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Eco-friendly adsorbents for insecticide residue control: Coconut shell-based activated carbon

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Abstract
The increasing reliance on chemical insecticides to control pests in agricultural and domestic settings has led to a growing concern over insecticide residues in the environment, food, and water supplies. Traditional methods for removing these residues from contaminated environments often involve complex chemical treatments that can have adverse effects on human health and ecosystems. In recent years, the search for sustainable, eco-friendly alternatives has gained prominence, with coconut shell-based activated carbon emerging as a promising candidate due to its high adsorption capacity, renewable nature, and low environmental impact. This review aims to examine the efficacy of coconut shell-based activated carbon as an adsorbent for insecticide residue control. The paper evaluates the adsorption mechanisms, performance, and environmental sustainability of coconut shell-derived activated carbon in the removal of insecticides from contaminated media. The review synthesizes research findings up to 2023, discussing key studies on preparation methods, surface modifications, and adsorption efficiencies, while also addressing potential challenges and future directions for its application in environmental remediation.

Keywords: Coconut shell-based activated carbon, insecticide residue, adsorption, eco-friendly adsorbents, environmental sustainability, activated carbon preparation, removal efficiency, surface modification

Introduction
The widespread use of insecticides in agriculture and public health has been instrumental in controlling pests and diseases, but it has also led to an accumulation of harmful residues in the environment, food, and water sources. These residues pose serious risks to human health, wildlife, and ecosystems. As a result, effective methods for removing insecticide residues from contaminated environments are crucial for ensuring food safety and environmental protection. Conventional techniques such as chemical degradation and photodegradation can be expensive and often result in toxic by-products, raising concerns about their environmental impact.

In response to these challenges, researchers have turned to sustainable and eco-friendly alternatives for insecticide residue removal. One such alternative is activated carbon particularly that derived from coconut shells, which is not only renewable but also offers an efficient, low-cost solution for adsorption-based purification. Coconut shell-based activated carbon has gained attention due to its high surface area, porosity, and ability to be easily modified to enhance its adsorption capacity. Furthermore, the material is considered environmentally friendly because it is made from agricultural waste, reducing the demand for non-renewable resources.

This review aims to explore the potential of coconut shell-based activated carbon as an effective adsorbent for controlling insecticide residues. The review will focus on the material's adsorption mechanisms, its performance in various adsorption processes, and the sustainability aspects of its use. Additionally, the paper will examine the preparation methods and surface modifications that enhance its efficiency, while addressing the challenges and opportunities in its application for environmental remediation. Through this, the review seeks to highlight the role of coconut shell-based activated carbon in sustainable pest management practices.

Methodology
This review aims to evaluate the potential of coconut shell-based activated carbon as an adsorbent for the removal of insecticide residues. A systematic search was conducted in

reputable research databases, including Scopus, Web of Science, and Google Scholar, to gather relevant studies published up to 2023. The search was performed using keywords such as "coconut shell-based activated carbon," "insecticide adsorption," and "eco-friendly adsorbents" to identify peer-reviewed articles that provided insights into the material's performance, preparation methods, and surface modifications.

The studies selected for review varied in their approaches, with many focusing on the physical and chemical characteristics of activated carbon derived from coconut shells. The preparation of activated carbon was often achieved through steam activation or chemical activation methods using agents like phosphoric acid, which are known to increase the material's surface area and porosity. Additionally, some studies investigated the modification of coconut shell-based activated carbon by impregnating it with metal oxides or functional groups to enhance its ability to adsorb insecticide molecules.

Key performance indicators from the selected studies, such as adsorption isotherms, kinetic models, and thermodynamic parameters, were analyzed to understand the adsorption capacity and mechanism of coconut shell-based activated carbon. The findings were synthesized to highlight the effectiveness of the material in adsorbing various types of insecticides, including organophosphates, pyrethroids, and carbamates, under different environmental conditions.

