Natural Mineral and Clay Adsorbents for Aflatoxin Removal: A Survey

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Abstract

This survey paper examines the efficacy of natural mineral and clay adsorbents in the removal of aflatoxins, toxic compounds primarily produced by *Aspergillus* species, from contaminated environments. Aflatoxins, especially Aflatoxin B1 (AFB1), pose significant health risks, including carcinogenic effects, necessitating effective remediation strategies. The paper highlights the role of natural adsorbents, such as bentonite, montmorillonite, and zeolite, which leverage their high cation exchange capacities and large surface areas to adsorb aflatoxins effectively. The study further explores the enhancement of adsorption efficiency through organic modification, which improves the selectivity and capacity of these adsorbents. Case studies, such as the use of rice husk-based MCM-41, illustrate the potential of integrating agricultural waste into advanced adsorbent development, promoting sustainable environmental remediation practices. Despite the promise of these materials, economic and regulatory challenges, along with limitations in detection technologies, hinder their widespread application. The survey underscores the need for ongoing research to optimize adsorbent performance, address scalability issues, and ensure environmental compatibility. By advancing these areas, the integration of natural mineral and clay adsorbents into aflatoxin control strategies can be fully realized, enhancing food safety and protecting public health.

1 Introduction

1.1 Overview of Aflatoxins

Aflatoxins, primarily produced by the Aspergillus species, particularly *Aspergillus flavus* and *Aspergillus parasiticus*, are highly toxic and carcinogenic compounds that contaminate various food and feed products, including groundnuts, maize, and rice, posing significant health risks to humans and livestock [1, 2, 3]. As potent environmental contaminants, aflatoxins predominantly affect agricultural commodities, with Aflatoxin B1 (AFB1) being a notable example due to its high carcinogenic potential. The presence of these mycotoxins in food and feed represents serious health threats, including carcinogenic effects, liver toxicity, and immunosuppression, with exposure leading to acute or chronic mycotoxicoses. Aflatoxin contamination occurs widely in various food sources, often resulting from fungal infections during both pre-harvest and post-harvest stages. Effective detection and management strategies are crucial to mitigate these risks and ensure food safety [4, 5, 1]. Moreover, the contamination of animal feed exacerbates these risks, affecting livestock health and performance while posing potential human health risks through the consumption of contaminated animal products.

1.2 Significance of Aflatoxin Removal

The removal of aflatoxins from the environment is critical due to their severe health implications and widespread presence in the food supply chain. Aflatoxins, particularly Aflatoxin B1 (AFB1), are potent carcinogens linked to liver cancer and acute aflatoxicosis, presenting significant health

