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Review Article

Effectiveness Comparison of Activated Carbon/MnO_2 Composite and $Mg(OH)_2$-Impregnated Activated Carbon as Adsorbents for Uranium Removal from Nuclear Waste : A Review

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***Abstract*—**Uranium contamination in nuclear wastewater poses significant environmental and health risks due to its radiotoxicity and persistence, necessitating the development of efficient adsorbent materials for its removal. This article discusses the effectiveness of two types of adsorbents: Activated Carbon/MnO_2 Composite and $Mg(OH)_2$-Impregnated Activated Carbon, in removing uranium from nuclear waste. Activated carbon/MnO_2 composites exhibit high surface area and oxidative properties, enhancing uranium adsorption. In this study, Adsorption isotherm and kinetic analyses revealed that the composite achieved a maximum adsorption capacity of 65.5%, following the Langmuir model and pseudo-second-order kinetics. Meanwhile, $Mg(OH)_2$-Impregnated Activated Carbon enhances the electrostatic interaction between adsorbents and uranium ions, thanks to its alkaline properties that favor the formation of chemical bonds. The maximum adsorption capacity of the predicted $Mg(OH)_2$ reached 85 mg/g, with behavior that was also in accordance with the Langmuir isothermal model. Although both adsorbents show significant potential, the comparison shows that the choice between the two depends on the specific application conditions. The results of this research are expected to contribute to the development of more effective and sustainable nuclear waste management methods, as well as encourage innovation in water purification technology to overcome uranium contamination.

***Keywords*—** *Activated carbon/MnO_2 composite; $Mg(OH)_2$-impregnated carbon; Nuclear waste; Uranium adsorption*

1. INTRODUCTION

Nuclear waste is material residue produced from activities involving nuclear reactions, both in nuclear power plants, medical uses, and scientific research. This waste is made up of different types of radioactive isotopes that have different levels of danger and different half-lives. Nuclear waste management is one of the most significant environmental challenges of the modern era. Nuclear waste is generated from a variety of sources, including nuclear power plants, research, and medical use [1]. This waste contains a wide variety of radioactive isotopes, one of which is uranium that can remain hazardous for thousands of years [2]. One of the biggest challenges in nuclear waste management is its radioactive nature which can last for thousands to millions of years. This requires countries that use nuclear energy to design safe and durable storage systems. The health risks to humans are high, as exposure to radiation can cause a variety of health problems, including cancer, genetic disorders and premature death [3]. In addition, these wastes can contaminate water sources, soil, and ecosystems, affect flora and fauna, and jeopardize public safety. One of the biggest challenges in nuclear waste management is the lack of effective and safe solutions for long-term storage [4]. Many countries still rely on temporary storage methods, which provide no guarantee of long-term protection [5]. These methods often raise concerns of leaks or accidents that can have fatal consequences.

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Uncertainty over nuclear waste storage sites also creates public discontent and opposition to related projects, making the issue even more complex [6].

Uranium in nuclear waste comes from a variety of sources, mainly from activities related to nuclear power plants and research applications. In the fission process, uranium-235, which is an isotope of uranium that can be split, is used as fuel in nuclear reactors [7]. When uranium-235 is fissioned, it produces energy that is used for power generation, but it also produces a number of radioactive byproducts. Uranium contamination has a significant impact on human health and the environment. Long-term exposure to uranium can cause a variety of health problems, including cancer, immune system disorders, and kidney damage [8]. Uranium is chemically toxic, and when it accumulates in the body, it can interfere with organ function and cause serious diseases. In addition, uranium can affect fetal development if pregnant women are exposed, thus having an impact on future generations [9].

