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MICROSCOPIC ANALYSIS OF THE SORPTION OF BASIDIOMYCETE FUNGI ON MODIFIED MATERIALS — ALUMINUM COMPOSITE OXIDE COATINGS

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Zahro Rakhmatovna Akhmedova
Institute of Microbiology, Academy of Sciences of the Republic of Uzbekistan, Doctor of Biological Sciences, Professor.
Munavvar Abdukahkharovna Yakhyaeva
Institute of Microbiology, Academy of Sciences of the Republic of Uzbekistan, Junior Researcher
Ziyoda Tashtemirovna Khamraeva
Institute of Microbiology, Academy of Sciences of the Republic of Uzbekistan, Junior Researcher
Abdulaziz Adkhamovich Ibragimov
Institute of Microbiology, Academy of Sciences of the Republic of Uzbekistan, Research Doctoral Candidate

Abstract: *This article analyzes the structure, phase and compositional characteristics, as well as optimization methods of aluminum-based composite oxide coatings exhibiting sorption activity toward microbiological objects and modification materials prone to separation. The material phases involved in the formation of composite sorbents, their interactions, and their influence on sorption properties were investigated using electron microscopy, X-ray phase analysis, and infrared spectroscopy.*

Keywords: *aluminum oxide, sorbent, composite coating, microbiological objects, phase analysis, modification, structural optimization.*

Аннотация: *В статье проанализированы структура, фазовый и композиционный состав, а также методы оптимизации алюминий содержащих композитных оксидных покрытий, обладающих сорбционной активностью по отношению к микробиологическим объектам и модификационным материалам, склонным к разделению. Материальные фазы, используемые при создании композитных сорбентов, их взаимное взаимодействие и влияние на сорбционные свойства были исследованы с применением электронной микроскопии, рентгенофазового анализа и инфракрасной спектроскопии.*

Ключевые слова: *оксид алюминия, сорбент, композитное покрытие, микробиологические объекты, фазовый анализ, модификация, оптимизация структуры.*

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Annotatsiya: *Ushbu maqolada bazidial zamburug'larni alyuminiy kompozit qoplamali plastinkali sorbentlarga immobilizatsiya qilish, sorbentning sorbsion faolligini aniqlash,. sorbentlar potensial immobilizatsiya maydonida zamburug' mitseliyini saqlash va alyuminiyning korroziyasini nazorat qilish usullari tahlil qilingan. Bundan maqsad: bazidial zamburug' biomassasini alyuminiy plastinkaga immobillash, metallarni sorbsion quvvatini oshirish va qayta qo'llash imkoniyatlarini o'rganish.*

Kalit so'zlar: *bazidial zamburug'lar, alyuminiy plastinka, sorbent, immobilizatsiya, metal sorbsiyasi, mitseliy*

INTRODUCTION

In modern nanomaterials technology, aluminum composite oxides play a key role in the isolation and elimination of biological objects, including bacteria, viruses, and various microorganisms. These materials possess not only high sorption capacity but also antibacterial properties, which makes them highly significant for microbiological analysis, biotechnology, and environmental monitoring.

Modified composites are characterized by structural flexibility, phase composition, and degree of porosity, which determine their sorption properties. The present study focuses on issues related to optimizing the structure and phase state of sorbents based on aluminum oxide coatings.

Aluminum composite sorbents demonstrate high efficiency in the sorption of microorganisms, which is explained by their developed surface structure, high porosity, and the presence of active centers on the surface. The attachment of microorganisms to the sorbent surface occurs mainly due to electrostatic interactions, hydrogen bonding, Van der Waals forces, and physical adsorption mechanisms. Positively charged centers on the surfaces of aluminum oxide and hydroxide phases effectively interact with negatively charged components of the microbial cell wall, thereby enhancing the sorption process [1,2].

The degree of sorption of microorganisms on aluminum composites depends on the morphological characteristics of cells, the composition of the cell wall, the size of microorganisms, as well as environmental factors such as pH, ionic strength, and contact time. The introduction of additional phases into the composition of the composite sorbent increases surface activity, improves sorption capacity, and enhances the efficiency of microorganism retention [3,4].

