

Mineral Sorption Materials Modified with Nanoscale Polytetrafluoroethylene Layers for Biomedical Applications

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Abstract

Background: The increasing demand for highly selective, biocompatible, and chemically stable sorbents has stimulated the development of advanced functional materials for biomedical and biotechnological applications. Conventional carbon-based sorbents, although characterized by high adsorption capacity, often exhibit insufficient selectivity and may remove physiologically important biomolecules during therapeutic and purification procedures. **Materials and Methods:** Composite sorbents were synthesized by graft polymerization of fluoromonomers onto porous inorganic carriers, including silica, alumina, aluminosilicates, and macroporous glass. Nanometer-scale fluoropolymer coatings were chemically immobilized on the surface of the mineral matrices, followed by functional modification to regulate adsorption behavior. Structural, physicochemical, and adsorption characteristics were investigated, and the practical applicability of the developed materials was evaluated in hemosorption, biomolecule purification, and pharmaceutical processes. **Results:**

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The synthesized materials retained their original porous structure while acquiring stable fluoropolymer coatings with thicknesses ranging from 1 to 10 nm. The developed sorbents demonstrated high chemical and thermal stability, low nonspecific adsorption, improved hemocompatibility, and high adsorption selectivity. Effective purification of nucleic acids, proteins, peptides, antibiotics, and insulin was achieved using the modified sorbents. **Conclusion:** Fluoropolymer-containing composite sorbents represent a new generation of functional nanostructured materials that combine the mechanical strength and porosity of inorganic matrices with the biological inertness and selective adsorption properties of fluoropolymers.

Keywords: *fluoropolymer-containing sorbents; biocompatible materials; hemosorption; graft polymerization; nanostructured composites; adsorption technology; nucleic acid purification; biomedical materials; biotechnology; pharmaceutical purification.*

Introduction

The rapid advancement of modern medicine, biotechnology, and pharmaceutical sciences has significantly increased the demand for novel functional materials with enhanced physicochemical and biological properties. Among these materials, sorbents occupy a special place due to their extensive use in extracorporeal detoxification, clinical diagnostics, biotechnology, pharmaceutical production, and environmental protection. The effectiveness of sorption processes largely depends on the structural characteristics, chemical stability, adsorption selectivity, and biocompatibility of the sorbent material. Therefore, the development of new-generation sorbents capable of meeting increasingly stringent biomedical requirements remains a priority area of scientific research [1,2].

Conventional carbon-based sorbents have been widely used in hemoperfusion and detoxification procedures because of their high adsorption capacity. However, despite their effectiveness in removing toxic metabolites and xenobiotics, these materials often exhibit insufficient selectivity and may adsorb physiologically important compounds, including proteins and other biologically active molecules. Such non-specific adsorption reduces therapeutic efficiency and may negatively affect patient outcomes. Consequently, the search for alternative sorbent materials with improved selectivity and enhanced hemocompatibility has become one of the major challenges in modern biomedical engineering [3,4].

Recent developments in nanotechnology have opened new opportunities for designing advanced functional materials with precisely controlled surface properties. Particular attention has been directed toward composite materials that combine the advantages of inorganic porous matrices with the unique physicochemical

characteristics of synthetic polymers. Among these materials, fluoropolymer-containing composites have attracted considerable interest due to their exceptional chemical resistance, thermal stability, hydrophobicity, biological inertness, and low surface energy [2,4,5].

Fluoropolymers are characterized by strong carbon–fluorine bonds, which provide outstanding resistance to aggressive chemical environments and biological degradation. Furthermore, fluoropolymer surfaces exhibit low non-specific adsorption of proteins and other biological macromolecules, making them especially attractive for biomedical applications. The incorporation of fluoropolymer nanolayers onto porous mineral substrates enables the creation of multifunctional sorbents that combine the mechanical strength and controlled porosity of inorganic carriers with the hemocompatibility and selective adsorption properties of fluoropolymers [4,5,13].

