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POLYMER COMPOSITE MATERIALS WITH SORPTION PROPERTIES: STRUCTURE, MODIFICATION AND APPLICATIONS

Abstract. Polymer composite materials with sorption properties have attracted increasing attention due to their potential application in environmental technologies, particularly in water purification systems. Recent advances in polymer chemistry and materials science have enabled the development of functional composites with controlled physicochemical characteristics and improved adsorption performance. Among various materials, cellulose- and chitosan-based composites are considered promising due to their biodegradability, availability and the presence of reactive functional groups capable of interacting with different classes of pollutants. This review analyzes recent progress in the design and modification of polymer composite sorbents, focusing on the relationship between structural organization, functional group accessibility and adsorption efficiency. Particular attention is given to the role of intermolecular interactions, pore architecture and chemical modification in controlling sorption behavior toward heavy metal ions, dyes and pharmaceutical contaminants. The results of recent studies demonstrate that adsorption performance is determined not only by chemical composition but also by structural parameters governing diffusion processes and stability of polymer matrices. The analysis indicates that modern research trends are directed toward development of multifunctional hybrid materials with improved selectivity, regeneration ability and stability under realistic conditions. Future progress in this field is associated with integration of structure–property analysis, predictive modelling and scalable synthesis approaches for creation of efficient and environmentally safe sorbent materials.

Keywords: polymer composite sorbents, cellulose, chitosan, adsorption, water purification

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Introduction. In recent decades, increasing environmental pollution caused by industrial development, population growth and intensive use of chemical substances has stimulated the search for new functional materials capable of ensuring effective purification of water and air environments. The presence of heavy metal ions, dyes, pharmaceutical residues and other toxic compounds in wastewater represents a serious global ecological problem, requiring the development of efficient, economically accessible and environmentally safe purification technologies [1-3]. In this context, special attention has been paid to sorption materials characterized by high efficiency, structural stability and the possibility of multiple reuse.

Among various classes of materials, polymer composite systems occupy a particular place due to the possibility of regulating their physicochemical properties through modification of structure and composition. Polymer composites demonstrate high mechanical strength, developed specific surface area and a wide range of functional properties, which makes them promising for application in environmental technologies, catalysis, membrane separation and biomedical fields [4,5]. The combination of organic polymer matrices with functional additives allows obtaining materials with improved sorption capacity, chemical resistance and controlled porosity.

Particular scientific interest is associated with natural polymers such as cellulose and chitosan, which possess a number of advantages compared to synthetic analogues, including biodegradability, low toxicity, availability and the presence of reactive functional groups capable of participating in intermolecular interactions [6-8]. Cellulose is the most common natural polysaccharide, with a linear structure consisting of β-D-glucopyranose units linked by β-1,4-glycosidic bonds. The presence of a large number of hydroxyl groups in the cellulose structure ensures the formation of a developed system of hydrogen bonds, which influence the mechanical and adsorption properties of the material [9].

Chitosan, obtained by deacetylation of chitin, is characterized by the presence of amino groups capable of forming coordination bonds with metal ions and participating in electrostatic interactions with various organic compounds [10]. The combination of cellulose and chitosan in composite materials makes it possible to obtain structures with improved physicochemical characteristics, including increased sorption capacity, hydrophilicity and structural stability [11].

Modern research demonstrates that modification of polymer matrices plays an important role in regulating the structure and functional properties of composite materials. Introduction of nanoparticles, cross-linking agents and functional modifiers contributes to changes in pore size distribution, surface activity and chemical stability of materials [12]. As a result, it becomes possible to obtain composites with controlled adsorption properties and improved interaction with target pollutants.

An important advantage of polymer composite materials is the possibility of tailoring their physicochemical properties depending on the field of application. Regulation of porosity, hydrophilic-hydrophobic balance and surface charge allows optimization of adsorption processes and increases efficiency of pollutant removal from aqueous solutions [13]. In addition, the use of renewable raw materials corresponds to the principles of sustainable development and green chemistry, which is one of the priority directions of modern chemical science [14].

Despite the significant number of studies devoted to polymer composites, the relationship between structure, physicochemical properties and functional characteristics of materials remains insufficiently systematized. Many studies focus on specific modification methods or particular applications, while comprehensive analysis of structure-property relationships is still limited [15]. Therefore, systematization of modern literature data and identification of key factors influencing sorption properties of polymer composite materials represent an important scientific task.