Given the harmful impacts of nuclear waste, there is an urgent need to develop effective technologies in uranium removal. Uranium released into the environment can contaminate soil and water, resulting in long-term impacts that are difficult to repair [10]. Therefore, the development of efficient and sustainable removal methods is a priority. Current technologies are often inadequate in terms of effectiveness and cost efficiency, creating an impetus to seek innovative new solutions. One promising approach is the use of adsorbent materials that can bind uranium from solution [7]. By utilizing the specific physical and chemical properties of these materials, removal technologies can be optimized to increase process capacity and speed. In this context, activated carbon-based composites, such as those combined with MnO_2 or impregnished with $Mg(OH)_2$, show great potential [11]. The development of these technologies will not only help reduce risks to human health and the environment, but will also strengthen the regulatory and policy frameworks governing nuclear waste management [12], [13].

Adsorption is a physical or chemical process in which molecules of a substance, such as a contaminant, bond to the surface of a solid or liquid known as an adsorbent. Adsorption is affected by a variety of factors, including temperature, pH, contact time, and concentration of contaminants in the solution, all of which can affect process efficiency. Adsorbents function by creating physical or chemical interactions with contaminant molecules. This process allows contaminants dissolved in water or solution to be captured and bound by adsorbents, thus separating them from the larger media [14]. Activated carbon is one of the most effective materials as adsorbents, thanks to a number of unique properties. One of the main properties is its very high surface area, which can reach up to 1,500 m² per gram [15]. This surface area allows activated carbon to bind significant amounts of contaminants. In addition, activated carbon has a high porosity, with a micropore and mesoporous structure that allows small particles to be trapped in it. This porosity increases adsorption ability as it provides more room for interaction with contaminant molecules [16].

The development of activated carbon composites with MnO_2 has shown significant synergistic benefits. MnO_2 not only improves the adsorption ability of activated carbon, but also plays a role in redox processes that can convert uranium species into a form that is easier to adsorbize [17]. This combination creates a more reactive environment and increases the adsorption capacity of uranium from the solution, making it more effective compared to pure activated carbon. In addition to the development of composites with MnO_2, activated carbon can also be impregnished with $Mg(OH)_2$. The process of impregnation of activated carbon with $Mg(OH)_2$ aims to improve carbon performance in uranium removal. This impregnation involves the adsorption of $Mg(OH)_2$ into the activated carbon structure, which increases its adsorption capacity. $Mg(OH)_2$ serves to raise the pH of the solution, creating more optimal conditions for uranium removal. At higher pH, uranium species become more ionized and, consequently, more easily adsorbed by activated carbon. The increase in pH also affects the equilibrium of the adsorption reaction, thereby increasing the efficiency of uranium removal from the solution [18].

2. METHOD

2.1. Making Adsorbents from Activated Carbon Activated Carbon (AC) Composite with MnO_2

The procedure for making activated carbon composite with MnO_2 was carried out using an in-situ deposition lens with a mass ratio of KA:MnO_2 (1 : 1.2). In this research, 20 g of activated carbon was mixed with 0.552 M MnO_2 made from a mixture of $MnSO_4$ and $KMnO_4$. 28 g of $MnSO_4$ and 18 g of $KMnO_4$ were dissolved in 500 mL of aquademin. The Solution was mixed with 10 g of NaOH and stirred at a temperature of ±80°C[12]. The mixture was allowed to cool to room temperature, filtered, washed with distilled water, left to dry for 24 hours. This was followed by calcination at ±250°C for 3 hours, and the concentration of the separated filtrate was determined using permanganometric titration [12].

2.2. Activated Carbon impregnated with $Mg(OH)_2$

Coconut shells were inserted into pyrolysis reactor and carbonized for 150 min at 400 ± 10 °C. Then, the activated charcoal is further impregnated with 150 mL activator in the form of 1 N NaOH for 24 h. A further impregnation of $MgCl_2$ was performed using 250 mL $MgCl_2$ solution (variation of impregnation ratio (IR) of 0.3, 0.6, and 1.0) for 24 h. The materials were treated at 600 °C for 30 min to form $Mg(OH)_2$/activated carbon as described in literature [13].