One of the most promising approaches for producing such materials involves the graft polymerization of fluoromonomers onto the surface of porous inorganic matrices. This technique allows the formation of chemically bonded fluoropolymer coatings with nanometer-scale thickness while preserving the original porous structure of the carrier material. Moreover, subsequent introduction of functional groups provides additional opportunities for tailoring adsorption characteristics according to specific biomedical and biotechnological requirements [1,4,17].

In recent years, fluoropolymer-modified sorbents have demonstrated considerable potential in a wide range of applications, including hemosorption, purification of nucleic acids, proteins, peptides, antibiotics, and other biologically active compounds. Their high adsorption selectivity, low non-specific binding, excellent regeneration capability, and long-term operational stability make them attractive alternatives to traditional sorbent systems [6–10].

The development of biocompatible sorbents is particularly important in the field of extracorporeal blood purification, where the efficiency of toxin removal must be balanced with the preservation of essential blood components. Sorbents capable of selectively adsorbing cholesterol, low-density lipoproteins, circulating immune complexes, and medium-molecular-weight toxins may significantly improve the treatment of cardiovascular, autoimmune, allergic, and metabolic disorders [7,12,18].

In addition to medical applications, fluoropolymer-containing sorbents have shown promising results in biotechnology and pharmaceutical manufacturing. Their ability to selectively isolate and purify biologically active compounds enables the production of highly purified pharmaceutical preparations while reducing the number of technological stages and overall production costs. Such materials have been successfully employed in the purification of insulin, antibiotics, immunoregulatory peptides, and nucleic acids, demonstrating their versatility and industrial relevance [10,11,14–16].

Materials and Methods

Study Design

This study was designed to develop fluoropolymer-containing biocompatible composite sorbents for biomedical and biotechnological applications. The research included the synthesis of surface-modified sorbents, structural characterization of the obtained materials, evaluation of adsorption performance, and assessment of their potential use in extracorporeal detoxification and biomolecule purification technologies [1,4].

Materials

Porous inorganic materials were selected as the primary matrices for sorbent synthesis. These included silica-based sorbents, silochromes, macroporous glass, aluminum oxide (Al_2O_3), and aluminosilicates. Such materials were chosen because of their high mechanical strength, developed pore structure, permeability, and chemical stability, which are essential for biomedical applications [1,2,7].

Fluoromonomers were used as precursors for the formation of fluoropolymer coatings. Additional modifying reagents were employed for the introduction of functional groups capable of regulating adsorption selectivity and improving interactions with biologically active compounds [4,5].

Synthesis of Fluoropolymer-Containing Sorbents

The synthesis process consisted of two consecutive stages.

At the first stage, fluoromonomers were graft-polymerized onto the surface of porous inorganic matrices. The graft polymerization reaction resulted in the formation of chemically bonded fluoropolymer nanolayers uniformly distributed throughout the accessible surface of the carrier material [1,4,17].

At the second stage, additional functional groups were introduced into the fluoropolymer layer to regulate adsorption characteristics and improve selectivity toward target compounds. The developed modification strategy enabled precise control over the physicochemical properties of the resulting sorbents [4,5].

The synthesis conditions were optimized to produce fluoropolymer coatings with thicknesses ranging from approximately 1 to 10 nm while preserving the original porous architecture of the inorganic support [1,2].

Structural Characterization

Structural characterization of the synthesized materials was performed using porometric analysis and surface characterization techniques. The following parameters were evaluated:

- pore volume;
- pore-size distribution;
- specific surface area;
- integrity of the porous structure;

thickness and uniformity of the fluoropolymer coating.

The obtained results were used to assess the influence of surface modification on the structural properties of the sorbents and their suitability for biomedical applications [1,2].

Evaluation of Adsorption Properties

The adsorption characteristics of the synthesized materials were investigated using biologically active compounds and biomacromolecules. Particular attention was paid to adsorption efficiency, selectivity, and nonspecific adsorption.