The purpose of this review is to analyze modern approaches to the synthesis and modification of polymer composite materials and to evaluate the influence of structural characteristics on their physicochemical properties and functional performance. Particular attention is paid to intermolecular interactions, hydrogen bonding systems and the role of functional groups in formation of adsorption centers.

The results of the review may contribute to the development of new functional materials with controlled properties for environmental and technological applications.

Materials and Methods. The methodological framework of this review is based on the systematic analysis and critical evaluation of scientific publications devoted to polymer composite materials with sorption properties, with particular emphasis on cellulose- and chitosan-based systems. The study focuses on the investigation of structure-property relationships, physicochemical characteristics and functional performance of polymer composites used in environmental and chemical applications.

The literature search was conducted using international scientific databases, including Scopus, Web of Science, ScienceDirect, SpringerLink, and Google Scholar. Priority was given to peer-reviewed journal articles, review papers and monographs published mainly during the last 10-15 years in the field of polymer chemistry, materials science and environmental chemistry. Classical fundamental studies widely recognized in the scientific community were also considered to ensure continuity of theoretical approaches.

The search strategy included combinations of keywords related to polymer composite materials and sorption processes, such as polymer composites, cellulose, chitosan, physicochemical properties, adsorption, functional materials, biopolymers, composite structure, and surface modification. Boolean operators (AND, OR) were applied to refine the search and obtain relevant scientific publications. Additional sources were identified through analysis of reference lists in highly cited articles.

The selection of publications was carried out according to the following inclusion criteria:

- relevance to polymer composite materials with sorption properties
- presence of information on physicochemical characteristics of materials
- investigation of structural features of polymer matrices
- analysis of modification methods and functionalization approaches
- availability of experimental or theoretical data describing adsorption mechanisms

Studies not directly related to polymer composite systems or lacking sufficient scientific justification were excluded from consideration. Particular attention was paid to works describing the influence of functional groups, intermolecular interactions and structural organization on adsorption capacity and stability of materials.

The collected literature sources were classified according to several parameters, including type of polymer matrix, method of modification, physicochemical characteristics and field of application. Comparative analysis of literature data made it possible to identify the main directions of development of polymer composite materials and determine key factors influencing their functional properties.

Special attention was devoted to the analysis of intermolecular interactions occurring in polymer matrices, including hydrogen bonding, electrostatic interactions and coordination interactions between functional groups and adsorbed substances. These interactions play a fundamental role in formation of adsorption centers and determine sorption capacity of composite materials.

The methodological approach used in this review allows systematization of modern scientific knowledge in the field of polymer composite materials and identification of promising future research directions. The obtained results provide a theoretical basis for the development of new functional materials with controlled physicochemical properties and improved sorption performance.

Research results. *Structural organization of polymer composites as the main factor controlling sorption behavior*. Analysis of recent studies shows that the adsorption efficiency of polymer composite sorbents is determined not simply by the chemical nature of cellulose or chitosan, but by the way these polymers are organized into a three-dimensional structure. In the publications of the last five years, the most effective systems are consistently those in which the polymer matrix combines high accessibility of functional groups with a developed pore network and sufficient mechanical integrity under aqueous conditions. This explains the sustained interest in hydrogels, aerogels and porous monoliths rather than in non-structured polymer powders.

The adsorption performance of polymer composite sorbents is strongly influenced by structural organization of the polymer matrix, which determines accessibility of functional groups and diffusion of pollutant molecules. Porous architecture improves contact between adsorption sites and contaminants, contributing to enhanced sorption efficiency. The relationship between structural parameters and adsorption performance is schematically illustrated in Figure 1.

