

Recent advances in carbon-based adsorbent materials for ammonium removal from water

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Abstract. This systematic review examines recent advancements in carbon-based adsorbent materials for ammonium removal from water, a critical issue due to contamination from agricultural, domestic, and industrial sources. Elevated ammonium levels disrupt aquatic ecosystems and compromise water quality. Among various technologies, ion exchange and adsorption using materials such as activated carbon (AC) and biochar are highlighted for their efficiency, cost-effectiveness, and environmental benefits. Modified adsorbents, like manganese oxide-loaded AC, significantly enhance removal performance. Biochars, particularly those modified with NaOH and Mg²⁺, show improved capacities, especially when combined with heterotrophic nitrifying bacteria (HNB). Carbon nanotubes (CNTs), especially multi-walled CNTs, demonstrate superior adsorption capabilities. Direct contact membrane distillation (DCMD) with CNT-immobilized membranes also shows promise. Lignite, a low-rank coal, proves to be an economical natural adsorbent with enhanced performance through aerobic dewatering and oxidation. Future research should optimize these materials for real-world applications, pilot-scale studies, and complex wastewater matrices.

1 Introduction

Ammonium levels in pure streams are usually very low [1]. Ammonium pollution of surface and groundwater resources, however, is largely caused by modern runoff and agricultural, residential, and industrial effluents. Numerous point sources, such as leachate and runoff from waste disposal sites, building sites, animal feedlots, and municipal and industrial wastewater, allow this contamination to enter these vital water sources [2, 3]. Furthermore, the problem is made worse by non-point sources such as air deposition, agricultural runoff, and land developments close to rivers [4]. Increased nutrient loads in contaminated waterways can encourage the growth of nuisance algae, which can result in hypoxic or anoxic conditions

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and negatively impact the structure and function of ecosystems [5]. Furthermore, because ammonium poses health hazards, especially in wastewater from swimming pools, restrooms, and laundry, it must be eliminated from greywater that is meant for reuse [2]. Ammonium (NH_4^+) and unionized ammonia (NH_3) can readily interconvert depending on the pH and temperature of both natural and urban waters [6]. Despite being a neutral chemical, unionized ammonia is much more dangerous than ammonium because it can easily penetrate aquatic species' epithelial membranes [7]. Asphyxiation may result from this diffusion's harm to the gill epithelium. It may also raise acidity by blocking the Krebs cycle and promoting glycolysis. This acidity damages blood vessels, lowers the blood's ability to carry oxygen, and affects how well the kidneys and liver work [8]. On the other hand, because natural waters normally have a pH that is almost neutral, ammonium is usually found in considerably larger proportions than ammonia.

A number of guidelines have been developed to lessen the consequences of eutrophication in response to worldwide concerns about the ecological effects of ammonium [9]. Ammonium can be extracted from wastewater and other point sources using a variety of methods that include physical, chemical, biological, and hybrid approaches. These techniques include reverse osmosis, chemical precipitation, breakpoint chlorination, air stripping, biological treatments, ion exchange and adsorption, microwave radiation, and supercritical water oxidation [10–12]. An overview of these technologies' benefits and drawbacks is given in Table 1. Notwithstanding their potential, these techniques have significant disadvantages, including exorbitant expenses, poor removal effectiveness, susceptibility to changes in pH and temperature, and the possibility of adding more pollutants [10, 13, 14]. Because of their strong affinity for ammonium, excellent removal efficiency, affordability, simplicity of use and operation, and environmental friendliness, ion exchange and adsorption stand out among these methods [12, 15]. Ion exchange and adsorption are especially well-suited for extensive application in industrial and water treatment facilities because of these characteristics. As a result, this study focuses on these methods, analyzing more than 70 adsorbents and contrasting their efficacy in terms of ammonium removal efficiency, cost, usability, and environmental sustainability.

Table 1. Technologies to remove ammonium from water and wastewater.