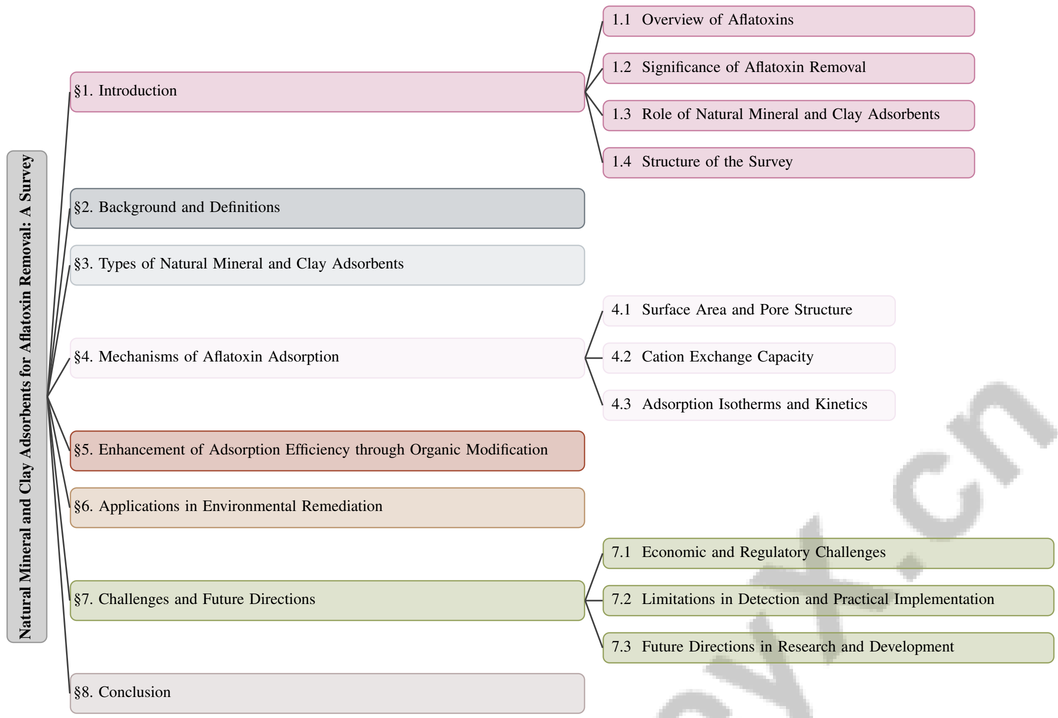

Figure 1: chapter structure

hazards to both humans and animals. Approximately 25% of the world's food crops are affected by these toxins, leading to profound economic and food safety challenges. Despite existing safety measures, detecting low concentrations of aflatoxins remains difficult, necessitating advanced detoxification methods. Current techniques, including chemical treatments and microbial degradation, have limitations and may inadvertently generate new toxins [6]. Additionally, aflatoxin contamination in animal feed not only jeopardizes livestock health but also poses potential risks to humans through the consumption of contaminated animal products. Therefore, effective strategies for quantification, detection, and control of aflatoxins are essential to mitigate their impact on health and the environment [4]. The environmental compatibility of remediation methods, particularly those involving chemically modified nanoclays, must also be considered to avoid additional ecological risks.

1.3 Role of Natural Mineral and Clay Adsorbents

Natural mineral and clay adsorbents are vital in removing aflatoxins from contaminated environments, utilizing their inherent adsorption capacities to mitigate these potent toxins. Clay nano-adsorbents, in particular, have demonstrated efficacy in adsorbing aflatoxins, such as Aflatoxin B1 (AFB1), from various matrices, including food and feed products [7]. The adsorption process involves the binding of aflatoxins to the surface of these adsorbents, thereby decreasing their bioavailability and toxicity. This mechanism is critical for agricultural commodities, where contamination of products like peanut oil with AFB1 poses severe health risks [6]. The application of natural mineral and clay adsorbents offers a promising alternative to traditional chemical and physical detoxification methods, which may generate undesirable byproducts or require extensive processing. Furthermore, these adsorbents are effective not only in food products but also in reducing aflatoxin contamination in livestock feeds, addressing a significant vector of toxin exposure in the food supply chain [5]. Integrating natural mineral and clay adsorbents into aflatoxin control strategies signifies a substantial advancement in environmental remediation efforts, providing a sustainable and efficient approach to reducing the prevalence of these hazardous compounds [4].

1.4 Structure of the Survey

This survey is systematically organized to provide a comprehensive understanding of the role of natural mineral and clay adsorbents in the removal of aflatoxins from contaminated environments. The

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introduction discusses the significance of aflatoxins as environmental contaminants and the importance of efficient removal methods. The background section defines key terms and principles of adsorption, establishing a foundational understanding for subsequent sections. The survey explores various types of natural mineral and clay adsorbents, highlighting specific examples and their properties. It then examines the mechanisms by which these adsorbents remove aflatoxins, focusing on factors such as surface area, pore structure, and cation exchange capacity. The enhancement of adsorption efficiency through organic modification is discussed, providing insights into how these modifications can improve the performance of natural adsorbents. Practical applications in environmental remediation are explored, with case studies illustrating successful implementations. Finally, the survey addresses challenges and future directions, identifying economic, regulatory, and technological hurdles while suggesting areas for future research and development. The conclusion summarizes the key points and emphasizes the significance of these adsorbents in aflatoxin removal.The following sections are organized as shown in Figure 1.

