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Green processing of natural products using steam-activated adsorbents derived from coconut shells

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Abstract
The increasing demand for sustainable and eco-friendly methods of natural product extraction has prompted research into green processing techniques that minimize environmental impact. One such method involves using steam-activated adsorbents derived from coconut shells for the extraction of bioactive compounds from natural products. This study explores the potential of steam activation to enhance the adsorption capacity of coconut shell-based adsorbents for efficient extraction processes. The research aims to optimize the activation conditions, including temperature and steam flow rates, to maximize the efficiency of adsorption while maintaining the environmental integrity of the process. Experimental data collected through the use of various characterization tools such as BET surface area analysis and adsorption isotherms demonstrate a significant increase in adsorption capacity when using steam-activated coconut shells compared to conventional methods. The findings suggest that this green processing technique offers a promising alternative to traditional solvent-based extractions, with enhanced environmental sustainability and economic feasibility. Further studies are needed to explore the scalability and industrial application of steam-activated adsorbents in the extraction of a wider range of natural products.

Keywords: Steam activation, coconut shell adsorbents, green processing, natural product extraction, adsorption capacity, bioactive compounds, environmental sustainability, surface area enhancement, adsorption isotherms, eco-friendly extraction methods, biomass adsorbents, polyphenols adsorption, sustainable extraction techniques, adsorbent characterization, mesoporous materials, green chemistry

Introduction

The need for sustainable extraction processes has become increasingly critical as industries look for environmentally friendly alternatives to conventional chemical and solvent-based methods. Traditional extraction techniques, such as solvent extraction, often involve the use of toxic solvents and produce large amounts of waste, contributing to environmental degradation. In contrast, green processing methods, which utilize natural and non-toxic materials, have gained attention due to their minimal environmental impact and potential for enhancing sustainability in industrial operations.

One promising approach in green processing is the use of adsorbents derived from natural resources such as coconut shells. Coconut shells, a by-product of the coconut industry, are abundant, renewable, and cost-effective. These shells, primarily composed of lignocellulosic material, can be processed to create adsorbents with high surface areas, which are ideal for removing or capturing various bioactive compounds from natural products.

Steam activation, a widely studied technique for enhancing the properties of carbon-based adsorbents, involves subjecting the raw material to high temperatures in the presence of steam. This process leads to the creation of a highly porous structure, significantly increasing the surface area and enhancing adsorption capacity. The use of steam for activation provides a more sustainable alternative to other activation methods, such as chemical activation, which often requires hazardous chemicals.

In this study, the potential of steam-activated coconut shell adsorbents for the green processing of natural products is explored. By optimizing the steam activation conditions, such as temperature and steam flow rate, the research aims to achieve a balance between high adsorption capacity and minimal environmental impact. The results of this study will provide insight into the viability of using these green adsorbents for the extraction of valuable bioactive compounds in various industries, including pharmaceuticals, food, and cosmetics.

Methodology
This study investigates the use of steam-activated coconut shell-based adsorbents for the green processing of natural products. The research design focuses on optimizing the steam activation conditions to enhance the adsorbent's performance in extracting bioactive compounds from natural matrices. The methodology encompasses the preparation of adsorbents, their activation using steam, and the characterization of the adsorbents' properties. Additionally, adsorption experiments were conducted to assess the efficiency of these adsorbents in comparison with conventional methods.

Adsorbent Preparation
Coconut shells were collected from a local supplier and thoroughly washed to remove any debris or contaminants. The shells were then dried in an oven at 110 °C for 24 hours to eliminate any remaining moisture. The dried coconut shells were mechanically ground into small particles, which were then sieved to achieve a uniform particle size of 1-2 mm. This uniformity in size ensures consistent activation and adsorption properties across all samples.

Steam Activation Process
The coconut shell particles were subjected to steam activation in a lab-scale reactor. The activation conditions were varied to optimize the adsorbent's surface area and adsorption capacity. Activation temperatures were set at 600 °C, 700 °C, and 800°C, with steam flow rates of 30, 50, and 70 mL/min. The coconut shell particles were placed in a furnace, and steam was introduced into the reactor for 60 minutes under these conditions. After activation, the samples were cooled in a nitrogen atmosphere to prevent further oxidation.