Electron microscopy is an important method for studying the micro- and nanostructure of aluminum composite sorbents, as well as the spatial distribution of microorganisms on their surface. **Scanning electron microscopy (SEM)** makes it possible to determine the surface morphology of the sorbent, the

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shape and size of pores, and the adsorption of microorganisms. **Transmission electron microscopy (TEM)** provides the opportunity to analyze in detail the structural changes at the sorbent–microorganism interface and the mechanisms of interaction. The results of electron-microscopic studies serve as a basis for understanding sorption mechanisms and for the targeted optimization of aluminum composite sorbents [5].

Research Object and Methodology

Objects and materials. The research objects included the basidiomycete fungi *Pleurotus ostreatus* and *Agaricus bisporus* obtained from the collection of the Laboratory of "Biotechnology of Nature Protection" of the Institute of Microbiology, as well as aluminum composite oxide plates (AMg6, D16, ZnAl).

Primary material. Aluminum oxide (Al_2O_3) plates: AMg6 – 100% γ-Al_2O_3; D16 – 94% γ-Al_2O_3 + 6% α-Al_2O_3; ZnAl – 18% γ-Al_2O_3, 46% $ZnAl_2O_4$, 26% ZnO.

Modifiers. Aluminum oxides with different percentage compositions and α and γ phase configurations.

Methods used. Scanning electron microscopy (SEM), BET porosity analysis, cultivation of microorganisms in selective media, passage of spores through thin-layer sorption filters, collection of biomass from the filtrate, sorption of biomass on aluminum plates in isotonic solutions, repeated washing of the sorbent followed by counting the number of immobilized microorganisms.

Preparation of coatings. Aluminum oxide composites were prepared using sol–gel, anodization, or chemical vapor deposition (CVD) methods. The surface was modified with the introduction of bioactive functional groups. Plates of different thicknesses were used: AMg6 – 45–50 µm, D16 – 40–45 µm, ZnAl – 50 µm.

Results and Discussion. The studies showed that aluminum-based coatings contain γ-Al_2O_3 and α-Al_2O_3 phases. Microscopic analysis revealed a nanocrystalline structure and high porosity of the composites.

The sorption activity of aluminum oxide composites was investigated using both liquid and dry microorganisms (bacterial cells and fungal spores). Optimal porosity (30–80 nm) and the presence of functional groups such as –OH, –COOH, and –NH_2 on the surface ensure a high level of microorganism sorption.

Within the framework of the study, the sorption of spores of the basidiomycete fungi *Pleurotus ostreatus* and *Agaricus bisporus*, cultivated in liquid medium and on agar surfaces, was examined. After washing with isotonic solutions, the sorption of spores on the porous surface of the sorbents was confirmed by SEM analysis using the JSM-210 microscope manufactured by JEOL (Japan).

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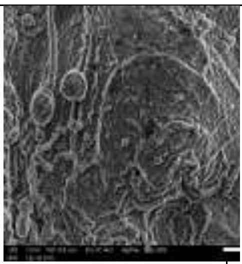
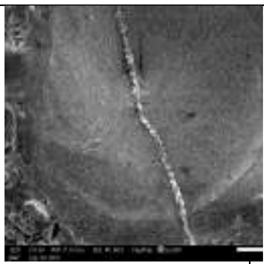
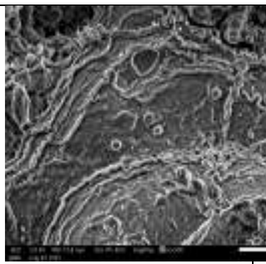
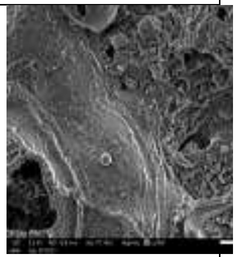
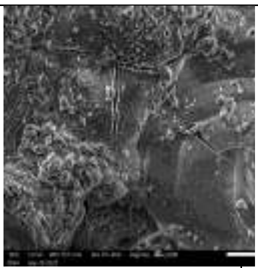
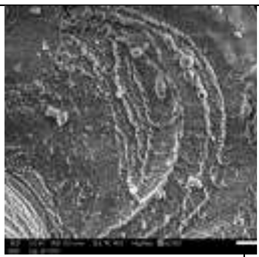
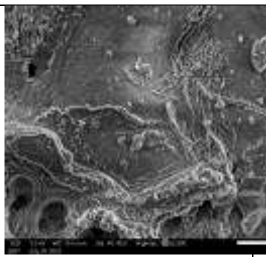
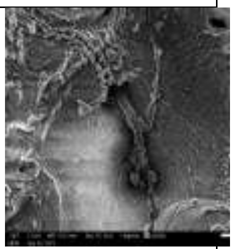
Sorbent AMg6: Alloy: AMg6, **Coating:** 100% γ-Al_2O_3, **Coating Thickness:** 50–55 µm			
			