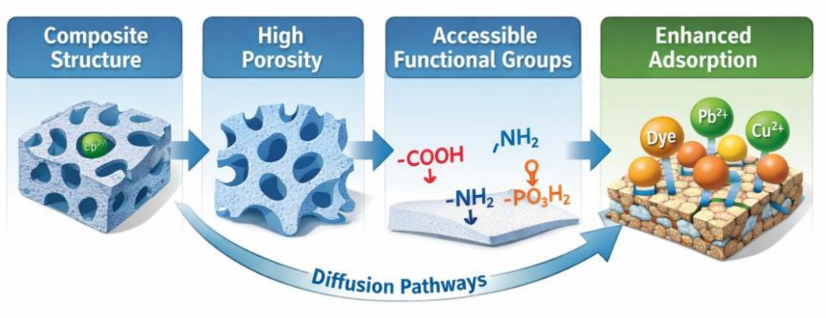

Fig. 1. Structure-property relationship in polymer composite sorbents

Figure 1 illustrates the relationship between structural organization of polymer composite materials and their adsorption performance. The scheme demonstrates how porous architecture, accessibility of functional groups (–OH, $–NH_2$, –COOH, $–PO_3H_2$) and diffusion pathways influence interaction between the sorbent surface and pollutant molecules. The hierarchical structure of polymer matrices facilitates mass transfer and improves accessibility of adsorption sites, resulting in enhanced removal efficiency of heavy metal ions and organic contaminants.

In a 2024 review on cellulose-based adsorbents for toxic metal removal, El Mahdaoui et al. emphasize that cellulose modification is valuable not only because it increases the number of binding sites, but because it also allows one to tune robustness, selectivity and reusability, which are decisive for practical application. The same review makes clear that porosity, surface area and chemical stability must be considered together, since improvement in one parameter does not automatically produce superior adsorption in real systems [16,17].

This tendency is well illustrated by recent cellulose-chitosan composite hydrogels and aerogels. In the work of Yang et al. (2024), cellulose-chitosan hydrogels served as a stable matrix for in situ grown β-FeOOH nanoparticles, and the authors directly linked the nanoporous framework with improved contact between active sites and methyl orange molecules. Under optimal conditions, the material reached a removal rate of 97.75% within 40 minutes and retained 80.81% efficiency after five cycles, indicating that hierarchical structure can support both adsorption and catalytic conversion rather than adsorption alone. Importantly, the study also showed that increasing β-FeOOH loading did not lead to a uniformly positive effect: although photocatalytic contribution improved, excessive loading reduced specific surface area and could slow the adsorption stage. This is a recurring result in recent literature: the best-performing composites are not those with the highest additive content, but those where the active phase remains structurally accessible [18].

A similar structure–performance relationship appears in cellulose/chitosan systems combined with metal–organic frameworks. Liu et al. (2021) reported that incorporation of HKUST-1 into a cellulose/chitosan aerogel increased the BET surface area from 9.74 to 457.75 m^2 g^{-1}, while the adsorption capacity toward methylene blue reached 526.3 mg g^{-1} with good recyclability. However, the significance of this result is not only the high numerical capacity. More importantly, it shows that cellulose/chitosan matrices can act as stabilizing scaffolds for more fragile or aggregation-prone functional phases. At the same time, such hybridization introduces a new challenge: high porosity and strong dye uptake may be achieved at the expense of synthesis complexity, cost and possible reduction in long-term hydrolytic stability compared with simpler biopolymer-only materials. Thus, the current literature indicates that architecture engineering is productive, but the performance gains must be interpreted together with fabrication feasibility [19].

Functional group engineering: from passive biosorbents to selective chemisorption systems. A second major trend in the 2021-2025 literature is the transition from unmodified polysaccharide sorbents to chemically engineered composites with targeted binding groups. Native cellulose and chitosan already provide hydroxyl and amino functionalities, but recent studies increasingly show that these groups alone are often insufficient when rapid uptake, high capacity and ion selectivity are required simultaneously. As a result, current research is shifting toward phosphonation, amination, oxidation, grafting and hybrid inorganic modification. The rationale is straightforward: sorption performance improves when the surface contains donor groups with stronger coordination ability toward metal ions or more specific electrostatic affinity toward ionic dyes and pharmaceuticals. This general pattern is also supported by broader reviews on cellulose- and chitosan-based sorbents published in 2023-2025 [20,21].