Characterization of Adsorbents
The prepared adsorbents were characterized using several techniques to assess their physical and chemical properties. The surface area of each adsorbent was determined using the BET (Brunauer-Emmett-Teller) method, employing nitrogen adsorption-desorption isotherms. The pore size distribution was analyzed using the Barrett-Joyner-Halenda (BJH) method. Scanning Electron Microscopy (SEM) was used to observe the morphological structure of the activated coconut shell adsorbents, while Fourier-Transform Infrared (FTIR) spectroscopy was employed to identify functional groups on the surface of the adsorbents.

Adsorption Experiments
To evaluate the performance of the steam-activated adsorbents, adsorption experiments were conducted using a model bioactive compound, such as polyphenols, which are commonly found in natural products. A stock solution of polyphenols was prepared, and the adsorbents were exposed to varying concentrations of this solution. The amount of polyphenols adsorbed was determined by measuring the concentration of the remaining solution after adsorption using UV-Vis spectroscopy. Adsorption isotherms were constructed to assess the capacity of the adsorbents at different concentrations, and the results were compared to those obtained from conventional solvent-based extraction methods.

Results
This section presents the findings from the characterization and adsorption experiments conducted on the steam-activated coconut shell-based adsorbents. The key results include the surface area, pore size distribution, and adsorption capacity of the adsorbents under different steam activation conditions. The data indicate that the steam activation significantly enhances the adsorbent's properties, improving its efficiency in extracting bioactive compounds compared to conventional methods.

Surface Area and Pore Size Distribution
The BET surface area analysis of the steam-activated coconut shell adsorbents revealed a significant increase in surface area with higher activation temperatures. The surface area of the adsorbents ranged from 200 m^2/g to 1100 m^2/g, depending on the activation conditions. As shown in Table 1, the adsorbent activated at 800 °C with a steam flow rate of 70 mL/min exhibited the highest surface area, making it the most promising candidate for adsorption applications.

The pore size distribution, analyzed using the BJH method, showed that the adsorbents had a mesoporous structure, with pore sizes ranging from 2 to 50 nm. The adsorbents activated at higher temperatures (700 °C and 800 °C) exhibited a higher concentration of mesopores, which are ideal for the adsorption of bioactive compounds.

Table 1: Surface area and total pore volume of steam-activated coconut shell adsorbents under different activation conditions

Activation Temperature (°C)	Steam Flow Rate (mL/min)	Surface Area (m^2/g)	Total Pore Volume (cm^3/g)
600	30	320	0.48
600	50	430	0.55
600	70	560	0.60
700	30	680	0.70
700	50	830	0.80
700	70	950	0.85
800	30	1020	1.00
800	50	1050	1.05
800	70	1100	1.10

Adsorption Capacity
The adsorption experiments demonstrated that steam-activated coconut shell adsorbents had a significantly higher adsorption capacity for polyphenols than those activated under conventional methods. The adsorption isotherms obtained from UV-Vis spectroscopy indicated a high affinity for polyphenols, with the adsorbents activated at higher temperatures (700 °C and 800 °C) showing superior adsorption capacity.

Table 2: Maximum adsorption capacity of steam-activated coconut shell adsorbents for polyphenols.

Adsorbent Type	Maximum Adsorption Capacity (mg/g)
Conventional Activated Carbon	15.2
Steam-Activated (600°C, 50 mL/min)	30.4
Steam-Activated (700°C, 50 mL/min)	50.6
Steam-Activated (800°C, 70 mL/min)	62.1

Adsorption Isotherms

The adsorption data were analyzed using Langmuir and Freundlich isotherms. The Langmuir model, which assumes monolayer adsorption on a surface with a finite number of adsorption sites, best fit the data for the adsorbents activated at 700 °C and 800 °C, indicating that the adsorption process is likely to be uniform and occurs at specific sites.

Discussion

This study highlights the potential of steam-activated coconut shell-based adsorbents as a green alternative for the extraction of bioactive compounds, particularly polyphenols, from natural matrices. The findings reveal that steam activation significantly enhances the surface area and adsorption capacity of coconut shell-based adsorbents, making them highly effective in bioactive compound removal, as compared to conventional methods. The increase in surface area and pore volume with higher activation temperatures aligns with previous studies, which have demonstrated the positive correlation between activation temperature and adsorption capacity.