SED 5.0kV WD 10.8mm Std.PC 40.0 HighVac x3.000 2845 juli 30. 2025 5µm	SED 5.0kV WD 11.0mm Std.PC 40.0 HighVac x3.500 2847 juli 30. 2025 5µm	SED 5.0kV WD 10.8mm Std.PC 40.0 HighVac x3.500 2848 juli 30. 2025 5µm	SED 5.0kV WD 10.8mm Std.PC 40.0 HighVac x3.000 2846 juli 30. 2025 5µm

Figure 1. Electron micrograph showing the immobilization of spores of the basidiomycete fungus *Pleurotus ostreatus* on the aluminum composite sorbent AMg6 (magnification: ×3000, ×3500).

The image illustrates the microscopic pattern of sorption of *Pleurotus ostreatus*. The fungal spores were cultivated on a nutrient medium, after which the Petri dish surface was covered with the AMg6 sorbent composed of aluminum plates for a certain period of time. After incubation, the plates were removed from the Petri dishes, washed ten times, and dried, and subsequently examined using an electron microscope.

The observation results demonstrate that fungal hyphae and a small number of spores were immobilized on the surface of the sorbent.

Sorbent D16: Alloy: D16, **Coating:** 92% γ-Al_2O_3, 8% α-Al_2O_3, **Coating Thickness:** 40–45 µm			
			
SED 5.0kV WD 10.5mm Std.PC 40.0 HighVac x2.000 2834 juli 30. 2025	SED 5.0kV WD 10.5mm Std.PC 40.0 HighVac x3.500 2835 juli 30. 2025	SED 5.0kV WD 10.5mm Std.PC 40.0 HighVac x2.000 2837 juli 30. 2025	SED 5.0kV WD 10.5mm Std.PC 40.0 HighVac x3.000 2838 juli 30.

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10µm	5µm	10µm	2025 5µm

Figure 2. Electron micrograph showing the immobilization of spores of the basidiomycete fungus *Pleurotus ostreatus* on the aluminum composite sorbent D16 (magnification: ×2000, ×3000, ×3500).

The presented electron micrograph demonstrates that the sorption of *Pleurotus ostreatus* occurred on the surface of the plate with the aluminum coating D16. The spores are distributed over a significant portion of the sorbent surface, confirming the successful immobilization of the microorganisms.

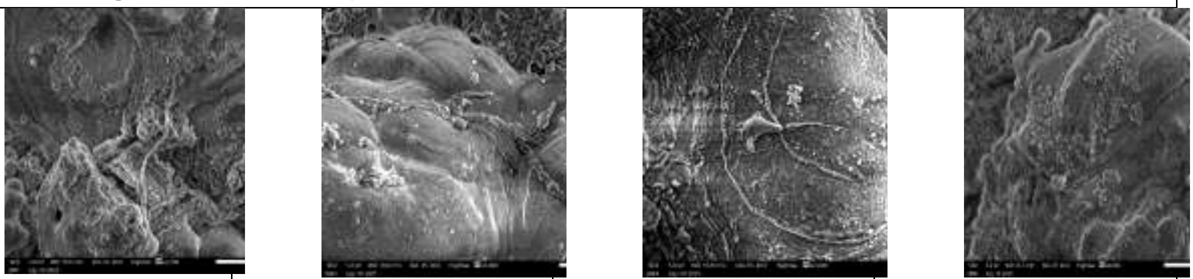
Sorbent ZnAl: Alloy: GDN ZnAl, **Coating:** 18% γ-Al_2O_3, 46% $ZnAl_2O_4$, 26% ZnO, **Coating Thickness:** 50 µm			
			