2 Background and Definitions

2.1 Definitions of Key Terms

Adsorption, a pivotal process for aflatoxin mitigation, involves the attachment of aflatoxins to adsorbent surfaces, thereby decreasing their bioavailability and toxicity [7]. Natural mineral adsorbents, sourced from naturally occurring minerals, are utilized to extract pollutants like aflatoxins from contaminated settings [7]. Their intrinsic properties enhance their capacity to bind aflatoxins, playing a crucial role in environmental cleanup. Notably, natural clay adsorbents are characterized by their layered structures and high cation exchange capacities, significantly boosting their adsorption efficiency for aflatoxins [4]. Enhancing these adsorbents with organic compounds is essential for increasing their adsorption capacity and selectivity for specific contaminants such as aflatoxins, thereby improving their efficacy in complex environmental matrices [8].

2.2 Principles of Adsorption in Environmental Remediation

Adsorption principles are integral to environmental remediation, especially in eliminating contaminants like aflatoxins from water and soil. This process involves the binding of aflatoxins to adsorbent surfaces, reducing their mobility and bioavailability [7]. The interactions are primarily governed by physical forces, such as van der Waals forces and electrostatic interactions, and chemical bonding, contingent on the characteristics of the adsorbent and the contaminant. Key factors affecting adsorption efficiency include the adsorbent's surface area, pore size, and cation exchange capacity, which collectively influence its pollutant capture potential [7].

In the context of aflatoxin removal, adsorption offers a viable alternative to traditional degradation methods, which often fall short due to the chemical resilience of aflatoxins and the limitations of conventional processes like cooking or freezing [9]. The employment of natural mineral and clay adsorbents, with their high surface areas and advantageous physicochemical properties, enhances aflatoxin adsorption capacity, making them effective in reducing contamination in environmental and agricultural domains. This highlights the importance of adsorption principles in advancing sustainable and efficient environmental remediation technologies.

3 Types of Natural Mineral and Clay Adsorbents

3.1 Specific Examples of Natural Adsorbents

Natural adsorbents such as bentonite, montmorillonite, and zeolite are pivotal in aflatoxin remediation due to their distinct structural and chemical properties [7]. Bentonite, rich in montmorillonite, exhibits a high cation exchange capacity and extensive surface area, enhancing its effectiveness in extracting aflatoxins from contaminated environments [10]. Montmorillonite shares these beneficial attributes, making it efficient for aflatoxin removal in food and feed [7]. Zeolite, noted for its microporous structure and thermal stability, further augments aflatoxin adsorption capabilities [10].

Additionally, novel materials like MCM-41, derived from rice husk ash, have been investigated for their structural and adsorption potential [6]. Incorporating such advanced materials into remediation processes offers improved aflatoxin removal, especially in complex matrices like peanut oil, where traditional adsorbents may be inadequate. These instances highlight the adaptability and efficacy of natural mineral and clay adsorbents in environmental remediation, emphasizing their crucial role in mitigating aflatoxin contamination across diverse applications.

The mechanisms underlying aflatoxin adsorption are complex and multifaceted, necessitating a comprehensive understanding of the factors that influence this process. As illustrated in Figure 3, the hierarchical structure of these mechanisms is categorized into several key factors that significantly affect adsorption efficiency. This figure illustrates the classification of natural adsorbents and novel materials used for aflatoxin remediation, highlighting key natural adsorbents, novel materials like MCM-41, and the mechanisms underlying their adsorption capabilities. Among these factors are surface area and pore structure, cation exchange capacity, as well as adsorption isotherms and kinetics. Each of these categories is further delineated into specific aspects, including adsorbent optimization, external influences, and practical applications. This structured approach not only underscores the importance of these factors in enhancing food safety but also emphasizes their critical roles in mitigating the health risks associated with aflatoxin exposure.