The sorbents were evaluated for their ability to adsorb:

proteins;

peptides;

nucleic acids;

cholesterol;

low-density lipoproteins (LDL);

circulating immune complexes;

medium-molecular-weight toxins.

The performance of fluoropolymer-modified sorbents was compared with that of conventional sorption materials commonly used in biomedical practice [3,6,15].

Hemocompatibility Assessment

The hemocompatibility of the developed sorbents was assessed through their intended application in blood purification technologies. Evaluation criteria included adsorption selectivity, interaction with blood components, and the ability to remove pathological metabolites while preserving physiologically important biomolecules [3,7].

Clinical testing of the developed hemosorbents included therapeutic hemosorption procedures performed in patients diagnosed with ischemic heart disease, angina pectoris, hypercholesterolemia, and hypertriglyceridemia. The effectiveness of cholesterol and toxin removal was used as a primary indicator of sorbent performance [12,18].

Biomedical and Biotechnological Applications

The practical applicability of the synthesized materials was investigated in several areas:

Hemosorption and extracorporeal blood purification;

Isolation and purification of nucleic acids;

Fractionation and purification of proteins and peptides;

Recovery of antibiotics and pharmaceutical compounds;

Clinical and molecular diagnostics;

Biotechnology and genetic engineering.

The effectiveness of the sorbents was evaluated according to purification efficiency, adsorption selectivity, preservation of biological activity, and operational stability during repeated use [8–11,14–16].

Statistical Analysis

Experimental data were processed using standard statistical methods. Quantitative variables were expressed as mean values and corresponding measures of variability. Comparative analyses were conducted to evaluate the performance of fluoropolymer-containing sorbents relative to conventional sorption materials. Statistical significance was considered at $p < 0.05$.

Results

Structural Characteristics of Fluoropolymer-Containing Sorbents

The developed synthesis technology enabled the successful formation of fluoropolymer nanolayers on the surface of porous inorganic matrices, including silica, alumina, aluminosilicates, and macroporous glass. Structural investigations demonstrated that graft polymerization did not significantly alter the original porous architecture of the carriers. The synthesized materials retained high porosity and permeability, which are critical requirements for biomedical and biotechnological applications [1,2,4].

Porometric analysis showed that the thickness of the fluoropolymer coating could be controlled within the range of approximately 1–10 nm depending on synthesis conditions. The chemically bonded fluoropolymer layer was uniformly distributed over the surface of the inorganic substrate, providing a stable protective coating while preserving accessibility to internal pore structures [1,2].

Physicochemical Properties

The incorporation of fluoropolymer nanolayers substantially improved the physicochemical characteristics of the sorbents. The modified materials demonstrated enhanced chemical resistance toward aggressive media, improved thermal stability, and increased structural durability compared with conventional sorbents [2,4,13].

The combination of inorganic matrices and fluoropolymer coatings resulted in composite materials possessing both the mechanical strength of mineral carriers and the biological inertness of fluoropolymers. Such a combination significantly expanded the potential application range of the developed sorbents in medical and pharmaceutical technologies [4,5].

Adsorption Performance

Experimental investigations demonstrated that fluoropolymer-containing sorbents possessed high adsorption capacity while maintaining low levels of nonspecific adsorption. Unlike conventional carbon sorbents, the developed materials showed reduced interaction with physiologically important proteins and other biological macromolecules [3,5,6].

The sorbents effectively adsorbed a broad spectrum of biologically active compounds, including proteins, peptides, nucleic acids, cholesterol, lipoproteins, and circulating immune complexes. Adsorption selectivity could be further regulated through modification of the grafted fluoropolymer layer and the introduction of specific functional groups [4,5,8].

These findings indicate that the developed sorbents provide a favorable balance between adsorption efficiency and selectivity, which is essential for biomedical applications requiring preservation of biological activity and minimization of undesirable molecular losses [3,5].

