorganic Chemistry,
Academy of Sciences of the Republic of Uzbekistan

Abstract: This study evaluated the material balance and techno-economic efficiency of the technology for producing activated sorbent materials from local plant-based raw materials, particularly Paulownia tomentosa biomass. The main objective of the research was to assess the feasibility of implementing the developed technology by determining raw material consumption, product yield, technological losses, and economic indicators during the sorbent production process.

The technological process consisted of biomass drying, grinding, pyrolysis, activation using steam and microwave treatment, cooling, washing, and final product recovery. Material balance calculations revealed systematic relationships between the initial biomass mass, carbonizate yield, activation losses, and the final adsorbent yield. The obtained results demonstrated that Paulownia tomentosa biomass can be effectively converted into carbonaceous adsorbents with high sorption properties and satisfactory product yields.

Techno-economic analyses indicated that the utilization of locally available raw materials can significantly reduce production costs, decrease dependence on imported adsorbents, and improve overall economic efficiency. Based on the calculations performed, the industrial-scale application of the developed sorbents was found to be economically feasible and justified.

The results of this study provide an important scientific and technological basis for converting local biomass resources into high-value sorption materials, promoting import substitution technologies, and ensuring both environmental and economic sustainability.

Keywords: Paulownia tomentosa, sorption material, activated adsorbent, material balance, techno-economic efficiency, biomass, carbonaceous sorbent, technological process, import substitution.

Introduction

In recent years, the demand for highly efficient sorbent materials has increased significantly in the fields of water and gas purification, oil and gas industries, chemical technologies, food production, and environmental protection. Activated carbon adsorbents are among the most widely used sorption materials due to their high specific surface area, well-developed porous structure, and excellent adsorption properties [1–3].

At present, a substantial portion of activated carbon adsorbents utilized in various industrial sectors consists of imported products. This situation leads to an increase in production costs, greater dependence on foreign markets, and additional expenditure of foreign currency resources.

Therefore, the development of import-substituting sorption materials based on locally available raw materials has become one of the most important scientific and practical challenges [4–6].

Technologies for producing sorbents from renewable biomass resources, particularly agricultural and wood-processing wastes, have been extensively investigated worldwide in recent years [7–9]. Such raw materials are characterized by their low cost, renewability, and environmental friendliness. Paulownia tomentosa is considered a promising feedstock for sorbent production due to its rapid growth rate, high biomass yield, and significant content of cellulose and lignin.

However, before any technology can be implemented on an industrial scale, it is essential to determine its material balance and evaluate its techno-economic efficiency. Material balance calculations make it possible to assess material flows within the technological process, determine product yield, and estimate technological losses. Meanwhile, techno-economic analysis serves to evaluate production costs, product cost price, and overall economic performance indicators [10–11].

In this regard, the aim of the present study is to calculate the material balance of the technology for producing activated carbon sorbents from Paulownia tomentosa waste, evaluate product yield and technological losses, and determine the techno-economic efficiency of the developed technology.

Results and Discussion

Accurate determination of the material balance and evaluation of product cost are of great importance when implementing technological processes on an industrial scale. Material balance calculations make it possible to assess raw material consumption, intermediate product yields, and final product formation patterns, whereas economic analyses serve to determine the practical feasibility and efficiency of the technology.

In the present study, a material balance was calculated for the production process of activated carbon sorbents derived from Paulownia tomentosa biomass waste. In addition, the economic efficiency of locally produced sorbents was comparatively evaluated against the imported BAU-A activated carbon adsorbent. The material balance for the production of sorption materials before and after carbonization is presented in Table 1.

According to the calculation results, processing 2000 kg of Paulownia tomentosa waste yields approximately 720 kg of carbonizate. During the pyrolysis process, mass losses occur due to the removal of moisture, volatile organic compounds, and tar-like substances contained in the raw material. These transformations lead to a significant reduction in mass while simultaneously increasing the carbon content and sorption potential of the resulting carbonaceous material.

table-1

Material balance for sorption material production

Components	**Quantity, kg**	**Output streams**	**kg**
Carbonization stage		Activation stage	
Paulownia waste biomass	2000	Paulownia waste	2000
Pyrolysis gas products	650	Carbonizatte	720
Tar and condensable products	420	Activation loss	180

Moisture and volatile matter	210	Ready-made adsorbent	540
Char (carbonizate)	720	Balance: 720 = 180 + 540	
Ready-made adsorbent	540		
Balance: 2000 = 650 + 420 + 210 + 720			

In the next stage, the carbonizate is activated using steam or microwave interaction. During the activation process, a portion of the carbon matrix gasifies, leading to an additional loss of mass, which results in obtaining 540 kg of finished adsorbent from 720 kg of carbonizate. Thus, the yield of the finished product relative to the raw material is approximately 27%. This is considered a satisfactory indicator for technologies producing biomass-based activated carbon sorbents and confirms the stability of the technological process. The economic efficiency indicators based on the total consumption costs for obtaining the sorbent material, derived from the presented material balance, are given in Table 2."