One of the clearest examples is the phosphonate-functionalized chitosan/cellulose hydrogel reported by Sun et al. (2024). The authors explicitly positioned their material against earlier cellulose/chitosan hydrogels, noting that previously reported systems frequently suffered from either long equilibrium times or insufficient adsorption capacity. Their two-step strategy, involving phosphorylation and a Mannich reaction, was designed to introduce stronger chelating sites without abandoning the advantages of a biomass-derived hydrogel framework. The study is important in a review context because it does not merely claim that “modification improves adsorption”; it demonstrates why chelating functionalization matters chemically. At the same time, the authors also highlight a key synthetic limitation: once polysaccharides are chemically modified, their solubility and processability change, meaning that standard co-dissolution/regeneration routes are no longer always suitable. In other words, functionalization increases affinity but can complicate fabrication. This trade-off is central to the current stage of the field [22].

Recent work on magnetic chitosan composites reveals a comparable pattern. Zhang et al. (2023) prepared a Fe_3O_4/chitosan/sludge-biochar composite that reached 99.77% Cu^{2+} removal and a maximum adsorption capacity of 55.16 mg g^{-1}, while also allowing rapid solid–liquid separation under a magnetic field. From a practical standpoint, this is highly relevant because separation and regeneration are often overlooked bottlenecks in adsorption research. Yet the capacity itself is moderate compared with some highly functionalized hydrogels and MOF-containing aerogels. This comparison is instructive: magnetic modification may not always produce the absolute highest uptake, but it adds operational value through recoverability. Therefore, recent results suggest that the “best” sorbent depends on the target criterion-maximum capacity, fastest kinetics, easiest separation, or best cyclic stability-not on a single adsorption number [23,24].

Influence of pollutant type on adsorption efficiency. A critical reading of recent publications shows that adsorption results are often discussed too generally, whereas the actual removal mechanism depends strongly on the pollutant class. For heavy metal ions, the dominant factors are usually coordination ability, surface charge and accessibility of oxygen- and nitrogen-containing donor sites. For dyes, pore architecture and electrostatic attraction play a stronger role, and for pharmaceutical molecules, additional interactions such as hydrogen bonding, π–π interactions and steric selectivity become increasingly important. As a consequence, a composite optimized for Cu(II) or Pb(II) capture cannot automatically be assumed effective for tetracycline, ciprofloxacin or mixed dye systems. Recent reviews focused on cellulose-based wastewater materials and chitosan-based pollutant removal repeatedly stress this point [25].

For heavy metal removal, recent cellulose-based systems remain particularly strong because hydroxyl-rich matrices can be readily converted into chelating adsorbents. According to the 2024 review by El Mahdaoui et al., modification strategies are increasingly directed not only toward increasing capacity, but also toward tailoring selectivity for toxic cations and improving regeneration performance. This is consistent with the broader trend toward adsorbents that are chemically “programmed” for target ions rather than broadly adsorptive but poorly selective substrates. In practice, this means that aminated, phosphorylated and magnetic cellulose/chitosan systems are more likely to move forward than unmodified biopolymer matrices [16].

For dyes, however, the literature suggests a somewhat different design logic. The HKUST-1/cellulose/chitosan aerogel described by Liu et al. (2021) performed extremely well for methylene blue, largely because the hybrid architecture created a very high surface area and a porous network favorable for cationic dye uptake [19]. Likewise, the double-cross-linked bamboo-paper/chitosan aerogel reported by Qiu et al. (2022) was designed for both cationic and anionic dyes in single and binary systems, using sequential physical and chemical cross-linking to reinforce the bead structure. This is important because many dye-removal studies still evaluate only one model dye under ideal conditions, whereas binary systems are far more representative of real wastewater. The newer literature is beginning to address this gap, but not yet consistently [26].

Pharmaceutical contaminants remain the least mature application area among the three. Recent reviews note growing interest in chitosan-based adsorbents for antibiotics, but also emphasize that selectivity, matrix interference and pilot-scale validation are still insufficiently developed. Kurczewska et al. (2024), for example, reported chitosan/halloysite-supported molecularly imprinted polymer beads with high selectivity for tetracycline, and the adsorption properties were maintained in real water and soil samples. This is a notable step beyond standard batch tests because it introduces molecular recognition into a biopolymer-based adsorbent. Similarly, a 2025 study on cellulose/chitosan composites for ciprofloxacin removal combined adsorption experiments with DFT analysis, showing that the adsorbed state was energetically favorable. Such studies indicate that the field is beginning to move from empirical screening toward mechanism-informed design. Nevertheless, compared with metal-ion adsorption, the evidence base for pharmaceuticals is still narrower and less standardized [27].