Removal Technologies	Removal Efficiency	Advantages	Disadvantages	References
Supercritical Water Oxidation	>95%	<ul style="list-style-type: none"> Destroys organic trash quickly. Generates molecular nitrogen, carbon dioxide, and water. 	<ul style="list-style-type: none"> Pricey Needs high pressure and temperature Affected by high oxygen levels and temperature Precipitation of salt 	[14]
Microwave Radiation	~80%	<ul style="list-style-type: none"> Reasonably priced Beneficial for elevated ammonium levels 	<ul style="list-style-type: none"> Aeration, pH, radiation duration, and beginning ammonia content all have an impact. Evaporation of NH_3 Difficult for widespread implementation 	[13]

<p>Reverse Osmosis</p>	<p>60%–90%</p>	<ul style="list-style-type: none"> • Energy-efficient • Requires minimal space • Easy and continuous operation • Simple, modular design 	<ul style="list-style-type: none"> • Expensive • Membranes can be fouled by colloidal matter • Iron and manganese can decrease scaling potential • Requires regular membrane cleaning 	<p>[10]</p>
<p>Chemical Precipitation</p>	<p>20%–30%</p>	<ul style="list-style-type: none"> • Generates beneficial slow-release fertilizer • Reasonably priced • Lowers maintenance and sludge expenses 	<ul style="list-style-type: none"> • Requires a certain temperature and pH • Affected by additional ions and the chemical makeup • Brings in new contaminants 	<p>[16]</p>
<p>Breakpoint Chlorination</p>	<p>80%–95%</p>	<ul style="list-style-type: none"> • Needs minimal room • Eliminates ammonium efficiently • Impervious to harmful chemicals and changes in temperature • Adaptable to current facilities 	<ul style="list-style-type: none"> • sensitive to pH • Generates byproducts of disinfection • High levels of organic materials and chlorine use • Needs knowledgeable operators 	<p>[11]</p>
<p>Air Stripping</p>	<p>50%–90%</p>	<ul style="list-style-type: none"> • Frequently employed for pre-treatment of wastewater • Easy to use equipment • Able to withstand harmful toxins 	<ul style="list-style-type: none"> • Requires particular flow rate, pH, and temperature • Large stripping towers are necessary. • Time-consuming • A high demand for energy • Leads to packing scaling and fouling. 	<p>[17]</p>
<p>Biological Method</p>	<p>70%–95%</p>	<ul style="list-style-type: none"> • The most common methodology in use • Effective means of removing ammonium 	<ul style="list-style-type: none"> • Expensive in nature • Depending on the particular temperature and weather conditions that are present • Heavy reliance on energy sources • The succeeding stages are fraught with danger. • A high quantity of ammonium at 	<p>[12]</p>

			completion of therapy	
Ion Exchange and Adsorption	80%–95%	<ul style="list-style-type: none"> • Simple to operate • Effectively eliminates ammonium • Low-cost • Produces effluent with relatively low TDS 	<ul style="list-style-type: none"> • Requires specific pH ranges • Varying adsorbents lead to different efficiencies • Needs disposal of waste brine 	[15]

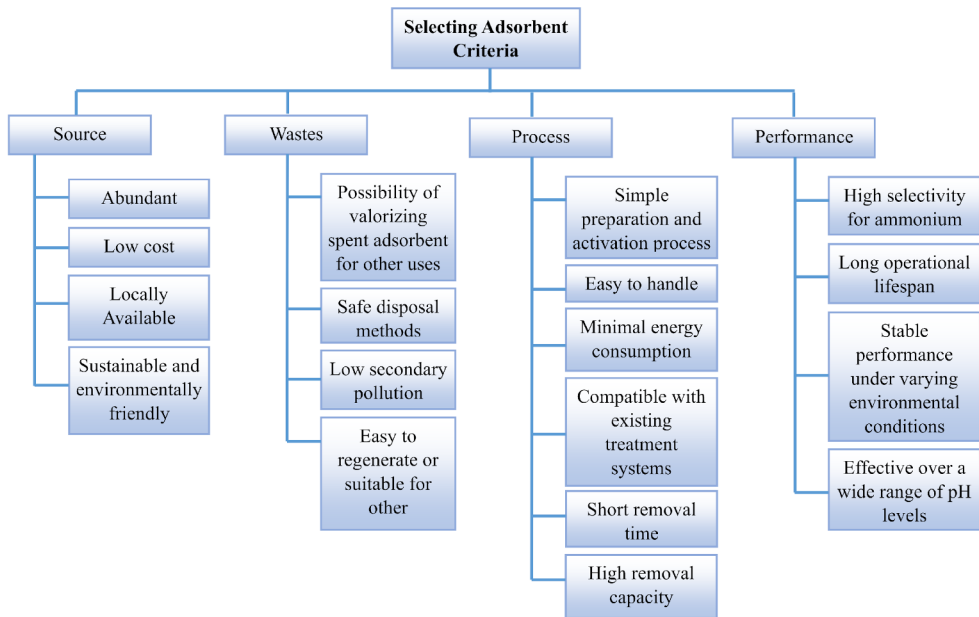


Fig. 1. Selection criteria for an appropriate adsorbent to eliminate ammonium from water and wastewater.