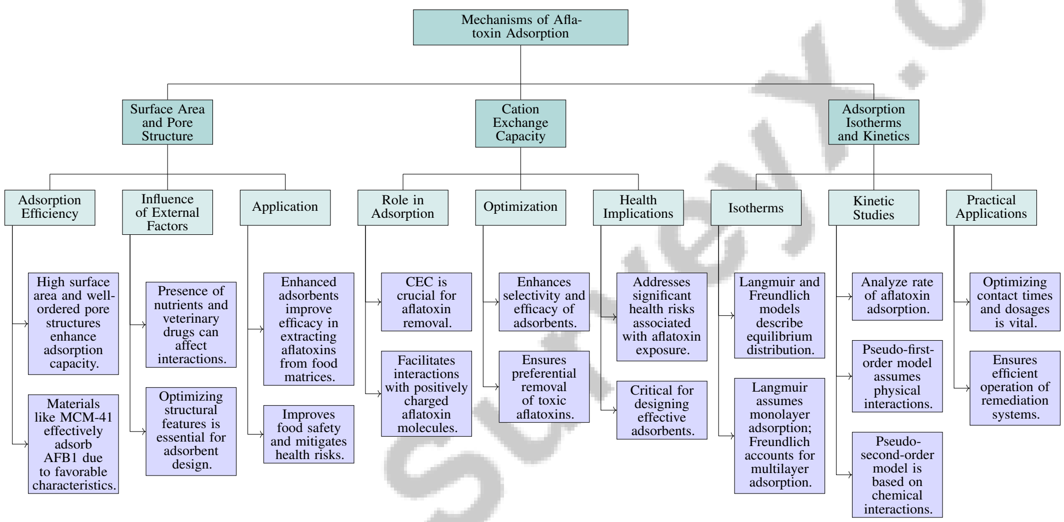

Figure 2: This figure illustrates the hierarchical structure of mechanisms involved in aflatoxin adsorption using natural mineral and clay adsorbents. It categorizes the key factors affecting adsorption efficiency, including surface area and pore structure, cation exchange capacity, and adsorption isotherms and kinetics. Each category is further divided into specific aspects such as adsorbent optimization, external influences, and practical applications, highlighting their roles in enhancing food safety and mitigating health risks associated with aflatoxin exposure.

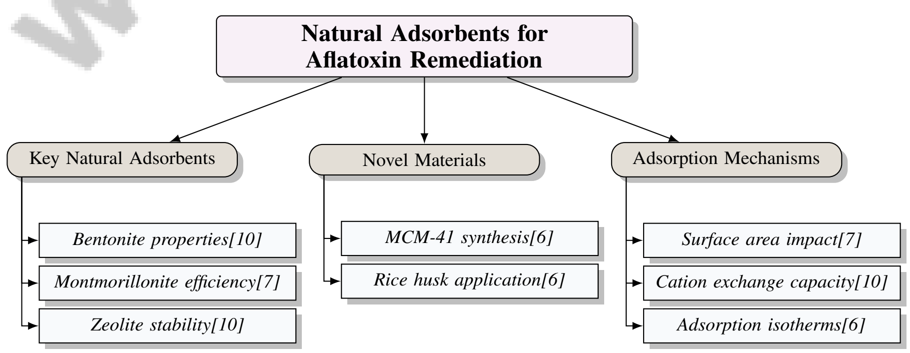

Figure 3: This figure illustrates the classification of natural adsorbents and novel materials used for aflatoxin remediation, highlighting key natural adsorbents, novel materials like MCM-41, and the mechanisms underlying their adsorption capabilities.