The BET surface area analysis showed a significant increase in surface area for adsorbents activated at higher temperatures, particularly at 800 °C with a steam flow rate of 70 mL/min. This is consistent with the work of Kumar *et al*. (2020) [1], who observed a similar trend in the activation of biomass-derived adsorbents for the adsorption of organic contaminants. They reported that higher activation temperatures led to the creation of more micropores and mesopores, which are ideal for the adsorption of small and medium-sized molecules. Additionally, studies by Rajput *et al*. (2021) [2] found that the surface area of activated coconut shell adsorbents increased with temperature, resulting in higher efficiency in adsorbing various organic pollutants. These findings support our results, where higher temperatures enhanced the adsorbent's performance in extracting polyphenols.

The pore size distribution of the steam-activated adsorbents also indicated a mesoporous structure, which is desirable for the adsorption of polyphenolic compounds. This finding corroborates the research of Singh *et al*. (2019) [3], who demonstrated that mesoporous adsorbents are particularly effective in adsorbing polyphenols due to their ability to accommodate larger molecules. The presence of these mesopores allows for efficient mass transfer during the adsorption process, enhancing the overall adsorption capacity of the adsorbents.

The adsorption capacity of the steam-activated coconut shell adsorbents was significantly higher than that of conventional activated carbon, as shown in Table 2. This result is in line with the study by Zhang *et al*. (2021) [4], which demonstrated that steam-activated carbon exhibits superior adsorption properties compared to chemically activated carbon. The study attributed this to the higher degree of porosity and the increased surface area of the steam-activated material. Similarly, our findings show that steam activation not only improves the adsorbent's capacity but also offers a more sustainable method of activation compared to chemical activation, which often requires toxic chemicals.

Furthermore, the adsorption isotherms obtained in this study were best described by the Langmuir model, indicating that the adsorption of polyphenols on the steam-activated coconut shell adsorbents follows a monolayer adsorption process. This suggests that the adsorbent sites become saturated with polyphenols at higher concentrations, a phenomenon also observed by Patel *et al*. (2020) [5], who studied the adsorption of phenolic compounds using activated carbon. The Langmuir model fitting supports the notion that steam-activated coconut shell adsorbents have a finite number of adsorption sites, and once these sites are occupied, the adsorption capacity reaches its maximum.

When comparing the results with conventional solvent-based extraction methods, steam-activated coconut shell adsorbents demonstrated a higher adsorption efficiency, as seen in Table 2. This suggests that steam activation could replace traditional methods, offering a more environmentally friendly and cost-effective solution. Conventional solvent-based methods are often associated with the use of harmful solvents and generate significant waste, whereas steam activation eliminates the need for such chemicals, aligning with the growing demand for sustainable processes in natural product extraction. These findings are consistent with the work of Yadav *et al*. (2018) [6], who also highlighted the benefits of using activated carbon derived from natural biomass in reducing the environmental footprint of extraction processes.

Conclusion

This study demonstrates the significant potential of steam-activated coconut shell-based adsorbents as a sustainable alternative for the extraction of bioactive compounds from natural products. The results indicate that steam activation enhances the surface area and adsorption capacity of coconut shell-derived adsorbents, making them more effective in removing polyphenols compared to conventional methods. The optimization of steam activation conditions, such as temperature and steam flow rate, plays a crucial role in achieving the highest adsorption capacity, with the adsorbent activated at 800 °C and 70 mL/min steam flow exhibiting the best performance.

In comparison to traditional solvent-based extraction methods, steam-activated coconut shell adsorbents offer a greener, more environmentally friendly approach, eliminating the need for toxic chemicals and reducing waste generation. The findings are consistent with previous research, which has highlighted the benefits of biomass-derived adsorbents in improving the sustainability of extraction processes.

While the study's results are promising, further research is needed to assess the scalability and industrial applicability of steam-activated adsorbents. Future studies should explore the regeneration of these adsorbents for multiple uses and evaluate their performance in the extraction of other bioactive compounds. Additionally, investigating the economic feasibility of scaling up the steam activation process will be essential for implementing this technology in large-scale operations.

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