2 Materials and methods

This research establishes criteria for selecting the most suitable adsorbents for large-scale ammonium removal from water and wastewater, based on their source, waste, technique, and performance (Fig. 1). The selected adsorbents should be readily available, cost-effective, easy to handle, and environmentally safe for disposal. Utilizing published data, the study compiles a list of both current and potential adsorbents. Adsorbents with high removal capacities, highlighted in italics within each section, are further evaluated using various parameters due to the extensive range of available options. The ultimate objective of this study is to identify an economical and eco-friendly adsorbent for widespread application in commercial and wastewater treatment facilities.

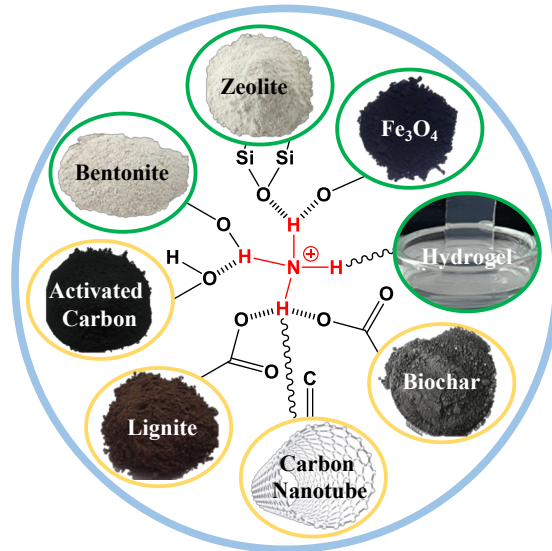


Fig. 2. Adsorbent materials for ammonium removal

A diverse range of materials, including bentonite, zeolite, Fe_3O_4 , activated carbon, hydrogel, biochar, carbon nanotubes, and lignite, are utilized as adsorbents for ammonium removal (Fig. 2). These materials have been extensively researched due to their effectiveness in eliminating ammonium from aquatic environments. Each material possesses unique properties that make it suitable for specific applications. For instance, zeolite and bentonite are valued for their ion exchange capabilities, while activated carbon and biochar are renowned for their high surface area and porosity. The efficiency of these adsorbents has been further enhanced by incorporating advanced materials such as carbon nanotubes and Fe_3O_4 nanoparticles, making them highly effective in both industrial and environmental applications.

Activated carbon (AC) is particularly notable for its extensive network of tiny, low-volume pores, which significantly increase the surface area available for adsorption. Remarkably, a single gram of AC can offer up to 3000 m^2 of surface area. This well-known adsorbent effectively removes a wide variety of organic and inorganic contaminants from aqueous solutions [18]. AC is prized for its strong mechanical strength, high surface reactivity, substantial adsorption capacity, and resistance to radiation and heat [19]. In addition to AC, biochar—produced as a precursor to activated carbon through modern pyrolysis techniques—is also highly effective for ammonium adsorption due to its fine-grained structure and high carbon content (Fig. 2). Meanwhile, carbon nanotubes (CNTs) have gained significant attention for their potential as adsorbents, demonstrating effectiveness in removing a wide range of pollutants, including dyes, heavy metals, and organic contaminants. This section highlights and compares the ammonium removal capabilities of various carbon-based adsorbents [20–22].