The diversity of modification strategies and pollutant-specific adsorption mechanisms reported in recent literature demonstrates that polymer composite sorbents cannot be evaluated using a single performance parameter. Table 1 summarizes representative studies published between 2021 and 2025, highlighting differences in modification approaches, adsorption performance and reusability characteristics of cellulose- and chitosan-based composites.

Table 1

Comparison of recent polymer composite sorbents

Material	Modification	Pollutant	Capacity ($mg\ g^{-1}$)	Reusability cycles	Ref
Cellulose/chitosan/β-FeOOH hydrogel	in situ growth of β-FeOOH nanoparticles	methyl orange	97.75% removal	5 cycles (80.81% retained)	[18]
Cellulose/chitosan aerogel/HKUST-1	MOF incorporation	methylene blue	526.3	5 cycles	[19]
Phosphonate-functionalized cellulose/chitosan hydrogel	phosphorylation + Mannich reaction	Pb^{2+}, Cu^{2+}	high removal efficiency	5 cycles	[22]
Magnetic chitosan/sludge biochar composite	Fe_3O_4 incorporation	Cu^{2+}	55.16	multiple cycles	[23]
Chitosan/halloysite molecularly imprinted polymer	molecular imprinting	tetracycline	high selectivity adsorption	repeated use	[27]

Stability and reusability of polymer composite sorbents. One of the clearest distinctions between stronger and weaker recent studies is the extent to which they go beyond equilibrium capacity as the principal performance metric. In many adsorption papers, the headline result is still a maximum capacity fitted by the Langmuir model. Yet the more informative studies published in the last five years increasingly report kinetics, cyclic stability, competitive effects, and in some cases real-sample behavior. This is a meaningful methodological improvement because capacity alone often overestimates practical value. A material with a lower nominal uptake but faster adsorption, easier separation and better regeneration may be more suitable for application than a high-capacity sorbent requiring long equilibrium times or delicate synthesis [28].

Recent literature demonstrates that long-term operational stability is becoming a central criterion for evaluating the applicability of polymer composite sorbents in water treatment technologies. While earlier studies often focused primarily on equilibrium adsorption capacity, more recent investigations emphasize the importance of maintaining structural integrity and adsorption efficiency during repeated adsorption-desorption cycles. This shift reflects the growing recognition that practical implementation requires materials capable of functioning under dynamic conditions, including fluctuations in pH, ionic strength, and pollutant concentration. In particular, cyclic adsorption performance has become a key indicator of economic feasibility, as regeneration ability directly influences operational costs and environmental sustainability [29,30].

A number of recent studies show that stability of polymer composite sorbents depends strongly on the nature of cross-linking interactions within the polymer matrix. Covalent cross-linking is often associated with improved resistance to swelling and dissolution, which are common limitations of polysaccharide-based materials. For example, Zia et al. (2019) demonstrated that epichlorohydrin-crosslinked chitosan composites retained high adsorption efficiency toward Cu(II) ions after multiple regeneration cycles due to enhanced rigidity of the polymer network [31]. Similarly, Liu et al. (2015) reported that chemically stabilized cellulose hydrogels maintained stable adsorption capacity for methylene blue after repeated desorption processes, indicating that preservation of the three-dimensional polymer structure is essential for maintaining accessibility of functional groups [32].

Another important factor influencing reusability is the reversibility of interactions between sorbent surface and adsorbed molecules. Polymer composites containing functional groups capable of forming coordination or electrostatic interactions often exhibit improved regeneration performance when desorption is carried out using mild eluents such as dilute acid or ethanol solutions. According to Hsu et al. (2024), chitosan-based adsorbents demonstrated relatively stable removal efficiency for Pb(II) after several regeneration cycles, confirming that reversible binding interactions can provide a balance between strong adsorption affinity and effective desorption. In contrast, excessively strong chemisorption may reduce regeneration efficiency due to incomplete removal of adsorbed species from active sites [33].

Recent investigations also highlight the influence of structural heterogeneity on durability of adsorption performance. Porous polymer networks containing interconnected macro- and mesopores facilitate diffusion of adsorbate molecules and reduce accumulation of pollutants within the internal structure of the sorbent. Jain et al. (2022) showed that cellulose aerogels with hierarchical porosity exhibited stable adsorption behavior during repeated cycles, which was attributed to improved mass transfer and reduced pore blockage. These findings suggest that transport properties of polymer matrices represent an important parameter determining long-term operational stability [34].