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4 Mechanisms of Aflatoxin Adsorption

4.1 Surface Area and Pore Structure

The adsorption efficiency of natural mineral and clay adsorbents for aflatoxins is critically determined by their surface area and pore structure, which influence the availability of active sites for contaminant attachment. High surface area and well-ordered pore structures enhance adsorption capacity by providing numerous interaction sites for aflatoxins, as demonstrated by materials like MCM-41, which effectively adsorb Aflatoxin B1 (AFB1) due to these favorable characteristics [7, 6]. Microporous materials such as zeolite and montmorillonite facilitate the entrapment of aflatoxins within their lattice structures [10].

As illustrated in Figure 4, the key factors influencing the adsorption efficiency of mineral and clay adsorbents for aflatoxins are highlighted, emphasizing the importance of surface area, pore structure, and external influencing factors. However, the presence of nutrients and veterinary drugs can affect these interactions, influencing the binding efficiency and selectivity of the adsorbents [10]. Optimizing these structural features is essential for improving adsorbent design and application in environmental remediation. Enhancing the structural and chemical properties of adsorbents, such as rice husk-based mesoporous silica (MCM-41), can improve their efficacy in extracting aflatoxins from diverse food matrices, including peanut oil, thus enhancing food safety and mitigating health risks [1, 6].

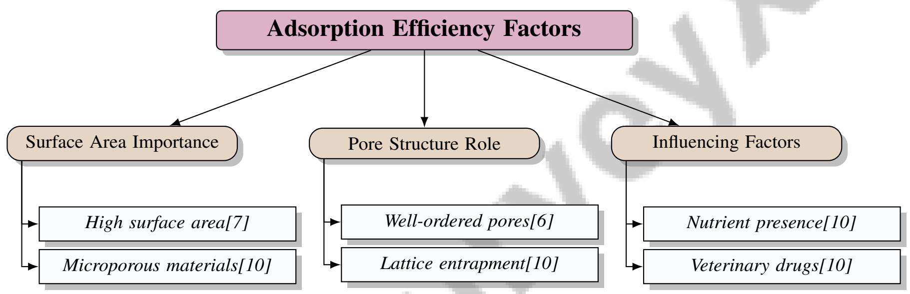

Figure 4: This figure illustrates the key factors influencing the adsorption efficiency of mineral and clay adsorbents for aflatoxins, highlighting the importance of surface area, pore structure, and external influencing factors.

4.2 Cation Exchange Capacity

Cation exchange capacity (CEC) is a crucial factor in the adsorption efficiency of natural mineral and clay adsorbents for aflatoxin removal. CEC indicates the adsorbent's ability to exchange cations between its surface and the surrounding environment, a key mechanism for capturing contaminants like aflatoxins [7]. Clay minerals such as montmorillonite and bentonite exhibit high CEC values due to their layered structures and negatively charged sites, facilitating effective interactions with positively charged aflatoxin molecules and enhancing overall adsorption capacity. Beyond direct aflatoxin binding, CEC aids in the adsorption of competing ionic species in contaminated matrices. Optimizing CEC enhances the selectivity and efficacy of adsorbents in complex environmental conditions, ensuring the preferential removal of toxic aflatoxins from food products like peanut oil while minimizing the adsorption of less harmful contaminants. This optimization is critical for addressing significant health risks associated with aflatoxin exposure in food and feed, a pressing global concern [1, 6, 9, 2]. Thus, considering CEC is paramount in designing effective adsorbents for environmental remediation.

4.3 Adsorption Isotherms and Kinetics

Adsorption isotherms and kinetics are fundamental in understanding interactions between aflatoxins and natural mineral and clay adsorbents, guiding the design of effective remediation systems [7]. Table 1 presents a detailed summary of the benchmarks employed in evaluating adsorption isotherms and kinetics, which are crucial for the effective design and assessment of aflatoxin remediation strategies. The performance of these adsorbents is assessed by determining the removal rate of Aflatoxin B1 (AFB1) at varying adsorbent concentrations, providing insights into adsorption capacity and

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Benchmark	Size	Domain	Task Format	Metric

Table 1: This table provides a structured overview of various benchmarks relevant to the study of adsorption isotherms and kinetics in the context of aflatoxin remediation. It details the size, domain, task format, and metric associated with each benchmark, facilitating a comprehensive understanding of their applicability and performance in environmental remediation systems.