3 Results and discussion

3.1 Activated carbon

A comprehensive investigation into the effects of backwashing on granular activated carbon (GAC) for ammonium removal in drinking water revealed several key insights. Notably, the study found that after backwashing, GAC exhibited a 12% higher ammonium removal

efficiency compared to its performance prior to prechlorination ($p < 0.01$). Conversely, with prechlorination, the ammonium removal efficiency of GAC decreased by 12% even after backwashing ($p < 0.01$). Ammonia-oxidizing archaea (AOA) were the dominant microbial group on the GAC during both sampling phases. Interestingly, the populations of ammonia-oxidizing bacteria (AOB) and AOA remained constant before and during backwashing, irrespective of prechlorination. Analysis of backwash water revealed that only a small fraction (0.08%–0.26%) of AOA and AOB were removed compared to their initial concentrations on the GAC (Fig. 3). This indicates that the biomass of ammonia oxidizers on the GAC is minimally affected by backwashing. However, the findings also suggest that both prechlorination and backwashing may negatively impact GAC's ammonium removal efficiency [23].

Additionally, great progress has been made in the creation of manganese oxide-loaded activated carbon (AC-MnOx) for the removal of ammonium from wastewater using this material. AC-MnOx revealed a stunning 15.6-fold improvement in ammonium removal efficiency and a five-fold enhancement in removal capacity, attaining 3.20 mg/g. This was in comparison to the typical activated carbon (AC) that was used. AC-MnOx was able to attain a maximum ammonium removal efficiency of 94.6% when the circumstances were ideal. These parameters included an initial $\text{NH}_4^+\text{-N}$ concentration of 15 mg/L, an adsorbent dose of 2.5 g, a pH of 6.5, and a temperature of 35 degrees Celsius. In addition, the research shed light on the unique functions that adsorption and catalytic oxidation play in the overall process of ammonium removal [24].

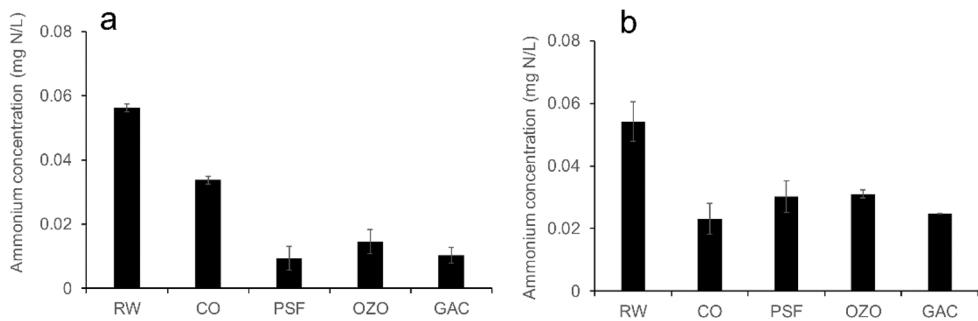


Fig. 3. Both the raw water and the water purification effluent were analyzed for ammonium concentrations, both without prechlorination (a) and with prechlorination (b). The error bars indicate the standard deviation. Abbreviations used are as follows: RW represents raw water, CO stands for coagulation/sedimentation, PSF denotes primary sand filtration, OZO indicates ozonation, and GAC refers to granular activated carbon [23]. Copyright 2018 MDPI.

A further investigation into the removal of ammonia and N-nitrosamine simultaneously via the use of zeolite and powdered activated carbon (PAC) has been carried out. Mordenite zeolite was used throughout the several phases of treatment in this study. These stages included lime softening, alum coagulation, and a combination of alum coagulation with PAC sorption. Lime softening produced results that were less than optimum for the performance of zeolite, but alum coagulation on its own did not have a substantial impact on the removal of ammonia and N-nitrosamine precursors. However, when alum coagulation was coupled with PAC sorption, the treatment produced significant removal efficiency, removing over 67% of ammonia and between 70% and 100% of N-nitrosamine precursors [25]. This was accomplished by combining the two processes simultaneously. In addition, a research was carried out to investigate the lowering of ammonia levels by the use of activated carbon that

was obtained from coffee grounds, and the findings were rather remarkable. Based on the findings of the experiment, the ideal conditions for ammonia reduction were determined to be 120 minutes of treatment time with an adsorbent weight of 0.8 grams. Under these circumstances, the procedure was able to achieve an impressively high level of ammonia removal efficiency, with a percentage yield of 97.3% [26].