2.3. Comparing Activated Carbon/MnO_2 Composite and Mg(OH)2-Impregnated Activated Carbon as Adsorbents for Uranium

In comparing the effectiveness between Activated Carbon/MnO_2 Composite and $Mg(OH)_2$-Impregnated

Activated Carbon as adsorbents for uranium removal from nuclear waste, this study adopts a systematic method that includes data collection, qualitative analysis, and interpretation of the results. This method aims to provide an in-depth understanding of the performance of both types of adsorbents in the context of environmental applications.

2.4. Systematic Literature Review

This study employed a systematic literature review approach to assess the performance of activated carbon-based adsorbents for uranium removal. Relevant peer-reviewed articles were retrieved from major scientific databases, including Scopus, Web of Science, and Google Scholar. Inclusion criteria were defined to ensure data consistency, focusing on studies reporting adsorption capacity and key operational parameters, such as initial uranium concentration, pH, contact time, temperature, and adsorbent dosage. The selected data were then analyzed to enable a reliable comparison between different adsorbent systems.

2.5. Data Collection

Once the relevant articles have been collected, the next step is to collect data related to the effectiveness of each adsorbent. The main parameters to be noted include the maximum adsorption capacity (in mg/g), equilibrium time, as well as the characterization of the kinetics and adsorption isotherms used in the study. In addition, the physicochemical properties of the adsorbents, including surface area, porosity, and morphology, were analyzed based on previously reported data, commonly characterized using BET and SEM techniques. This comprehensive data will be the basis for a more in-depth comparison (**Table 1**).

Table 1. Data analysis and interpretation stages

Stage	Description	Outout
Quality analysis	Collected data were analyzed and compared to evaluate the effectiveness of Activated Carbon/MnO_2 Composite and $Mg(OH)_2$-impregnated Activated Carbon.	Comparative adsorption performance
Data visualization	Graphs were generated to illustrate differences in adsorption capacity between the two adsorbents	Graphical comparison of adsorption capacity
Kinetic analysis	Adsorption kinetics were evaluated based on reported data using pseudo-first-order and pseudo-second-order models	Kinetic parameters and model fitting
Isotherm analysis	Adsorption isotherms were analyzed using Langmuir and Freundlich models to understand adsorption behavior.	Isotherm constants and adsorption mechanism
Discussion	The results were compared to identify the advantages and limitations of each adsorbent.	Performance comparison
Interpretation	Factors affecting adsorption, such as environmental conditions, uranium chemistry, and adsorbent properties, were analyzed.	Identification of trends and influencing factors

3. RESULT AND DISCUSSION

3.1. Overview of Nuclear Waste and Environmental Implications

Nuclear waste encompasses the residual materials generated from diverse activities involving nuclear reactions, including power generation, medical diagnostics, and scientific research. Proper management of these radionuclides is a critical environmental priority to mitigate long-term risks to human health and ecological systems. Based on the level of radioactivity and hazards, nuclear waste is divided into three main categories: low waste, medium waste, and high waste. Low and medium waste is usually generated from medical and industrial activities, while high waste is generated from nuclear fuel that has been used [19].

High waste, for example, should be stored in strong containers and in isolated locations to avoid environmental contamination. Currently, many countries choose to store nuclear waste in deep geology, where stable rock layers can provide protection against radiation [20].

In addition to technical challenges, nuclear waste management also involves social and ethical aspects. There are concerns from the public regarding the safety of this waste storage, especially in the event of leaks or accidents. Therefore, transparency in the decision-making process and effective communication with the community is very important. Several countries have developed policies and practices that involve local communities in the waste management process, to reduce mistrust and increase a sense of ownership towards the solutions taken [21].