efficiency under diverse conditions [6]. Adsorption isotherms, such as the Langmuir and Freundlich models, describe the equilibrium distribution of aflatoxins between the liquid phase and the adsorbent surface. The Langmuir isotherm assumes monolayer adsorption on a homogeneous surface, while the Freundlich isotherm accounts for heterogeneous surface energies and multilayer adsorption, often observed in natural adsorbents like bentonite and montmorillonite [7]. Kinetic studies analyze the rate of aflatoxin adsorption onto the adsorbent surface, offering insights into the dynamics of the adsorption process. Kinetic models, such as pseudo-first-order and pseudo-second-order kinetics, are employed to analyze adsorption rates. The pseudo-first-order model typically assumes physical interactions, whereas the pseudo-second-order model is based on chemical interactions, crucial for understanding the mechanisms involved, particularly in materials like modified nanoclays that show promise in environmental remediation [1, 7, 10, 6, 3]. Understanding the kinetics of aflatoxin adsorption is vital for optimizing contact times and adsorbent dosages in practical applications, ensuring efficient operation of remediation systems in reducing aflatoxin levels in contaminated environments.

5 Enhancement of Adsorption Efficiency through Organic Modification

5.1 Chemical Modifications of Clay Nano-Adsorbents

Enhancing the adsorption capabilities of clay nano-adsorbents through chemical modifications is pivotal in improving their efficacy against contaminants like aflatoxins [7]. By incorporating organic compounds onto the clay surface, these modifications increase selectivity and affinity for specific molecules. Surfactants and polymers, for instance, introduce functional groups that enhance hydrophobicity, thereby improving interactions with hydrophobic contaminants such as Aflatoxin B1 (AFB1). MCM-41, a mesoporous material derived from rice husk ash, exemplifies this approach. Its high specific surface area and pore volume are further augmented by chemical modifications, enhancing AFB1 adsorption [6]. The material's large pore volume facilitates the accommodation of larger molecules and provides abundant active sites, making it effective for aflatoxin removal. The strategic modification of clay nano-adsorbents, including rice husk-based mesoporous silica (MCM-41), significantly boosts their performance in environmental remediation. This tailored strategy enhances adsorption capacities and selectivities for aflatoxins, addressing the challenge of contamination in food products like peanut oil. MCM-41 demonstrates a maximum uptake of approximately 216 ng/mg for AFB1, underscoring its potential in promoting food safety and public health [1, 6, 9, 2].

5.2 Environmental Compatibility of Modified Adsorbents

Ensuring the environmental compatibility of modified adsorbents is crucial in aflatoxin remediation, as it prevents additional ecological risks. Although chemical modifications, such as those involving surfactants and polymers, enhance the adsorption efficiency of clay nano-adsorbents, they can also pose environmental hazards. Traditional surfactants used in nanoclay modifications may be toxic to living organisms in natural systems [3]. Therefore, it is essential to evaluate the biocompatibility and degradation potential of these modified adsorbents to minimize environmental impact. Advancing environmentally friendly modification techniques is vital for maintaining ecological balance while enhancing remediation efficacy and safety. This includes using biocompatible nanoclays and innovative materials that effectively remove contaminants from water and soil [1, 9, 7, 6, 3]. Strategies may involve biodegradable and non-toxic surfactants or designing adsorbents with minimal leaching potential. Additionally, assessing the long-term stability and reusability of modified adsorbents supports their sustainable application in environmental remediation, reducing the need for frequent replacements and minimizing waste generation.