3.2 Biochar

In contrast to ammonium, which presents a significant risk to aquatic habitats and has a particularly negative influence on fisheries, rice straw is a waste product that is ubiquitous in the agricultural sector, with millions of tons being generated annually around the world. The purpose of this research is to investigate the use of both physical and chemical modification strategies to improve the capacity of rice straw to remove ammonium from water. Taking into consideration a variety of parameters, including starting NH_4^+ concentration, contact duration, adsorbent dose, and ammonium removal effectiveness, a detailed investigation of kinetic and isothermal adsorption behaviors was carried out. Additionally, the effects of temperature and pH on the adsorption process were investigated and analyzed. The findings of the study revealed that the highest adsorption capacities of 2.9, 3.5, and 4.5 mg/g were attained at temperatures of $25 \pm 5^\circ\text{C}$, $35 \pm 5^\circ\text{C}$, and $45 \pm 5^\circ\text{C}$, respectively. These temperatures were accompanied by ammonium removal efficiencies of 43 percent, 53.7%, and 69.5%, respectively, when the pH of the solution was set at 7.5. It was discovered in the research that the adsorption isotherms were in agreement with both the Freundlich ($R^2 = 0.99$) and Langmuir ($R^2 = 0.98$) models. On the other hand, the ammonium adsorption kinetics of biochar that was generated from rice straw were shown to be in accordance with the pseudo-second-order model ($R^2 = 0.98$) [27].

It was also carefully explored how the temperature of the pyrolysis process affected the synthesis of biochar from digested sludge, as well as how successful the biochar was in eliminating ammonium from municipal wastewater. It was revealed in the research that biochar was able to obtain an ammonium removal capacity of 1.2 mg $\text{NH}_4^+\text{-N}$ per gram of biochar in municipal wastewater. This capacity was somewhat lower than the 1.4 mg $\text{NH}_4^+\text{-N}$ per gram capacity that was seen in identical studies using a synthetic ammonium solution (Fig. 4). The existence of this disagreement draws attention to the fact that the wastewater matrix has an effect on the adsorption performance of biochar under different pyrolysis settings [28]. A further experiment found that increasing the amount of biochar used resulted in an improvement in the effectiveness of ammonium removal. In particular, a biochar dose of 100 g/L was shown to be effective in removing 80 percent of the ammonium from the water. On the other hand, when the starting ammonium concentration was raised by fifty milligrams per liter, the removal efficiency dropped by fifteen percent. The pH range between 6 and 8 was determined to be the most effective for ammonium elimination, and equilibrium was established within three days of that range being reached. It was determined that the greatest ammonium adsorption capacity that could be observed was 0.96 mg/g when the starting concentration was 80 mg/L [29].

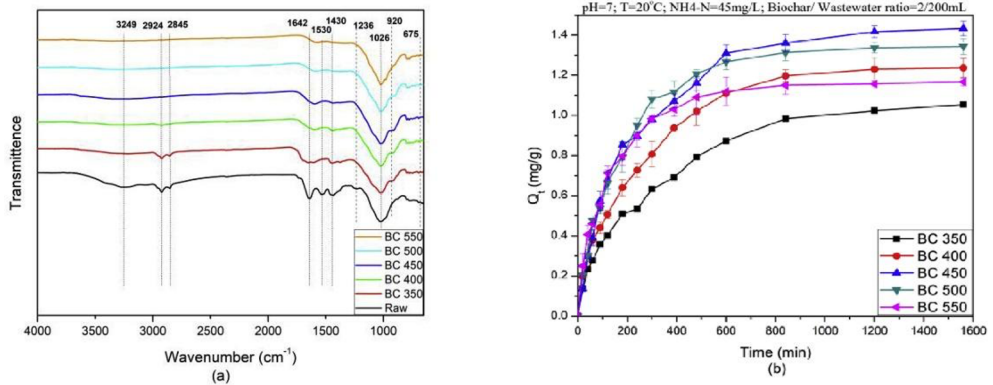


Fig. 4. (a) The FTIR spectra of biochars and digested sludge produced at various pyrolysis temperatures, as well as (b) the ammonia adsorption capacities of biochars prepared at different pyrolysis temperatures [28]. Copyright 2019 ELSEVIER.

