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Review of Recent Advances in Boron Removal from Water Using Adsorption: Materials, and Challenges

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Abstract: Boron is a naturally occurring element essential for various biological functions in plants and animals. However, its elevated concentrations in water sources often due to industrial discharges, agricultural runoff, and seawater intrusion pose serious environmental and public health risks. The removal of boron from aqueous media has thus garnered increasing attention over the past decades. Among the available technologies, adsorption has emerged as a promising method due to its cost-effectiveness, operational simplicity, and potential for regeneration and reuse. This review critically analyzes recent advances in boron removal using adsorption techniques, emphasizing the underlying mechanisms of interaction between boron species and various adsorbent materials. It categorizes adsorbents into functionalized composites, metal oxides, carbon-based materials, and bio-derived structures, offering comparative insights into their removal efficiencies, stability, and selectivity. Unlike earlier reviews, this paper identifies and discusses critical knowledge gaps in the literature, such as the lack of pilot-scale studies, limited performance evaluations under real-world conditions (e.g., high salinity, competing ions), and insufficient data on adsorbent regeneration and lifecycle sustainability. It also explores economic and environmental considerations, highlighting the need for low-cost, scalable, and eco-friendly materials. Furthermore, the review provides a brief comparative analysis between adsorption and alternative boron removal technologies such as reverse osmosis, ion exchange, and electrocoagulation, situating adsorption within the broader treatment landscape. By synthesizing findings from recent studies and proposing directions for future research, this work aims to serve as a foundational resource for researchers and practitioners seeking to advance boron removal technologies from laboratory research toward practical, real-world applications.

Index Terms: Boron removal; Adsorption process; Adsorbents; aqueous solutions.

I INTRODUCTION

Boron is a trace element naturally present in the environment, playing an essential role in the biological systems of plants, microorganisms, and, to a lesser extent, animals. While trace amounts are beneficial, elevated boron concentrations commonly originating from anthropogenic sources such as mining, glass manufacturing, detergent production, and agricultural fertilizers pose significant risks to ecosystems and human health. The World Health Organization (WHO) has set a guideline limit of 2.4 mg/l for boron in drinking water, prompting growing interest in developing effective removal technologies to meet environmental standards.

Various methods have been explored for boron removal, including reverse osmosis, ion exchange, electrocoagulation, and chemical precipitation. Among these, adsorption has received considerable attention due to its simplicity, low operational cost, and adaptability to different water matrices. Numerous materials ranging from activated carbons and biochars to advanced nanomaterials have been developed and tested as potential adsorbents for boron removal.

While several reviews have been published in the past, they often focus on summarizing existing data without offering in-depth critical analyses of adsorption mechanisms, limitations in practical applications, or strategic directions for future work. Moreover, limited attention has been given to real-world challenges such as adsorption in high-salinity matrices (e.g., seawater, wastewater with competing ions), economic feasibility, sustainability, and scale-up from laboratory to industrial settings [1, 2].

Therefore, this review aims to bridge these gaps by presenting a comprehensive and analytical overview of recent developments in boron adsorption technologies. Studies were categorized based on adsorbent types and treatment conditions. Key knowledge gaps including material reusability, selective adsorption in complex environments, and lack of pilot-scale implementations are identified and discussed. Furthermore, we offer a comparative context by briefly examining non-adsorptive removal methods and highlighting how adsorption fits into the broader technological landscape. This includes emphasizing challenges in boron removal from complex matrices like high-salinity and ion-rich waters.

In summary, this paper contributes a critical synthesis of current literature, outlines unresolved challenges, and proposes future research directions, thereby aiming to advance the development of efficient and sustainable boron removal solutions.

II BORON IN NATURE

Boron, an essential trace element, plays a vital role in various biological processes and is found abundantly in nature. This element is known to be present in the Earth's crust, oceans, soil, and plants, contributing to the overall ecosystem and influencing numerous biochemical reactions. Boron's presence in the Earth's crust is primarily due to geological processes such as volcanic activity and weathering of rocks. It is estimated that boron concentrations range from 10 to 20 ppm in the Earth's crust, making it a relatively low-abundance element [3]. The distribution of boron in different regions can vary significantly, with areas like Turkey, the United States, and China known for having substantial boron deposits [4]. In aquatic environments, boron is found in varying concentrations in oceans, lakes, and rivers. The average concentration of boron in seawater is approximately 4.6 ppm [5]. This significant presence of boron in marine ecosystems contributes to its bioavailability and uptake by marine organisms, including algae, sea grasses, and invertebrates, which form the basis of marine food chains [6]. The role of boron in marine organisms is not yet fully understood, but it is believed to play a crucial role in maintaining cellular functions and osmoregulation [7]. Boron's role in soil is essential for plant growth and development. It influences various physiological processes, including cell wall synthesis, hormone regulation, and carbohydrate metabolism [8].