In a global context, nuclear waste management is also regulated by various international treaties. The International Organization for Atomic Energy (IAEA) plays a crucial role in helping countries develop safe policies and practices in nuclear waste management. Even so, the issue of nuclear waste remains a controversial topic, especially with the increasing reliance on nuclear energy as a clean and efficient energy source [22]. A comprehensive and collaborative approach is needed to ensure that nuclear waste management is carried out in a safe and sustainable manner.

3.2. Comparative Analysis of Uranium Adsorption Performance

Uranium removal from nuclear waste is a crucial aspect of maintaining environmental safety and the sustainability of nuclear energy. To manage radioactive waste effectively, both activated carbon/MnO_2 composites and $Mg(OH)_2$ impregnated activated carbon have emerged as promising adsorbents. This discussion compares the effectiveness of these two materials based on research conducted by Anjarsari et al. [12] and Saputra et al. [13].

The Activated Carbon/MnO_2 Composite utilizes the high surface area of activated carbon combined with the oxidative properties of MnO_2 [23]. This synergy facilitates redox processes, potentially transforming uranium species into forms that are more easily adsorbed while utilizing an optimal pore structure to increase total capacity [24]. In contrast, $Mg(OH)_2$-Impregnated Activated Carbon focuses on enhancing electrostatic interactions. The alkaline properties of $Mg(OH)_2$ allow for the formation of chemical bonds with positive uranium ions and neutralize interfering negative ions in the solution [13], [25]. The physical and chemical characteristics, as well as the adsorption performance of these two materials, are summarized in **Table 2**.

Table 2. Comparative analysis of activated carbon-based adsorbents for uranium removal

Parameter	Activated Carbon/MnO_2 Composite	$Mg(OH)_2$-Impregnated Activated Carbon
Base Material	Oil Palm Empty Fruit Bunches (OPEFB)	Activated Carbon (Surface Modified)
Key Mechanism	MnO_2 oxidative properties and optimal pore structure [12], [23], [24]	Electrostatic interaction and surface neutralization via alkaline properties [13], [25]
Max. Capacity	65.5% (Removal efficiency) [12]	85 mg/g (Adsorption capacity at 303 K) [13]
Isotherm Model	Langmuir (Monolayer adsorption) [12]	Langmuir (Monolayer adsorption) [13]
Adsorption Kinetics	Pseudo-second-order (Chemisorption) [12]	Pseudo-second-order (Chemisorption) [13], [26]
Main Advantage	Redox transformation of uranium species for enhanced uptake [24]	Overcoming adsorption barriers by optimizing surface charge [13]

In this context, the "second pseudo-order" means that the rate of absorption reaction is directly proportional to the square of the adsorbate concentration. This means that as adsorbate concentrations increase, the adsorption rate also increases more significantly, suggesting that this process is not only affected by diffusion, but also by more complex interactions at the molecular level. This indicates that the adsorbate molecule interacts chemically with the adsorbent surface, which is referred to as the process of chemolysis [26], [27].

Chemotherapy is different from resorption, in that the bonds formed are weaker and physical in nature. In chemolysis, the bonds formed usually involve covalent bonds or stronger bonds, so the adsorbate will be more bound to the surface [28]. This process is often accompanied by a change in energy, either in the form of heat release or absorption. As a result, misabsorption can affect the stability and capacity of adsorbents, as well as the rate of future reactions.

Consequently, an understanding of chemisorption dynamics and the pseudo-second-order model is essential in various applications, such as water purification, pollutant removal, and the development of new materials for storage or separation. This knowledge enables scientists and engineers to design more efficient and effective adsorption systems. Saputra et al. [13] also explored the influence of various parameters, such as The results demonstrate that adsorption efficiency is significantly influenced by the temperature, adsorbent-to-wastewater ratio, and particle size. Specifically, the AC/MnO_2 composite achieved its optimal performance at 30°C with a removal efficiency of 65.5% (**Figure 1**), while the $Mg(OH)_2$-AC showed superior performance with a maximum adsorption capacity of 85 mg/g (**Figure 2**). These findings indicate that decreasing the particle size enhances the available surface area, thereby increasing the adsorption rate for both materials.