Through the use of biochemical and molecular biological investigation, a strain of heterotrophic nitrifying bacteria (HNB) was isolated from activated sludge and determined to be *Pseudomonas*. Over the same time period, biochars derived from rice husk that had been treated with HNO_3 , Mg^{2+} , NaOH , and $\text{NaOH}+\text{Mg}^{2+}$ were created. For the purpose of determining how successful these modified biochars are in removing $\text{NH}_4^+\text{-N}$ from water, they were put through a series of tests as HNB carriers alongside the original biochar that had not been changed. The findings demonstrated that free HNB was able to attain an elimination ratio of $\text{NH}_4^+\text{-N}$ that was 80.24% over a period of 72 hours. Compared to other carriers, biochar carriers that were treated with sodium hydroxide and sodium hydroxide combined with magnesium ion showed considerably increased $\text{NH}_4^+\text{-N}$ removal capabilities. After 5 hours, the $\text{NH}_4^+\text{-N}$ clearance ratios for NaOH - and $\text{NaOH}+\text{Mg}^{2+}$ -modified biochar-based HNB immobilization bodies were 57.78% and 58.35%, respectively, and after 48 hours, they were 88.66% and 90.93%, respectively. This was determined by using a starting $\text{NH}_4^+\text{-N}$ concentration of 100 mg/L and a biochar dosage of 10 g/L. These findings were much better than those obtained by the original biochar-based HNB immobilization bodies, as well as those obtained by HNO_3 and Mg^{2+} -modified biochar. The considerably increased bacterial adsorption capabilities of the NaOH - and $\text{NaOH}+\text{Mg}^{2+}$ -modified biochars, which reached 773.75 and 941.17 nmol P/g biochar, respectively, were due to the improved performance of the biochars that were changed with water and magnesium ions, respectively [30].

In yet another work, major new insights have been presented into the effective removal of ammonium from aqueous solutions by using biochar that has been ball-milled and treated with sodium hydroxide. The findings of the research demonstrated that the specific surface area of biochar grew from 20.9 m^2/g to 51.4 m^2/g after being modified with NaOH , and then it increased even more to 145.6 m^2/g after being subjected to ball-milling. The ammonium sorption capacity of the biochar was greatly improved as a result of these modifications throughout a broad pH range ranging from three to seven, with the best sorption capability occurring at a pH of roughly six. Ball-milling and treatment with sodium hydroxide were also factors that led to the enhanced ammonium sorption. It was found that the biochar that had been ball-milled and treated with sodium hydroxide had the maximum ammonium sorption capacity (8.93 mg/g). It was found that the Langmuir and pseudo-second-order models provided an accurate description of the sorption process. Cation exchange and surface complexation with oxygen-containing functional groups have been identified as the key processes that are responsible for ammonium sorption. The results of this study suggest that biochar that has been treated with sodium hydroxide and then ball-milled shows substantial potential for the removal of ammonium from water that has been polluted [31].

3.3 Carbon nanotubes

Discovered by Iijima in 1991, carbon nanotubes (CNTs) are among the most extensively studied carbon nanomaterials and are renowned for their exceptional adsorption properties. Due to their large specific surface area and hollow, multilayered structure, CNTs are highly effective at adsorbing a variety of hazardous chemicals. CNTs are generally classified into three forms: single-walled (SWCNTs), multi-walled (MWCNTs), and functionalized (f-CNTs). These materials have significantly contributed to the removal of organic pollutants from aquatic environments. For instance, MWCNTs have demonstrated notably higher efficiency in removing organic compounds from wastewater compared to conventional activated carbon. A recent study on the adsorption of ammonium ions onto MWCNTs, based on the Langmuir isotherm model, reported an impressive adsorption capacity of 129 mg/g with a removal efficiency of 95%. Additionally, equilibrium and adsorption kinetics data aligned well with the pseudo-second-order model. Batch adsorption tests confirmed the effectiveness of MWCNTs in removing ammonium ions from wastewater, highlighting their potential for real-world wastewater treatment applications [32].