SED 5.0kV WD 10.9mm Std.PC 40.0 HighVac x2.500 2841 juli 30. 2025 10µm	SED 5.0kV WD 10.8mm Std.PC 40.0 HighVac x3.000 2843 juli 30. 2025 5µm	SED 5.0kV WD 10.8mm Std.PC 40.0 HighVac x3.000 2844 juli 30. 2025 5µm	SED 5.0kV WD 10.7mm Std.PC 40.0 HighVac x4.000 2840 juli 30. 2025 5µm

Figure 3. Electron micrograph showing the immobilization of spores of the basidiomycete fungus *Pleurotus ostreatus* on the aluminum composite sorbent ZnAl (magnification: ×2500, ×3000, ×4000).

The presented image illustrates the process of sorption and immobilization of *Pleurotus ostreatus* spores on the surface and within the porous regions of the plate coated with the ZnAl aluminum composite. Sorption is observed in various areas of the sorbent surface.

During the study, the sorption of spores of another representative of basidiomycete fungi, *Agaricus bisporus*, cultivated in a liquid nutrient medium and forming spores on the surface of the medium, was also investigated. The results of sorption on three types of aluminum composite sorbents are presented in the corresponding figures.

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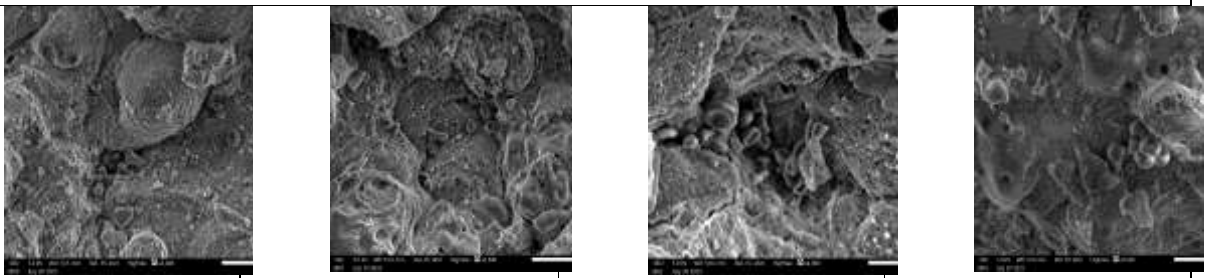
Sorbent AMg6: Alloy: AMg6, **Coating:** 100% γ-Al_2O_3, **Coating Thickness:** 50–55 µm