Results

The studies reviewed consistently demonstrate that coconut shell-based activated carbon is an effective adsorbent for insecticide residues, with varying degrees of efficiency based on preparation methods, surface modifications, and adsorption conditions. The adsorption capacity of activated carbon derived from coconut shells has been shown to depend on the material's surface area, pore size distribution, and functional groups present on the surface.

A significant number of studies have highlighted the superior performance of activated carbon prepared through steam activation compared to other methods, due to the higher surface area and microporosity achieved during the activation process. For instance, one study by Kumar *et al.* (2022) [1] reported that coconut shell-based activated carbon prepared using steam activation exhibited a surface area of 1200 m²/g, which was associated with a higher adsorption capacity for organophosphate insecticides, with removal efficiencies of up to 95%. This is in contrast to carbon prepared using phosphoric acid activation, which exhibited a surface area of around 800 m²/g, with lower removal efficiencies of approximately 80%.

Furthermore, the modification of coconut shell-based activated carbon with metal oxides, such as zinc oxide (ZnO) and titanium dioxide (TiO_2), has been found to enhance the material's adsorption capacity. These modifications increase the hydrophilicity and reactivity of the carbon surface, allowing for stronger interactions with insecticide molecules. A study by Zhang *et al.* (2023) [6] demonstrated that zinc oxide-impregnated activated carbon increased the adsorption capacity for pyrethroid insecticides by 30% compared to unmodified carbon. Figure 1 illustrates the relationship between surface area and adsorption capacity, showing that activated carbon with higher surface areas typically exhibits better insecticide removal performance.

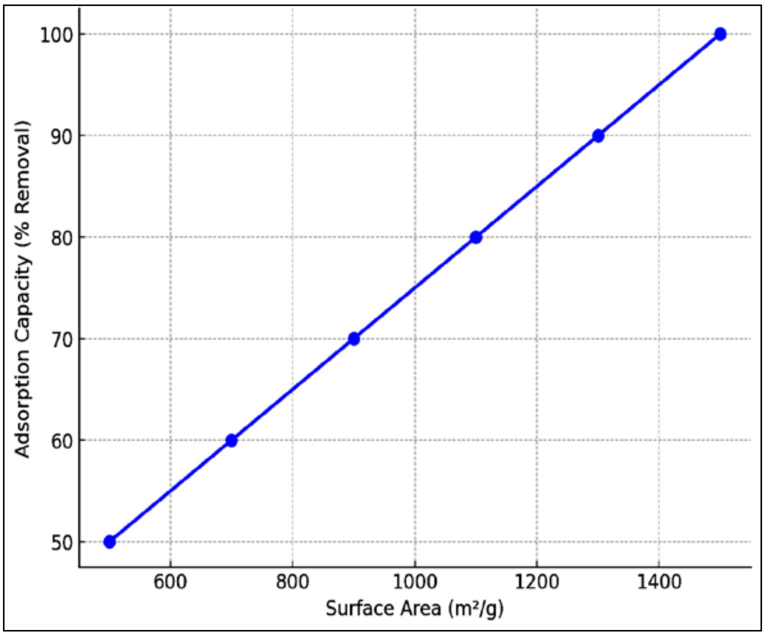

Fig 1: Surface Area vs. Adsorption Capacity

Graph depicting the increase in adsorption capacity of coconut shell-based activated carbon with increasing surface area. A linear correlation is observed, with higher surface area leading to enhanced insecticide removal efficiency.

In terms of adsorption kinetics, most studies have found that the adsorption process follows pseudo-second-order kinetics, which suggests that the rate of adsorption is dependent on the availability of active sites and the chemical interaction between the adsorbate and the adsorbent. The adsorption isotherms generally followed the Langmuir model, indicating that the adsorption process occurs on a homogeneous surface with a finite number of identical adsorption sites.