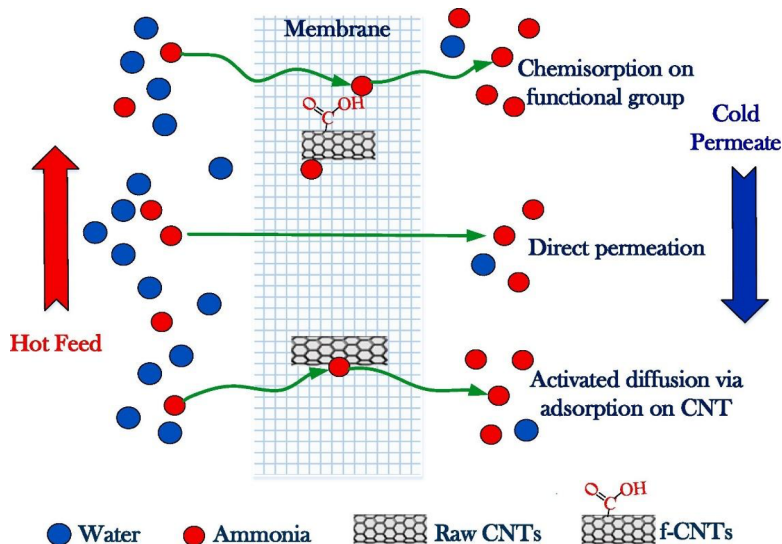


Fig. 5. Schematic diagram for mechanism proposed on CNIMs [33]. Copyright 2020 ELSEVIER.

Direct contact membrane distillation (DCMD) and carbon nanotube immobilized membranes (CNIMs) were used in a research that exhibited considerable gains in the separation of ammonia. Both highly polar carboxylated carbon nanotubes (f-CNTs) and raw carbon nanotubes (CNTs) were used in the production of these complex nanostructured materials (CNIMs). With regard to the removal of ammonia, CNIMs that were constructed from both raw CNTs and f-CNTs functioned better than the PTFE membrane that had not been changed. It is important to note that f-CNTs demonstrated the greatest flux, ammonia recovery, and mass transfer coefficients across all of the operating conditions that were studied. The membrane that was immobilized with f-CNT (CNIM-f) was able to attain a maximum flow of 32 g/m²·h, which is twice as high as the measurements that were previously published. In addition, the CNIM-f obtained the maximum ammonia removal efficiency, reaching 14%, when the parameters were as follows: a feed flow rate of 5 mL/min, a constant temperature of 40°C, and an ammonia concentration of 300 ppm [33]. Figure 5 depicts the potential

process that could be responsible for the increased ammonia flow that is caused by CNIMs. In an independent investigation, single-walled carbon nanotubes (SWCNTs) were investigated for their potential to act as adsorbents in the removal of ammonia from synthetic wastewater. Based on the findings, it was determined that a pH level of 9.5 had the maximum adsorption effectiveness, which may reach up to 90%. Furthermore, the adsorption efficacy was greatly improved by not only increasing the dose of SWCNTs but also by prolonging the adsorption period. The performance, on the other hand, did not improve since there was an inverse connection between the quantity of adsorbate and the temperature that was increasing [34].

3.4 Lignite

Coal is a natural adsorbent that may provide a cost-effective alternative to goods such as fly ash, activated carbon, activated coke, and zeolite when it comes to the treatment of wastewater. In particular, low-rank forms of coal, such as lignite, are especially useful. Lignite has been the subject of a significant amount of study because of the high composition of surface functional groups, the rich pore structure, and the remarkable calorific value it has. Studies have shown that lignite may, in some circumstances, perform better than activated carbons that are available for commercial use when it comes to adsorbing organic compounds [35]. There is a little quantity of NH_4^+ that is absorbed by lignite; nevertheless, the vast majority of these ions are retained in the aqueous phase. On the other hand, phenol is likely to be adsorbed into lignite surfaces with more ease. Cation- π interactions and $\text{O}\cdots\text{H}$ hydrogen bonds are the key mechanisms that influence the interaction between NH_4^+ and lignite due to their respective roles in the interaction. On the contrary, the process of phenol adsorption includes the formation of hydrogen bonds, the stacking of π - π bonds, and certain van der Waals interactions taking place. The large hydrogen bond energy of lignite's structural units in relation to NH_4^+ is shown by the fact that the overall binding energy percentages for the four conformations of NH_4^+ were 72.34%, 82.64%, 51.00%, and 51.02% respectively. The percentages of total binding energy for phenol were as follows: 40.94%, 53.42%, 62.18%, and 73.31%, respectively [36].