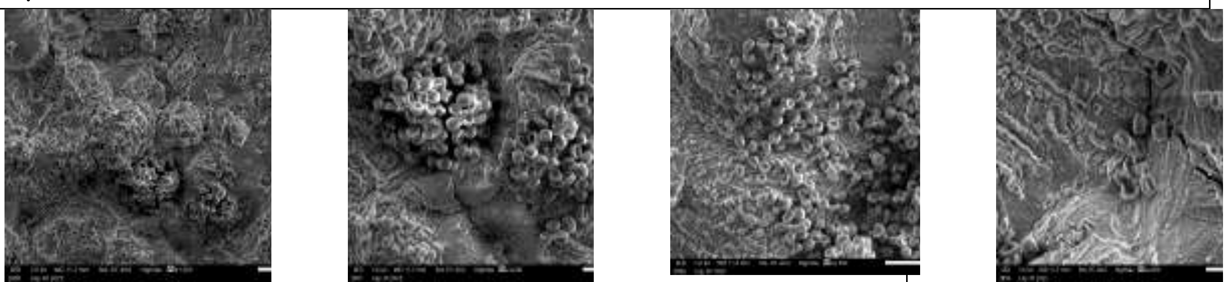


SED 5.0kV WD 10.5mm Std.PC 40.0 HighVac x2.000 2859 juli 30. 2025 10µm	SED 5.0kV WD 10.8mm Std.PC 40.0 HighVac x3.000 2845 juli 30. 2025 5µm	SED 5.0kV WD 10.8mm Std.PC 40.0 HighVac x3.000 2845 juli 30. 2025 5µm	SED 5.0kV WD 10.8mm Std.PC 40.0 HighVac x3.000 2845 juli 30. 2025 5µm

Figure 4. Electron micrograph showing the immobilization of spores of the basidiomycete fungus *Agaricus bisporus* on the aluminum composite sorbent AMg6 (100% γ-Al_2O_3) (magnification: ×2000, ×3000).

The presented electron micrograph shows that the sorption of *Agaricus bisporus* occurred on the surface of the plate with the aluminum coating AMg6, composed of 100% γ-Al_2O_3. The spores are distributed across certain areas of the sorbent surface, confirming the immobilization process. In addition, sorption of spores within the porous depressions of the plate is also observed.

Sorbent D16: Alloy: D16, **Coating:** 92% γ-Al_2O_3, 8% α-Al_2O_3, **Coating Thickness:** 40–45 µm



SED 5.0kV WD 10.8mm Std.PC 40.0 HighVac x3.000 2845 juli 30. 2025 5µm	SED 5.0kV WD 10.8mm Std.PC 40.0 HighVac x3.000 2845 juli 30. 2025 5µm	SED 5.0kV WD 10.8mm Std.PC 40.0 HighVac x3.000 2845 juli 30. 2025 5µm	SED 5.0kV WD 10.8mm Std.PC 40.0 HighVac x3.000 2845 juli 30. 2025 5µm

Figure 5. Electron micrograph showing the immobilization of spores of the basidiomycete fungus *Agaricus bisporus* on the aluminum composite sorbent D16 (92% γ-Al_2O_3, 8% α-Al_2O_3) (magnification: ×3000).

The presented images demonstrate the microscopic pattern of *Agaricus bisporus* sorption on the surface of the aluminum-coated plate D16, consisting of 92% γ-Al_2O_3 and 8% α-Al_2O_3. The spores are widely distributed across the sorbent surface and form a dense

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coverage. Therefore, this sorbent is highly effective for the immobilization and retention of *Agaricus bisporus* spores.

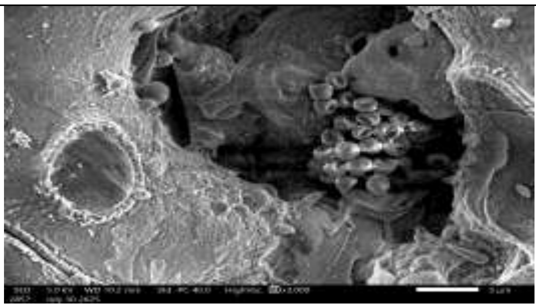
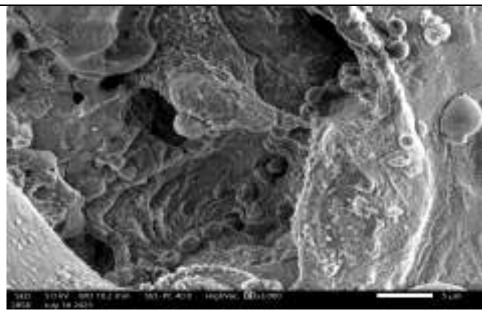
Sorbent ZnAl: Alloy: GDN ZnAl, **Coating:** 18% γ-Al_2O_3, 46% $ZnAl_2O_4$, 26% ZnO, **Coating Thickness:** 50 µm	
	
SED 5.0kV WD 10.8mm Std.PC 40.0 HighVac x3.000 2845 juli 30. 2025 5µm	SED 5.0kV WD 10.8mm Std.PC 40.0 HighVac x3.000 2845 juli 30. 2025 5µm

Figure 6. Electron micrograph showing the immobilization of spores of the basidiomycete fungus *Agaricus bisporus* on the aluminum composite sorbent ZnAl (18% γ-Al_2O_3, 46% $ZnAl_2O_4$, 26% ZnO) (magnification: ×3000).