The Langmuir model assumes monolayer adsorption on a homogeneous adsorbent surface. The high R^2 value of the Langmuir model shows that the experimental data are in accordance with the monolayer adsorption assumption, and the maximum adsorption capacity can be accurately predicted [29]. Freundlich's

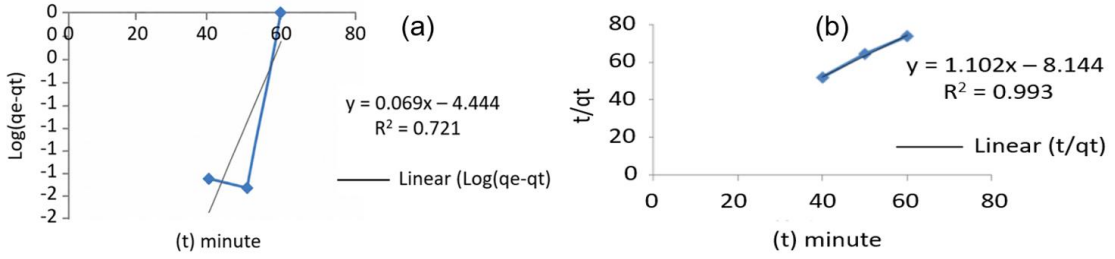

Figure 1. (a) Pseudo-first order and (b) pseudo-first-order uranyl adsorption kinetics by activated carbon/ MnO_2 composite [12]

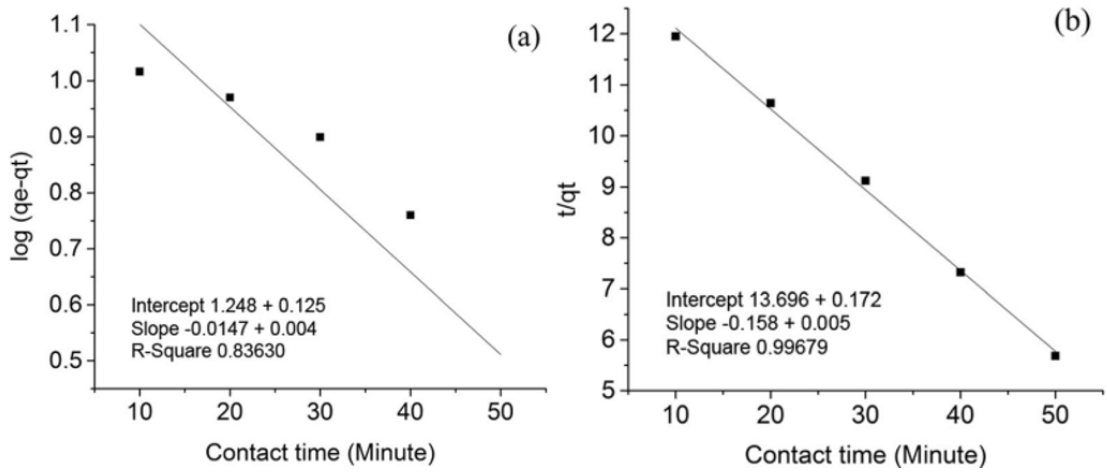

Figure 2. Pseudo-first order and (b) pseudo-first-order uranyl adsorption kinetics by $Mg(OH)_2$-AC [13]

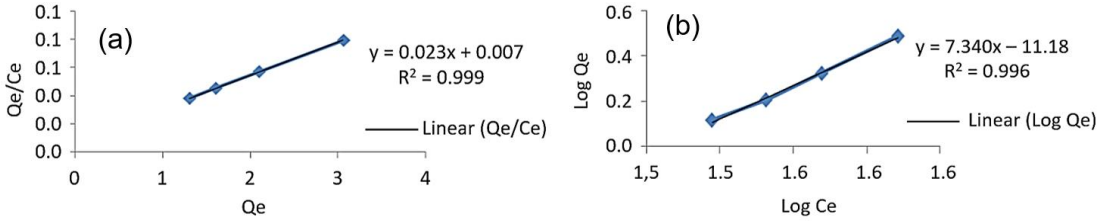

Figure 3. Langmuir (a) and Freundlich (b) isotherm model curve for uranyladsorption by activated carbon/MnO_2 composite [12]