table 2

Production costs of adsorbents and assessment of their expected economic efficiency

T/p	Name	Unit of measurement	BAU-A	MTPAK-A
1	Annual adsorbent requirement	tonna	0,540	0.540
2	Cost of One Ton of Adsorbent	mln. sum‘	131.560.0	82,637
3	Expenses for Purchasing the Adsorbent	mln. sum	71,042	-
4	Labor Costs	mln. sum	1,272	32,727
5	Taxes	mln. sum	0,154	-
6	Amount of Raw Material Required to Produce 540 kg of Finished Adsorbent	tonna	-	2.0
	Costs Associated with Purchasing the Raw Materials	mln. sum	-	4,000
7	Electricity Costs Incurred for Producing 540 kg of Finished Adsorbent	mln. sum	-	7,897
8	Total Production Costs	mln. sum	203,874	127,261
9	Annual Economic Savings of the Enterprise	mln. sum	203,874 – 127.261= 76,613	

The results of the economic analysis demonstrated that the production of the MTPAC-A adsorbent, obtained from local Paulownia waste, is economically feasible and advantageous. According to the calculations, satisfying the enterprise's annual demand of 540 kg of adsorbent through imported BAU-A activated carbon would require expenditures amounting to 203.874 million UZS.

In contrast, the total cost of producing the same quantity of adsorbent using the developed local technology is 127.261 million UZS. Consequently, the annual economic savings amount to 76.613 million UZS.

The obtained results indicate that the utilization of locally available raw materials makes it possible to reduce production costs, substitute imported products, and achieve significant savings in foreign currency expenditures.

table 3

Specification of technological equipment

Scheme No.	Equipment Name	Quantity	Material / Protection Method	Technical Characteristics
1	Raw Material Receiving Hopper	1	Steel, anti-corrosion coating	Capacity: 5–10 m³
2	Belt Conveyor	2	Steel frame, rubber belt	Capacity: 1–3 t/h
3	Crusher	1	Steel with wear-resistant lining	Particle size: 1–5 mm
4	Rotary Dryer	1	Heat-resistant steel	Temperature: 100–200°C; Capacity: 1–2 t/h
5	Screening Unit (Sieve)	1	Steel	Fraction size: 1–5 mm
6	Pyrolysis Furnace (Reactor)	1	Heat-resistant steel with thermal insulation	Temperature: 400–700°C; Inert atmosphere
7	Activation Furnace	1	Heat-resistant steel	Temperature: 700–900°C; Steam/Chemical activation
8	Cooling Unit	1	Steel	Discharge temperature: ≤ 50°C
9	Washing Apparatus	1	Stainless steel	Volume: 2–5 m³
10	Filter Press or Vacuum Filter	1	Stainless steel	Filtration rate: 0.5–1 m³/h
11	Final Dryer	1	Heat-resistant steel	Temperature: 100–120°C
12	Dust Collector (Cyclone/Filter)	2	Steel	Efficiency: 90–99%
13	Gas Cleaning Unit (Scrubber)	1	Stainless steel	Gas flow rate: 1000–3000 m³/h
14	Packaging Machine	1	Steel	Packaging in 10–50 kg bags
15	Storage Silos / Storage Tanks	2	Steel	Capacity: 5–20 m³

Based on the results of the conducted studies, the application areas and optimal operating conditions of activated sorbents obtained from Paulownia tomentosa waste were determined. The sorbents developed within the framework of the project were characterized by a highly developed micro- and mesoporous structure and demonstrated high adsorption activity toward organic compounds. One of the main application areas of the developed sorbents was also investigated for the deep purification of water–alcohol solutions. In previous studies, these adsorbents were tested for the removal of harmful impurities, and it was established that their sorption properties were not inferior to those of the imported BAU-A activated carbon adsorbent and, in some cases, were even superior.

Conclusion. Based on the additional results obtained during the research, the sorption properties of the developed sorbents in gaseous media were also evaluated in order to expand their potential fields of application. In particular, additional studies on the adsorption of hydrogen sulfide (H_2S) and carbon dioxide (CO_2) demonstrated that these sorbents possess high sorption activity toward these components. However, these investigations were not included among the primary objectives specified in the project work plan and were carried out as supplementary scientific studies aimed at assessing the broader application potential of the developed sorbents.

The obtained results indicate that the sorbents can be considered promising materials not only for the purification of water–alcohol solutions but also for applications in the oil and gas industry, including natural gas treatment, removal of hydrogen sulfide and carbon dioxide, capture of organic vapors, and purification of industrial wastewater.

The sorbents produced by the microwave activation method were found to be particularly promising for industrial-scale production due to their high sorption activity, short preparation time, and relatively low energy consumption.

Thus, the developed technological regulations and the identified optimal operating conditions provide a scientific and technological basis for the production of adsorbents with high sorption performance derived from Paulownia tomentosa waste. Furthermore, the additional studies demonstrated that these sorbents have significant potential not only for the purification of water–alcohol solutions but also for gas purification processes and various environmental technologies.

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