The image illustrates the immobilization process of *Agaricus bisporus* spores on both the surface and the porous regions of the ZnAl aluminum-coated plate, composed of 18% γ-Al_2O_3, 46% $ZnAl_2O_4$, and 26% ZnO. Spore sorption is predominantly observed on the porous areas of the plate, as clearly visible in the micrograph.

Analysis of the images showed that *Pleurotus ostreatus* spores, grown on agar nutrient medium, were placed on aluminum composite plates for a designated time. The plates were then washed ten times with isotonic solution, and sorption of the fungi on the porous surface was examined using electron microscopy.

The second fungus, *Agaricus bisporus*, was cultivated in liquid nutrient medium, passed through a specialized filter, and the collected biomass was placed in isotonic solution. The plates were immersed in the solution for a set time, then washed ten times. The spores immobilized on the porous surface were subsequently observed by electron microscopy.

The results demonstrate the high sorption capacity of aluminum composite sorbents for microorganisms. The sorption process varied depending on the sorbent composition, surface structure, and environmental factors.

Scanning electron microscopy (SEM) revealed a well-developed porous structure on the surface of the aluminum composites. Before sorption, open pores were observed; after interaction with microorganisms, some pores were

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partially filled with cells. SEM images showed spores and hyphae distributed individually and in aggregates, indicating high sorption efficiency.

Transmission electron microscopy (TEM) analysis revealed tight contact at the sorbent–microorganism interface. TEM images showed firm attachment of microbial cell walls to the sorbent surface, and in some cases, structural changes in the surface layer, confirming that sorption occurs not only via physical adsorption but also partially through electrostatic and chemical interactions.

X-ray phase analysis confirmed the presence of aluminum oxide and hydroxide phases in the composite sorbent. The high dispersity of these phases increases the sorbent surface area, providing favorable conditions for microorganism retention. After sorption, the phase composition remained largely unchanged, indicating the structural stability of the sorbent.

Infrared spectroscopy revealed the presence of surface functional groups such as –OH, Al–O, and others. After microorganism sorption, changes in the intensity of certain bands were observed, indicating interactions between functional groups and cell wall components, highlighting the role of hydrogen bonding and electrostatic forces in the sorption mechanism.

In summary, the results demonstrate that aluminum composite sorbents possess a high capacity for effective microorganism sorption, due to their developed morphology, high surface activity, and functional groups. The combined use of electron microscopy, X-ray phase analysis, and infrared spectroscopy allowed for a detailed study of the sorption mechanisms and highlighted the potential practical applications of these composite sorbents.

pplication Prospects and Conclusion

Application Prospects: **Biomedicine** - As filter elements for the isolation and elimination of pathogens; **Environmental Science** - For water and air purification, in biofilters; **Biotechnology** - In biological analysis equipment using selective sorption; **Microbiology** - For long-term preservation of microorganisms;

Pharmacy: For extraction of active compounds and in carrier systems for drug delivery.

In conclusion, aluminum composite oxide coatings are considered highly promising sorbents for microbiological objects and modified materials. Precise control of phase composition, surface structure, and modification methods significantly enhances sorption activity.

In the conducted study, the sorption of spores of the basidiomycete fungi *Pleurotus ostreatus* and *Agaricus bisporus* on aluminum oxide composite sorbents was observed and confirmed through microscopic analysis. Based on these results, technological criteria for sorbent preparation were developed, and the potential for their wide practical application was substantiated.

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