6 Applications in Environmental Remediation

6.1 Successful Applications of Clay Nano-Adsorbents

Clay nano-adsorbents have proven highly effective in environmental remediation, particularly for removing aflatoxins and other contaminants from water systems. Natural clays, such as montmorillonite and bentonite, possess high cation exchange capacities and large surface areas, facilitating the adsorption of toxic compounds and mitigating their environmental impact [7]. These materials have been successfully applied in treating industrial effluents and agricultural runoff, leading to significant reductions in contaminant levels. Rice husk-based mesoporous silica (MCM-41) stands out for its ability to capture aflatoxins, thus enhancing water safety and reducing risks from contaminated food sources [2, 1, 9, 10, 6]. Additionally, clay nano-adsorbents aid in soil remediation, promoting safer agricultural practices and ensuring food safety.

The adaptability of clay nano-adsorbents extends to the removal of diverse contaminants, including heavy metals, dyes, antibiotics, and organic chemicals. Their unique structures and high adsorption efficiencies have made them attractive for water treatment and environmental remediation, showcasing their potential to improve water purification processes and address critical environmental challenges [10, 7, 6, 3]. These materials offer a promising approach to tackling aflatoxin contamination and other pollutants, advancing remediation technologies and protecting public health and ecosystems.

6.2 Case Study: Rice Husk-Based MCM-41 in Aflatoxin Detoxification

Rice husk-based MCM-41 represents a significant advancement in using natural adsorbents for environmental remediation. Synthesized from rice husk ash, MCM-41 is an environmentally sustainable option due to its renewable source. The synthesis process involves extracting silica from rice husk ash and forming a highly ordered mesoporous structure with a large surface area and uniform pore size distribution [6].

In aflatoxin removal, MCM-41 derived from rice husk has demonstrated exceptional adsorption capabilities, particularly for Aflatoxin B1 (AFB1), a highly toxic compound found in contaminated food sources such as peanut oil. With a specific surface area of 1246 m^2/g and a maximum adsorption capacity of 215.93 ng/mg for AFB1, this material effectively addresses aflatoxin contamination in edible oils, enhancing food safety [1, 6, 9, 4]. The high surface area and pore volume of MCM-41 enable effective capture and immobilization of AFB1, significantly reducing its bioavailability and toxicity. This case study highlights the potential of utilizing agricultural waste materials to develop advanced adsorbents, offering a cost-effective and sustainable solution for aflatoxin detoxification.

However, the environmental compatibility of modified nanoclays, including those used in MCM-41 synthesis, requires careful consideration. Despite promising laboratory results, potential toxicity to biota could hinder their effectiveness in practical applications [3]. Comprehensive assessments of the environmental impact and biocompatibility of these adsorbents are essential to ensure their safe and effective use in environmental remediation. Continued research and development are crucial to optimizing the performance of rice husk-based MCM-41 and similar materials, balancing adsorption efficiency with ecological safety.

7 Challenges and Future Directions

7.1 Economic and Regulatory Challenges

The adoption of natural mineral and clay adsorbents for environmental remediation is impeded by significant economic and regulatory barriers. The high cost of advanced water treatment technologies utilizing these adsorbents limits their large-scale application [7]. Additionally, the scalability of current methods remains a challenge, as many studies do not translate effectively into real-world scenarios, necessitating optimization for greater feasibility and cost-effectiveness [2]. Regulatory challenges stem from the variability in the efficacy of mineral adsorbents, influenced by interactions with veterinary substances and nutrients, complicating consistent application across diverse environmental contexts [10]. The lack of comprehensive regulations can lead to inconsistent implementation, potentially undermining their effectiveness in aflatoxin removal [10]. The complexity of agricultural practices and difficulties in monitoring aflatoxin levels further complicate these challenges [5]. Al-

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though advancements in detection technologies and understanding of aflatoxin biosynthesis have been achieved, integrating these into regulatory frameworks is crucial for effective control measures [1]. Furthermore, addressing ecological risks associated with the biocompatibility of modified adsorbents is essential to ensure environmental safety [3]. Evolving the regulatory landscape to incorporate these considerations is vital for balancing effective aflatoxin remediation with ecological protection.