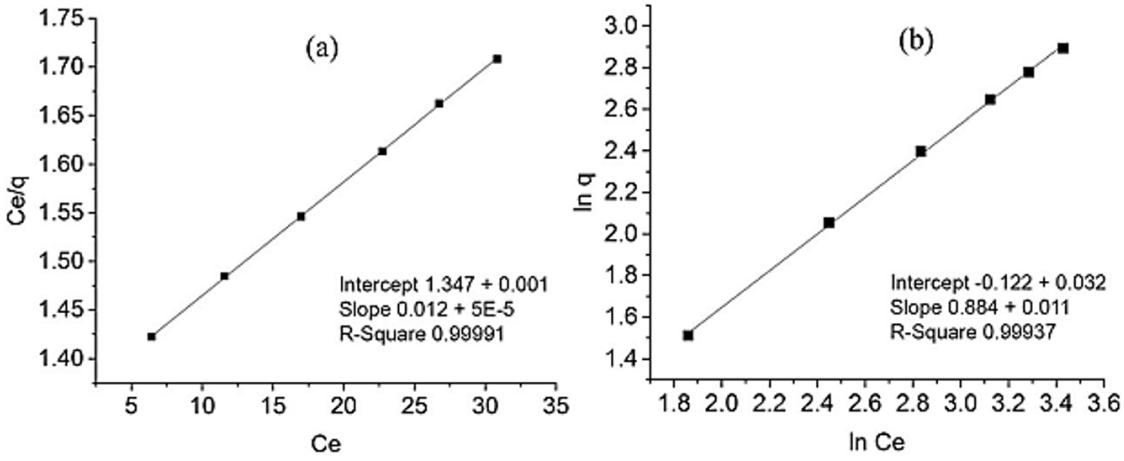

Figure **4.** Linearized of isotherm model of (a) Langmuir and (b) Freundlich of $Mg(OH)_2$-AC [13]

model describes multilayer adsorption on heterogeneous adsorbent surfaces. The high R^2 value of the Freundlich model shows that the experimental data are in accordance with the assumption of multilayer adsorption, and the adsorption capacity can be accurately predicted for higher adsorbate concentrations (**Figure 3** and **Figure 4**) [30].

The pseudo-first-order model describes the adsorption rate that depends on the adsorbate concentration. The high R^2 value in the pseudo-first-order model shows that the experimental data are in accordance with the adsorption rate assumption that depends on adsorbate concentration [31]. The pseudo second-order model describes the adsorption rate that depends on the number of active sites available on the adsorbent surface. A high R^2 value in the pseudo-second-order model indicates that the experimental data are in accordance with the assumption of adsorption rate which depends on the number of active sites available [32].

From the comparison of the two studies, it is evident that both materials demonstrate significant potential for removing uranium from nuclear waste. However, several key differences in their performance and characteristics are noteworthy. The activated carbon/MnO_2 composite studied by Anjarsari et al. [12] exhibits a different capacity profile compared to the $Mg(OH)_2$ impregnated activated carbon reported by Saputra et al. [13]. While the removal percentages are relatively competitive (**Figure 5** and **Figure 6**), the

specific adsorption capacities and structural influences vary. These differences are primarily attributed to the unique surface characteristics and pore structures of each adsorbent. To facilitate a clearer understanding of these essential findings, the comparison of the key parameters and results from both studies is summarized in **Table 4**.