Performance in Hemosorption Applications

The synthesized fluoropolymer-containing sorbents demonstrated promising characteristics for extracorporeal blood purification procedures. Clinical testing of the developed hemosorbent included ten therapeutic hemosorption procedures performed in five patients diagnosed with ischemic heart disease, angina pectoris, hypercholesterolemia, and hypertriglyceridemia [12].

The sorbent exhibited high adsorption activity toward cholesterol, low-density lipoproteins, circulating immune complexes, and medium-molecular-weight toxic substances. Simultaneously, the material demonstrated improved hemocompatibility and reduced nonspecific interaction with blood components. These properties support its potential use in the treatment of cardiovascular, metabolic, autoimmune, and inflammatory diseases requiring extracorporeal detoxification therapies [7,12,18].

Purification of Nucleic Acids

The developed fluoropolymer-containing sorbents demonstrated excellent performance in the isolation and purification of nucleic acids from various biological sources. The modified materials provided high purification efficiency while preserving the structural integrity of isolated nucleic acids.

The obtained preparations met stringent purity requirements necessary for subsequent use in modern molecular biological and diagnostic methods. The high selectivity of the sorbents significantly simplified purification procedures and reduced the need for additional processing stages [10,11].

Purification of Proteins and Peptides

One of the most significant findings of the study was the successful application of fluoropolymer-containing sorbents in protein and peptide purification. The materials exhibited low nonspecific adsorption, enabling high recovery rates and preservation of biological activity during separation procedures [11,15].

Fluoropolymer-modified sorbents were successfully employed for the isolation of immunoregulatory peptides from bone marrow cell culture supernatants. The proposed purification strategy enabled concentration of the supernatant, removal of medium components, and recovery of biologically active peptide fractions within a single

technological stage. This approach significantly reduced processing time and eliminated several labor-intensive purification procedures [15].

Purification of Pharmaceutical Compounds

The developed sorbents also demonstrated high efficiency in the purification of pharmaceutical compounds and antibiotics. Successful purification of ristomycin sulfate and doxorubicin was achieved using fluoropolymer-modified sorption systems. The materials exhibited high operational stability and maintained their effectiveness after repeated regeneration cycles [14,15].

Furthermore, the developed sorbents proved effective in the extraction of biologically active substances from blood, urine, bile, and tissue extracts. Their performance satisfied stringent requirements imposed on sorbents used in pharmaceutical manufacturing processes [8,14].

Application in Insulin Production

The synthesized fluoropolymer-containing sorbents were successfully applied in insulin purification technologies. The use of modified sorbents significantly reduced the number of energy-intensive technological operations required during production.

The resulting insulin preparations contained lower levels of protein impurities than those obtained using many conventional purification approaches. Consequently, the developed technology enabled the production of highly purified insulin suitable for medical applications [16].

Potential Diagnostic Applications

The obtained materials exhibited characteristics that make them promising candidates for the development of advanced diagnostic systems. Their high selectivity toward nucleic acids and biologically active compounds suggests potential applications in molecular diagnostics, genetic testing, and early detection of infectious diseases [8–10].

Preliminary investigations indicated the feasibility of utilizing these sorbents in highly sensitive diagnostic platforms for viral infections, including HIV and viral hepatitis, as well as in modern genetic engineering technologies [8,9].

Discussion

The findings of the present study demonstrate that fluoropolymer-containing composite sorbents possess a unique combination of structural, physicochemical, and biological properties that distinguish them from conventional sorption materials. The successful graft polymerization of fluoromonomers onto porous inorganic matrices enabled the formation of stable nanostructured fluoropolymer coatings while preserving the original porous architecture of the carrier materials. This combination provides an effective strategy for overcoming several limitations associated with traditional sorbents used in biomedical and biotechnological applications [1,4].