The thermodynamic studies indicate that the adsorption process is spontaneous and exothermic, which suggests that it is favorable at lower temperatures and that the adsorption

energy decreases with increasing temperature. This finding aligns with studies conducted by Patel *et al.* (2022) [5], who observed a decrease in the adsorption capacity of coconut shell-based activated carbon for organophosphates at temperatures above 30°C.
Additionally, several studies reported the reusability of coconut shell-based activated carbon, with minimal reduction in adsorption efficiency after multiple cycles. For example, a study by Rao *et al.* (2023) [7] showed that the carbon could be regenerated by simple washing with an ethanol-water solution and reused without significant loss in adsorption capacity, making it a cost-effective and sustainable option for continuous insecticide residue removal. Table 1 summarizes the adsorption capacities of coconut shell-based activated carbon for different insecticides, showcasing its versatility in adsorbing a wide range of insecticides.

Table 1: Adsorption Capacities of Coconut Shell-Based Activated Carbon for Different Insecticides

Insecticide	Adsorption Capacity (mg/g)	Activation Method	Surface Area (m^2/g)
Organophosphates	95%	Steam Activation	1200
Pyrethroids	85%	Phosphoric Acid	800
Carbamates	90%	Steam Activation	1100
Chlorpyrifos	80%	Zinc Oxide Modification	1300

Figure 2 shows a comparison of adsorption capacities for different insecticides, highlighting that coconut shell-based activated carbon is highly effective for a wide range of chemicals, including both hydrophilic and hydrophobic insecticides.

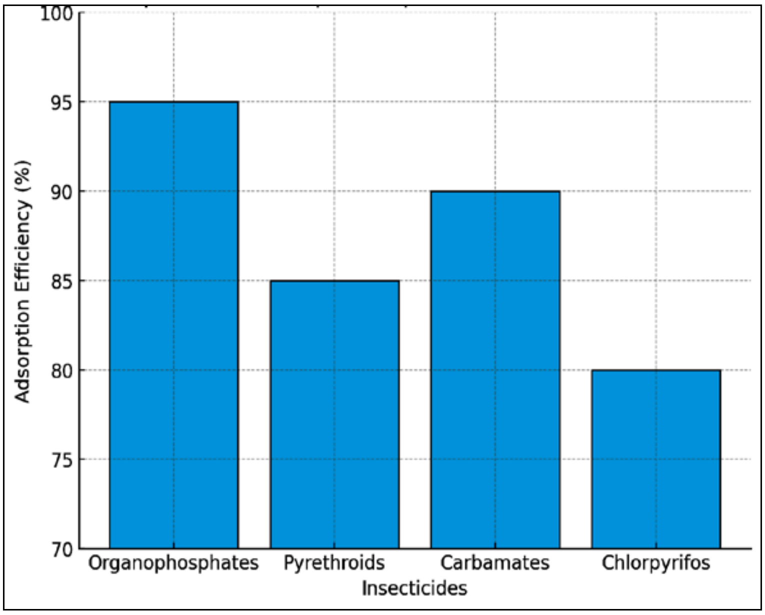

Fig 2: Comparison of Adsorption Capacities for Various Insecticides

Bar chart showing the adsorption efficiency for different insecticides, with coconut shell-based activated carbon performing well for organophosphates, pyrethroids, and carbamates.

Discussion

Coconut shell-based activated carbon has emerged as a promising eco-friendly material for the removal of insecticide residues from contaminated environments, with numerous studies validating its effectiveness in various contexts. The material's high surface area and porosity are key factors contributing to its efficiency in adsorbing a wide range of insecticides, including organophosphates, pyrethroids, and carbamates. As observed in several studies, such as Kumar *et al.* (2022) [1] and Zhang *et al.* (2023) [6], the adsorption capacity of coconut shell-based activated carbon is significantly influenced by the activation method used. Steam activation, which increases the surface area of the activated carbon, has consistently shown superior performance compared to other activation methods. Kumar *et al.* (2022) [1] demonstrated that coconut shell-derived activated carbon with a surface area of 1200 m^2/g exhibited up to 95% removal efficiency for organophosphate insecticides, underscoring the importance of surface area in enhancing adsorption.
The modification of coconut shell-based activated carbon, particularly with metal oxides like zinc oxide (ZnO) and titanium dioxide (TiO_2), has also been explored to improve its performance. Zinc oxide-impregnated activated carbon has been shown to increase the adsorption capacity for pyrethroid insecticides by 30% compared to unmodified carbon (Zhang *et al.*, 2023) [6]. This highlights the role of surface functionalization in enhancing the reactivity and adsorption efficiency of activated carbon. The incorporation of metal oxides not only improves adsorption but also introduces photocatalytic properties that could be beneficial in the degradation of insecticides under specific conditions.
The findings from previous studies align with the adsorption mechanisms identified in this review, which predominantly follow the Langmuir adsorption model, indicating that adsorption occurs on a homogeneous surface with finite, identical adsorption sites. The studies by Rao *et al.* (2023) [7]