Table 3. Comparison of R-Square values in isotherms and adsorption kinetics between activated Carbon/MnO_2 composite and $Mg(OH)_2$-Impregnated activated carbon

Parameter	Adsorbent	R-Square
Langmuir Isoterm	Activated Carbon/MnO_2 Composite	0.999
	$Mg(OH)_2$-Impregnated Activated Carbon	0.999
Freundlich Isoterm	Activated Carbon/MnO_2 Composite	0.996
	$Mg(OH)_2$-Impregnated Activated Carbon	0.999
Pseudo first order	Activated Carbon/MnO_2 Composite	0.721
	$Mg(OH)_2$-Impregnated Activated Carbon	0.836
Pseudo second order	Activated Carbon/MnO_2 Composite	0.993
	$Mg(OH)_2$-Impregnated Activated Carbon	0.997

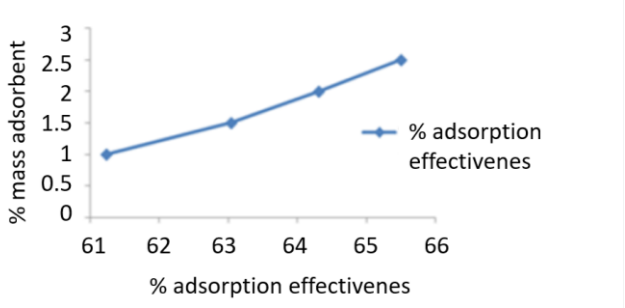

Figure 5. The curve of the influence of adsorbent mass on the % effectiveness of uranyl adsorption by activated carbon/ MnO_2 composite [12]

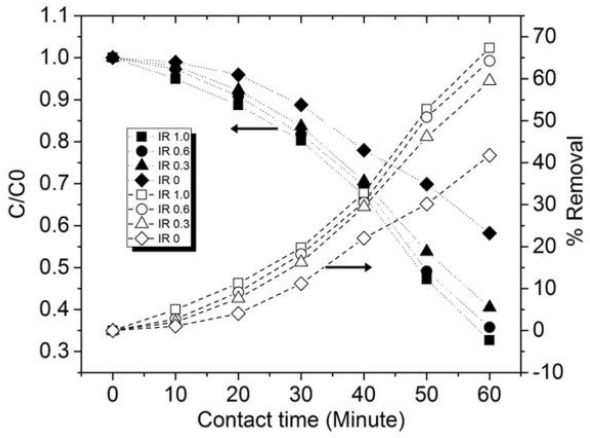

Figure 6. The concentration of remaining uranium (VI) per initial uranium (C/C0) and % removal as function of time (t) in various impregnation ratio (IR) [13]

Table 4. Summary of findings and performance comparison for uranium adsorption.

Feature / Finding	AC/MnO_2 Composite [12]	$Mg(OH)_2$-AC [13]
Max. Adsorption Capacity	65.5% Removal Efficiency (at 2.5 g mass)	85 mg/g (at 303 K)
Removal Percentage	65.5%	67.3%
Structural Highlight	Optimized pore structure with oxidative MnO_2 [24]	Modified surface with alkaline $Mg(OH)_2$ [25]
Isotherm & Kinetics	Langmuir & Pseudo-second-order	Langmuir & Pseudo-second-order
Main Mechanism	Redox transformation & Chemisorption	Electrostatic interaction & Chemisorption
Key Limitation/Barrier	Mass-dependent efficiency	Surface charge-dependent barriers

The study of Anjarsari et al. [12] also provides an in-depth analysis of the mechanism of adsorption, highlighting the formation of a coordinating bond between the uranyl ion and the MnO_2 component of the composite. This information is invaluable for understanding the adsorption process and optimizing adsorbent materials. The formation of these bonds can improve the stability and selectivity of adsorption of uranium ions, thus making the activated carbon/MnO_2 composite an attractive candidate for further research.