The purpose of this research is to evaluate the surface chemistry and ammonia adsorption capacity of lignite after it has been dewatered. The study focuses on the impacts of aerobic drying on the effectiveness of dewatering, the ability to adsorb NH_3 , the danger of spontaneous combustion, and the surface chemical features of lignite. As a result of the results, the water content of lignite was dramatically decreased from 61.6% to 4.2% by the process of aerobic dewatering at a temperature of 200 degrees Celsius. Additionally, the danger of spontaneous combustion was lowered. In addition to this, the adsorption capabilities of lignite for NH_4^+ and NH_3 rose significantly by 65.8% and 28.8%, respectively. Through the use of chemical analysis, these enhancements were linked to the partial oxidation of the surface of the lignite that occurred during the drying process. This resulted in an increase in the concentration of oxygen-containing functional groups. An observation was made that revealed a linear connection between the concentration of these functional groups and the adsorption of NH_4^+ . This finding provides vital insights into the surface chemical processes that are involved in the adsorption of NH_3 . Having this knowledge is essential for the creation of effective goods based on lignite, such as bedding for feedlots and other practical purposes [37,38].

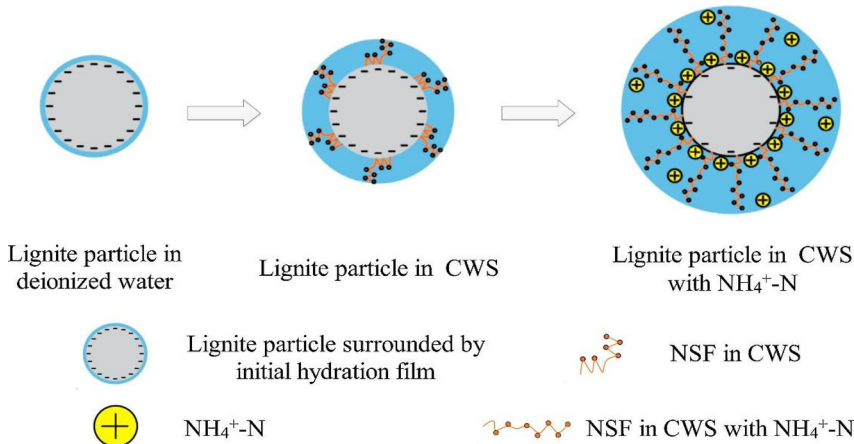


Fig. 6. Diagram showing the lignite particle's scheme in CWS, $\text{NH}_4^+\text{-N}$, and deionized water. [35] Copyright 2019 ELSEVIER.

Previous studies primarily employed short-term batch experiments using synthetic solutions to evaluate lignite's ability to remove NH_4^+ , focusing on adsorption capacity and removal efficiency (Fig. 6). However, given the complexity of wastewater treatment processes, further research is needed to explore the interaction of multiple factors influencing removal efficiency, as dynamic breakthrough analyses remain underdeveloped. Once laboratory-scale experiments are complete, the next step should involve designing and conducting pilot-scale studies to assess industrial feasibility. It is essential to test with actual wastewater rather than synthetic solutions, as the presence of organic matter and heavy metal ions may reduce ammonium exchange capacity due to competitive adsorption.

4 Conclusion

This review evaluates recent advancements in carbon-based adsorbent materials for ammonium removal from water, addressing the significant environmental issue of ammonium contamination due to agricultural, domestic, and industrial effluents. Elevated ammonium levels can disrupt aquatic ecosystems and water quality. Among various removal technologies, ion exchange and adsorption using carbon-based materials, such as activated carbon (AC) and biochar, have shown high efficiency, cost-effectiveness, and environmental benefits. Modified adsorbents like manganese oxide-loaded activated carbon (AC-MnOx) significantly improve removal efficiency. Biochars, especially those modified with NaOH and Mg^{2+} , exhibit enhanced adsorption capacities. Combining biochar with heterotrophic nitrifying bacteria (HNB) further boosts performance. Carbon nanotubes (CNTs), particularly multi-walled CNTs (MWCNTs), excel in removing ammonium and organic contaminants, outperforming traditional activated carbon. Direct contact membrane distillation (DCMD) with carbon nanotube immobilized membranes (CNIMs) also shows promise. Additionally, lignite, a low-rank coal, offers a cost-effective natural adsorbent, with aerobic dewatering and partial oxidation enhancing its capacity. Understanding these materials' surface chemistry and adsorption mechanisms is crucial for practical applications. Future research should optimize these adsorbents for real-world use, conduct pilot-scale studies, and explore the interactions affecting adsorption efficiency in complex wastewater matrices.

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