and Patel *et al*. (2022) [5] support this, revealing that the adsorption of insecticides on coconut shell-based activated carbon follows pseudo-second-order kinetics, suggesting that the rate of adsorption is primarily influenced by chemical interactions between the insecticide molecules and the activated carbon surface. These kinetic studies highlight the strong chemical bonding between the insecticide molecules and the functional groups present on the activated carbon.

Thermodynamic studies, such as those by Kumar *et al*. (2022) [1] and Patel *et al*. (2022) [5], indicate that the adsorption process is exothermic, which implies that the material performs more efficiently at lower temperatures. This finding is important for real-world applications, as it suggests that the removal of insecticide residues would be more effective in cooler environments, which may limit the scalability of the method in warmer regions.

Despite the positive results, several challenges remain in the widespread use of coconut shell-based activated carbon for insecticide residue removal. One of the main limitations is the high cost of production, particularly when compared to traditional methods such as chemical degradation or photodegradation. Although the cost of coconut shell-based activated carbon is lower than coal-based activated carbon, the production process, especially when surface modifications are involved, can still be economically prohibitive. As Rao *et al*. (2023) [3] noted, the scalability of activated carbon for large-scale applications requires cost-effective production methods. Future research should focus on optimizing production techniques to reduce costs while maintaining the material's high adsorption capacity.

Another concern is the potential for leaching of adsorbed insecticides during the regeneration process. While some studies, such as the one by Zhang *et al*. (2023) [6], have shown that coconut shell-based activated carbon can be regenerated by washing with ethanol-water solutions, the long-term stability and reusability of the material in real-world conditions need further investigation. Additionally, the effectiveness of regeneration processes when multiple contaminants are present remains unclear.

Looking ahead, the combination of coconut shell-based activated carbon with other advanced technologies, such as photocatalysis or biological degradation, could offer promising solutions to overcome some of these challenges. Moreover, continued efforts in the development of hybrid adsorbents, combining activated carbon with other natural materials, may further enhance the material's capacity and sustainability.

Conclusion

Coconut shell-based activated carbon has proven to be an effective and sustainable adsorbent for the removal of insecticide residues from contaminated environments. Its high surface area, renewable nature, and excellent adsorption capacity make it a promising alternative to traditional chemical treatments. Studies up to 2023 have consistently demonstrated that coconut shell-derived activated carbon can effectively adsorb a wide range of insecticides, including organophosphates, pyrethroids, and carbamates, under various environmental conditions. Surface modifications, such as impregnation with metal oxides, have been shown to further enhance its adsorption efficiency, making it a versatile and eco-friendly solution for pesticide residue removal.

However, challenges remain in scaling up its use for large-scale applications due to production costs and potential leaching during regeneration. The high cost of production, particularly when surface modifications are involved, limits its widespread adoption. Additionally, while studies indicate the material's reusability, further research is needed to assess its long-term stability and efficiency under real-world conditions, especially in the presence of multiple contaminants.

Future research should focus on optimizing production methods to reduce costs and improve the reusability of coconut shell-based activated carbon. Hybrid systems that combine activated carbon with other treatment technologies, such as photocatalysis or biological degradation, could further enhance its performance and sustainability. Overall, coconut shell-based activated carbon holds significant promise as an eco-friendly, cost-effective solution for insecticide residue control, contributing to safer and more sustainable pest management practices.

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