7.2 Limitations in Detection and Practical Implementation

Detecting aflatoxins, especially at low concentrations, presents significant challenges in environmental and agricultural contexts. Current detection technologies often lack the sensitivity and specificity necessary to accurately quantify aflatoxin levels in complex matrices, such as food and feed products [1]. This limitation hinders effective monitoring and management of aflatoxin contamination, as interference from other compounds can lead to false positives or negatives [5]. Environmental variability in aflatoxin production further complicates detection, underscoring the need for more robust analytical techniques. The practical implementation of natural mineral and clay adsorbents faces challenges due to competing substances, such as nutrients and veterinary drugs, which can diminish their adsorption capacity for aflatoxins [10]. Moreover, the scalability of adsorption technologies is a concern, as laboratory successes often do not translate to large-scale applications due to differing environmental conditions and contaminant loads [2]. Long-term stability and reusability of adsorbents are critical for practical applications, as degradation or loss of efficiency over time necessitates frequent replacements, increasing operational costs [7]. Addressing these limitations requires ongoing research and development to optimize adsorbent formulations and enhance detection technologies, ensuring that aflatoxin remediation strategies are both effective and economically viable.

7.3 Future Directions in Research and Development

Future research on aflatoxin remediation should focus on developing rapid detection methods for masked mycotoxins, which are challenging to identify due to their complex structures [1]. Enhancing the sensitivity and specificity of current analytical techniques is critical for accurate quantification of aflatoxins in diverse matrices, including food and feed products [5]. Innovative agricultural practices to minimize aflatoxin contamination at its source could reduce the need for post-harvest interventions [1]. Optimizing clay nano-adsorbents is crucial, with potential applications in treating emerging pollutants in wastewater [7]. Refining the structural and chemical properties of these materials can enhance their adsorption capacities and selectivities for a wider range of contaminants. Exploring novel technologies, such as nanozymes and bioremediation techniques, could provide new avenues for integrating multiple degradation methods, improving the overall efficacy of aflatoxin removal strategies [2]. Developing greener surfactants and biocompatible nanoclays is essential to minimize the environmental impacts of these remediation technologies [3]. Comprehensive studies on the ecological effects of modified adsorbents are necessary to establish safe and sustainable practices. Evaluating the safety and efficacy of modified mineral adsorbents, particularly their interactions with nutrients and veterinary drugs, will be crucial for establishing regulatory frameworks guiding their use in animal nutrition [10]. Emerging trends in biocontrol and genetic modifications for resistance to aflatoxins should be explored, considering the potential impact of climate change on aflatoxin production [4]. Standardizing experimental conditions and investigating the scalability of promising methods, particularly in industrial applications, will be vital for translating laboratory successes into practical solutions [9]. These efforts will contribute to advancing aflatoxin remediation technologies, ensuring their effectiveness and sustainability across various environmental contexts.

8 Conclusion

The effectiveness of natural mineral and clay adsorbents, particularly modified clay nano-adsorbents, in removing aflatoxins from contaminated environments and purifying water is a key focus of this survey. These materials, noted for their high cation exchange capacities and expansive surface areas, offer a sustainable and efficient approach to mitigating the impact of aflatoxins, which pose significant environmental and health challenges. Enhancements through organic modifications further increase the adsorption efficiency and selectivity for aflatoxins such as Aflatoxin B1 (AFB1), while maintaining environmental compatibility.

The development of innovative adsorbents, such as rice husk-based MCM-41, showcases the potential of transforming agricultural waste into advanced materials for aflatoxin detoxification, particularly in complex matrices like peanut oil. This approach not only addresses the issue of aflatoxin contamination but also fosters the sustainable utilization of agricultural byproducts, advancing green technology in environmental remediation.

The survey highlights the importance of ongoing research and development to optimize these adsorbents' performance, ensuring their effectiveness and safety in various applications. Addressing economic and regulatory challenges and enhancing detection technologies are crucial steps in realizing the full potential of natural mineral and clay adsorbents in aflatoxin removal, ultimately contributing to improved food safety and public health protection.

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