Resistance to interference from coexisting substances present in real wastewater systems is another aspect increasingly addressed in recent publications. The presence of competing ions or natural organic matter may reduce adsorption efficiency due to competition for active binding sites or partial surface fouling. According to the study by Nguyen et al. (2022), adsorption capacity of chitosan-based sorbents decreased in multicomponent systems compared with single-solute solutions, highlighting the importance of evaluating sorbents under realistic conditions. Such results confirm that laboratory-scale adsorption values may overestimate actual performance when complex water matrices are considered [35].

In practical water treatment applications, adsorption capacity alone is insufficient to evaluate the performance of polymer composite sorbents. Regeneration ability and stability of adsorption efficiency during repeated cycles represent key parameters determining economic and technological feasibility of sorbent materials. The cyclic adsorption–desorption process and preservation of structural integrity of polymer composites are illustrated in Figure 2.

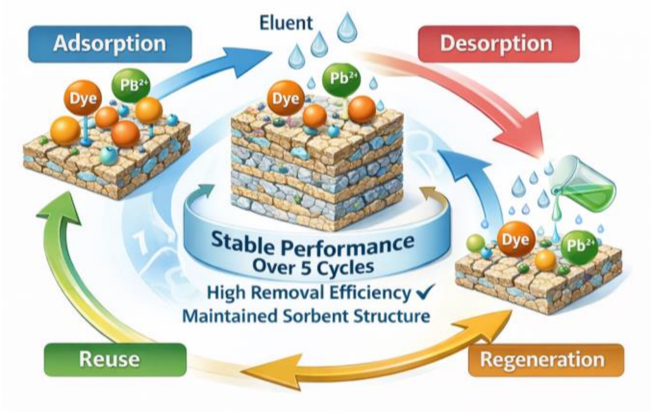

Fig. 2. Adsorption-desorption cycle and reusability of polymer composite sorbents

Figure 2 presents a schematic representation of adsorption–desorption regeneration cycles demonstrating stability of polymer composite sorbents during repeated use. The scheme illustrates reversible interaction between pollutant molecules and functional groups of the polymer matrix, followed by desorption using appropriate eluents and subsequent regeneration of active adsorption sites. Preservation of structural integrity over multiple cycles indicates the importance of cross-linking interactions and hierarchical porosity for maintaining long-term sorption performance.

Overall, recent research indicates that stability and reusability of polymer composite sorbents are governed by a combination of structural robustness, reversibility of adsorption interactions, and resistance to environmental interference factors. The most promising materials are characterized by the ability to maintain adsorption efficiency during repeated cycles without significant structural degradation or loss of active binding sites. Consequently, contemporary studies increasingly emphasize the importance of integrating adsorption performance with durability assessment in order to identify materials suitable for practical water purification applications.

Discussion. The rapid expansion of research on polymer composite sorbents reflects a broader shift in materials chemistry from empirical material development toward knowledge-driven design of functional systems with predictable physicochemical behavior. Contemporary literature demonstrates that adsorption efficiency is increasingly interpreted as an emergent property arising from the interplay between polymer architecture, distribution of active functional groups, and stability of intermolecular interactions under operational conditions. Rather than focusing exclusively on increasing adsorption capacity, recent investigations emphasize optimization of structural parameters governing accessibility of adsorption sites, diffusion pathways, and resistance of polymer networks to physicochemical degradation. Such an approach corresponds to the general trend toward rational engineering of materials based on structure–property relationships [36].

A key conceptual development in recent years involves the transition from single-component sorbents toward hybrid polymer composite systems integrating organic matrices with inorganic or carbon-based functional phases. These hybrid materials aim to overcome inherent limitations of individual polymers, including insufficient mechanical stability, sensitivity to environmental conditions, and limited selectivity toward structurally diverse pollutants. However, critical examination of recent studies indicates that increasing compositional complexity does not automatically translate into improved adsorption performance. In many cases, incorporation of nanofillers or additional functional modifiers leads to partial aggregation or reduced accessibility of active sites, ultimately limiting sorption efficiency despite increased theoretical surface area. Recent reviews highlight that the relationship between material complexity and performance remains non-linear, and excessive modification may reduce reproducibility and complicate large-scale synthesis [20].