Overall, the choice between these two types of adsorbents will depend on the specific conditions of the application and the relevant parameters. Further research is needed to explore the potential combination of these two materials or the development of new variants that can increase the capacity and speed of adsorption. By understanding the characteristics of each adsorbent and the factors that affect its performance, we can take more effective measures in managing nuclear waste and protecting the environment from the negative effects of radioactive contamination [33].

Both of these adsorbents show significant potential in the removal of uranium from water. In its application, Activated Carbon/MnO_2 Composite excels in situations where oxidation is required to improve ion capture efficiency. Meanwhile, $Mg(OH)_2$-Impregnated Activated Carbon may be more effective in conditions where electrostatic interactions and chemical bonds are more dominant. Further research is needed to explore the influence of factors such as pH, uranium ion concentration, and contact time on the performance of each adsorbent. The results of this study are expected to make a significant contribution to the development of more effective and sustainable water purification technology to deal with uranium contamination. Overall, a deep understanding of the physical and chemical characteristics of these two types of adsorbents is an important first step in optimizing the uranium adsorption process, and could pave the way for further innovations in water treatment and environmental protection.

4. CONCLUSION

In this study, the effectiveness of two adsorbents-Activated Carbon/MnO_2 Composite and $Mg(OH)_2$-Impregnated Activated Carbon—was compared for uranium removal. While both materials demonstrate significant potential in reducing contamination, they operate through distinct mechanisms and possess different physicochemical characteristics. These essential findings and comparative parameters are summarized in **Table 4**.

Activated Carbon/MnO2 Composite takes advantage of the unique properties of activated carbon which has a high surface area and good porosity, coupled with the oxidative ability of MnO2. This combination increases the adsorption capacity by converting uranium species into a more easily absorbed form. The adsorption performance of the AC/MnO_2 composite, including its maximum capacity, isothermal behavior, and kinetic profile, is detailed in **Table 4**. The findings indicate that the mechanism aligns with the Langmuir model and follows pseudo-second-order kinetics, suggesting a chemisorption-driven process [12].

On the other hand, Mg(OH)2-Impregnated Activated Carbon enhances the electrostatic interaction between the adsorbent surface and uranium ions, thanks to its alkaline properties that favor the formation of chemical bonds with uranium. This study showed that the maximum adsorption capacity of the predicted Mg(OH)2 reached 85 mg/g, also with adsorption behavior that followed the Langmuir isothermic model and the second pseudo-order kinetics.

The comparison of results shows that although Activated Carbon/MnO2 Composite has a higher adsorption percentage (65.5% vs. 67.3%), Mg(OH)2-Impregnated Activated Carbon shows a larger adsorption capacity in absolute terms. The choice between these two types of adsorbents depends on the specific application conditions and relevant parameters.

Overall, this study emphasizes the importance of understanding the physical and chemical characteristics of each adsorbent to improve the uranium adsorption process. Further development of this technology is expected to provide more effective and sustainable solutions for nuclear waste management and environmental protection from the impact of radioactive pollution. This research provides valuable insights that may contribute to the development of more efficient water purification technologies for addressing uranium contamination.

5. AUTHOR'S DECLARATION

5.1. Supporting Information

There is no supporting information in this paper. The data supporting this research's findings are available on request from the corresponding author.

5.2. Acknowledgements

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5.3. Conflict of Interest

There was no conflict of interest in this study.

5.4. Author Contributions

AS and DCT were responsible for writing the original draft, formal analysis, and review and editing of the manuscript. RA, HR, and ZAH collaborated on writing and revising the manuscript to its final form. AS provided supervision and managed the research direction. All authors have read and agreed to the published version of the manuscript.

5.5. AI Statement

AI was utilize to enhance the clarity, grammar, and overall readability of this manuscript. All technical content, data interpretation, and conclusion were solely developed and verified by the authors. The final version of the manuscript was thoroughly reviewed to ensure accuracy, coherence, and aligment with the study's findings.

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