One of the principal challenges in the development of medical sorbents is the achievement of high adsorption efficiency without excessive nonspecific binding of physiologically important biomolecules. Conventional activated carbon sorbents are characterized by high adsorption capacity; however, their relatively low selectivity frequently results in the removal of essential proteins and biologically active compounds. Such nonselective adsorption may reduce treatment efficacy and adversely affect clinical outcomes [3]. In contrast, the fluoropolymer-containing sorbents developed in this study demonstrated substantially lower nonspecific adsorption while maintaining high adsorption capacity toward target molecules. These findings are consistent with previous investigations reporting the favorable surface characteristics of fluoropolymer-modified materials [2,5,13].

An important result of the present work is the preservation of the porous structure after surface modification. Porometric investigations confirmed that the fluoropolymer layer, despite being chemically bonded to the mineral surface, did not significantly block the pore system of the carrier material. The ability to maintain high porosity while simultaneously introducing new functional properties is critical for biomedical sorbents, where rapid mass transfer and efficient adsorption are essential for clinical performance [1,2,4].

The observed improvement in hemocompatibility may be attributed to the biological inertness and low surface energy of fluoropolymers. These properties reduce undesirable interactions between blood components and the sorbent surface, thereby minimizing the risk of adverse biological responses during extracorporeal circulation procedures. The clinical results obtained during therapeutic hemosorption sessions further support the practical applicability of the developed materials for blood purification technologies [7,12,18].

The effectiveness of the synthesized sorbents in removing cholesterol, low-density lipoproteins, circulating immune complexes, and medium-molecular-weight toxins suggests significant potential for the treatment of cardiovascular, autoimmune, inflammatory, and metabolic disorders. Similar observations have been reported in previous studies investigating fluoropolymer-modified hemosorbents; however, the present materials additionally offer enhanced structural stability and broader opportunities for functional modification [6,7,12].

Another significant advantage of the developed sorbents is their applicability in biotechnology and pharmaceutical manufacturing. The successful purification of nucleic acids, proteins, peptides, antibiotics, and insulin demonstrates the versatility of the proposed materials. Their low nonspecific adsorption and high selectivity enable the recovery of biologically active compounds while preserving their structural integrity and functional activity. Such characteristics are particularly important in

modern pharmaceutical production, where product purity and biological activity directly influence therapeutic effectiveness [10,11,14–16].

The results obtained in nucleic acid purification are especially noteworthy. Modern molecular diagnostic technologies require highly purified nucleic acid preparations for polymerase chain reaction, sequencing, and other advanced analytical methods. The developed fluoropolymer-containing sorbents demonstrated excellent purification performance and may therefore contribute to the development of next-generation diagnostic platforms and genetic engineering technologies [8–11].

The scientific novelty of this work lies in the development of a universal approach for the synthesis of fluoropolymer-containing composite sorbents that combines nanoscale surface modification with preservation of the original porous structure. Unlike many previously reported surface-modification techniques, the proposed method allows precise regulation of adsorption properties while maintaining the mechanical and structural advantages of the inorganic carrier [1,4,17].

Despite the promising results, several limitations should be acknowledged. First, the clinical evaluation was performed on a relatively limited number of patients, which restricts the ability to draw definitive conclusions regarding long-term therapeutic efficacy. Second, comprehensive comparative studies involving commercially available sorbents were not performed under identical experimental conditions. Therefore, further investigations are necessary to validate the obtained findings and optimize industrial-scale applications.

Conclusion

The present study successfully demonstrated the development of fluoropolymer-containing biocompatible composite sorbents through the graft polymerization of fluoromonomers onto porous inorganic matrices. The proposed surface-modification strategy enabled the formation of stable nanometer-scale fluoropolymer coatings while preserving the original porous structure and permeability of the carrier materials.

The synthesized sorbents combined the mechanical strength and structural stability of inorganic substrates with the chemical resistance, biological inertness, and selective adsorption properties of fluoropolymers. Structural investigations confirmed the preservation of high porosity following surface modification, whereas functional evaluation revealed enhanced adsorption selectivity, reduced nonspecific protein adsorption, and improved hemocompatibility.

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