An important consideration emerging from recent literature is the need to balance structural stability with molecular accessibility of adsorption centers. While highly porous polymer networks typically demonstrate increased surface area, excessive porosity may compromise mechanical stability of the composite, particularly under repeated adsorption–desorption cycles or continuous flow conditions. Conversely, densely crosslinked polymer matrices often exhibit improved durability but reduced diffusion rates of pollutant molecules. Studies on polymer nanocomposites for dye removal show that hierarchical pore systems can provide improved mass transfer characteristics while maintaining sufficient structural integrity of the material [37]. This observation suggests that future material design strategies should consider pore connectivity and structural resilience simultaneously rather than treating surface area as an isolated performance parameter. Sustainability considerations increasingly influence the direction of research on polymer composite materials. Natural polymers such as cellulose and chitosan are widely regarded as promising alternatives to conventional synthetic sorbents due to their biodegradability, low toxicity, and availability from renewable resources. However, variability of natural feedstocks may influence reproducibility of physicochemical properties of derived composites. Differences in crystallinity, molecular weight distribution, and residual impurities may lead to significant variation in adsorption behavior even among materials prepared using similar synthesis procedures. Recent bibliometric analyses of chitosan-based adsorbents highlight the growing importance of standardization in characterization methods to ensure comparability of experimental results across different research groups [37].

Chemical modification strategies remain essential for enhancing selectivity of polymer composite sorbents toward specific classes of contaminants. Functionalization approaches introducing donor atoms such as nitrogen, sulfur, or phosphorus increase affinity toward heavy metal ions through coordination mechanisms, whereas incorporation of aromatic structures or polar functional groups may improve adsorption of organic pollutants and pharmaceutical residues. Nevertheless, excessive functionalization may disrupt intermolecular interactions responsible for formation of stable polymer networks. According to recent analyses of cellulose/chitosan-based composites, modification strategies should be carefully optimized to preserve supramolecular organization of polymer chains while enhancing interaction energy between sorbent and adsorbate [38].

Despite substantial progress achieved in recent years, several important limitations remain unresolved. Many studies still rely on batch adsorption experiments, which provide limited information about performance under dynamic flow conditions characteristic of industrial water treatment processes. In addition, comparison of adsorption capacities reported in the literature is complicated by differences in experimental parameters such as initial pollutant concentration, contact time, temperature, and pH conditions. Consequently, identification of optimal material architectures remains challenging. Future research should therefore focus on development of predictive models linking molecular structure of polymer composites with adsorption performance, as well as on integration of experimental data with process-level analysis.

Overall, the current state of research indicates a transition from discovery of new compositions toward identification of fundamental principles governing adsorption behavior of polymer composite sorbents. Further progress will depend on interdisciplinary integration of polymer chemistry, materials science, and environmental engineering approaches, enabling development of functional materials combining high efficiency, structural stability, and technological feasibility for real water purification systems.

Conclusions and Future Directions. This manuscript highlights that recent progress in polymer composite sorbents is increasingly associated with rational design approaches that consider both chemical functionality and structural organization of polymer matrices. Cellulose- and chitosan-based composites remain among the most promising materials due to their availability, environmental safety, and the presence of reactive functional groups capable of interacting with various pollutants. However, current research demonstrates that adsorption efficiency depends not only on chemical composition but also on accessibility of active sites, pore architecture, and stability of the polymer network under operational conditions.

An important conclusion is that improvement of sorption properties requires a balance between structural stability and diffusion accessibility. Highly porous materials may provide increased surface area, but insufficient mechanical strength can limit their long-term performance. At the same time, excessive chemical modification may reduce structural flexibility of polymer matrices. Therefore, future material development should focus on optimization of structural parameters that ensure both stability and effective interaction with pollutants.

Recent studies also indicate that adsorption capacity alone is not sufficient to evaluate practical applicability of sorbents. Increasing attention is given to adsorption kinetics, regeneration ability, and performance in complex aqueous environments containing competing ions and organic impurities. These factors play a decisive role in determining the feasibility of applying polymer composite sorbents in real water treatment systems.

Future research should focus on improving reproducibility of polymer composite materials derived from natural raw sources, as variability in biomass composition may influence physicochemical properties of the final product. In addition, integration of experimental studies with theoretical modeling may contribute to prediction of adsorption behavior and more efficient design of functional materials.

Overall, polymer composite sorbents represent a promising platform for development of sustainable water purification technologies. Further progress will depend on interdisciplinary approaches combining polymer chemistry, materials science, and environmental engineering to create materials with controlled structure, high stability, and practical applicability.

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СОРБЦИЯЛЫҚ ҚАСИЕТТЕРІ БАР ПОЛИМЕРЛІ КОМПОЗИТТІК МАТЕРИАЛДАР: ҚҰРЫЛЫМЫ, МОДИФИКАЦИЯСЫ ЖӘНЕ ҚОЛДАНЫЛУЫ

Аннотация. Сорбциялық қасиеттері бар полимерлі композиттік материалдар қоршаған ортаны қорғау технологияларында, әсіресе су тазарту саласында қолданылуына байланысты үлкен ғылыми қызығушылық тудырады. Полимер химиясы мен материалтану саласындағы соңғы жетістіктер бақыланатын физика-химиялық сипаттамалары және жоғары адсорбциялық тиімділігі бар функционалды композиттерді алуға мүмкіндік берді. Целлюлоза мен хитозан негізіндегі материалдар биоыдырағыштығы, қолжетімділігі және әртүрлі ластаушылармен әрекеттесе алатын функционалдық топтарының болуына байланысты перспективалы болып табылады. Бұл шолуда полимерлі композиттік сорбенттерді синтездеу және модификациялау бағытындағы соңғы жетістіктер қарастырылып, құрылымдық ұйымдасу, функционалдық топтардың қолжетімділігі және адсорбциялық тиімділік арасындағы байланыс талданады. Ауыр металл иондары, бояғыштар және фармацевтикалық қосылыстарды жоюдағы кеуекті құрылым мен химиялық модификацияның рөлі көрсетіледі. Зерттеулер адсорбциялық тиімділік химиялық құраммен қатар, диффузиялық процестер мен полимер матрицасының тұрақтылығына тәуелді екенін дәлелдейді. Болашақ зерттеулер құрылым-қасиет байланысын терең талдауға, модельдеу әдістерін қолдануға және өндірістік масштабтауға бейім тиімді әрі экологиялық қауіпсіз сорбенттерді әзірлеуге бағытталады.

Түйін сөздер: полимерлі композиттік сорбенттер, целлюлоза, хитозан, адсорбция, суды тазарту.

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ПОЛИМЕРНЫЕ КОМПОЗИТНЫЕ МАТЕРИАЛЫ С СОРБЦИОННЫМИ СВОЙСТВАМИ: СТРУКТУРА, МОДИФИКАЦИЯ И ПРИМЕНЕНИЕ

Аннотация. Полимерные композиционные материалы с сорбционными свойствами вызывают значительный научный интерес благодаря возможности их применения в экологических технологиях, особенно в процессах очистки воды. Современные достижения в области химии полимеров и материаловедения позволили создать функциональные композиты с контролируемыми физико-химическими характеристиками и повышенной адсорбционной эффективностью. Материалы на основе целлюлозы и хитозана считаются перспективными благодаря их биоразлагаемости, доступности и наличию функциональных групп, способных взаимодействовать с различными загрязнителями. В данном обзоре рассмотрены современные подходы к синтезу и модификации полимерных композиционных сорбентов, а также проанализирована взаимосвязь между структурной организацией, доступностью функциональных групп и эффективностью адсорбции. Показана роль пористой структуры и химической модификации в удалении ионов тяжелых металлов, красителей и фармацевтических соединений. Исследования подтверждают, что адсорбционная эффективность определяется не только химическим составом, но и структурными параметрами, влияющими на диффузионные процессы и устойчивость полимерной матрицы. Дальнейшие исследования направлены на углублённое изучение взаимосвязи структура–свойства, применение методов моделирования и разработку эффективных и экологически безопасных сорбентов, пригодных для масштабирования.

Ключевые слова: полимерные композитные сорбенты, целлюлоза, хитозан, адсорбция, очистка воды.