III. SOURCES OF BORON

Boron is an essential element that occurs naturally in various sources. Here are some common boron sources:

1. Minerals and Rocks: Boron is primarily obtained from borate minerals, such as borax (sodium borate decahydrate) and colemanite (calcium borate). These minerals are typically found in evaporate deposits formed from ancient lakes or seas. Borate deposits can also occur in volcanic regions. For example, the largest borate deposits in the world are found in the Mojave Desert in California [5].

2. Soils: Boron is present in soils, although its concentration can vary widely depending on the region. It is derived from the weathering of boron-containing minerals in rocks and minerals. Sandy soils tend to have lower boron levels, while clay-rich soils may have higher concentrations. Plants extract boron from the soil, and its availability to plants depends on factors such as soil pH, organic matter content, and moisture levels [9].

3. Oceans and Seawater: Boron is dissolved in seawater and is present in varying concentrations. The average boron content in seawater is about 4.6 milligrams per liter (mg/L) [10].

4. Coal and Oil: Boron can also be found in coal and oil deposits, although the concentration is relatively low. When coal or oil is burned, boron can be released into the atmosphere as a pollutant [11].

5. Agricultural Practices: The use of boron-based fertilizers in agriculture can contribute to the release of boron into the environment. These fertilizers are applied to the soil to correct boron deficiencies in crops or promote plant growth [12].

6. Industrial Processes: Several industrial activities can release boron into the environment. For example, boron is used in the production of glass, ceramics, and detergents. Discharge of industrial effluents containing boron can result in its release into water bodies [13].

7. Mining and Ore Processing: Boron minerals are mined for commercial purposes, and the extraction and processing of these minerals can lead to the release of boron into the environment. Mining activities may generate dust and wastewater containing boron compounds [14].

IV. BORON CHEMISTRY

Boron is the first and the only nonmetallic element in the group 13 (IIIA) in the periodic table. It has two naturally occurring and stable isotopes, ^{10}B (abundance of 19.9%) and ^{11}B (abundance of 80.1%) and its atomic weight is 10.81±0.02 [15].

The ground state configuration of boron is $1S^2\ 2S^2\ 2p^1$ as shown in Fig.1. This configuration would be a chemistry of monovalent boron, but the most excited electron configuration of boron $1S^2\ 2S^1\ 2p^2$. According to latest configuration, boron is trivalent in most cases and the oxidation state is (+3). The fact that three single bonds cannot maintain a stable electron configuration means that boron has an electron deficit. As a result, born has a significant tendency for stable covalent bonds to form with atoms that are electronegative, like oxygen which forms borates [16]. Boron's lack of electrons explains why it is a weak Lewis acid, so it can accept hydroxide $(OH)^-$ ions in the solution [13].

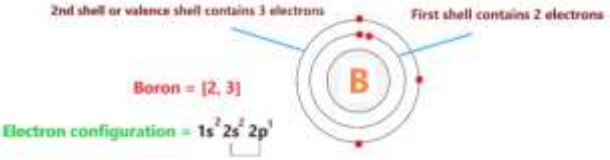

Figure1: State configuration of boron [16].

Table 1 shows the chemical and physical properties of boron compounds [17].

TABLE 1

Physical and chemical properties of boron and related compounds

Property	**Boron Oxide**	**Anhydrous Borax**	**Borax**	**Boric Acid**	**Boron**
Molecular Formula	B_2O_3	$Na_2B_4O_7$	$Na_2B_4O_7$ $10H_2O$	H_3BO_3	B
Molecular Weight	69.62	201.27	381.43	61.83	10.81
Boron Content (%)	31.06	21.49	11.34	17.48	100
Physical Form	white or colorless vitreous granules	white or colorless vitreous granules	white or colorless crystalline granules or powder	white or colorless crystalline granules or powder	black crystal or yellow-brown amorphous powder
Specific Gravity (@ 20°C)	2.46	2.37	1.73	1.51	2.34
Melting Point (°C) closed space	No data	No data	>62	171	2300
Melting Point (°C)	450	742	742	450	2300
Water Solubility (% w/w)	rapidly hydrates to boric acid	2.48 @ 20°C 34.5 @ 100°C	4.71 @ 20°C 65.63 @ 100°C	4.72 @ 20°C 27.53 @ 100°C	insoluble
Vapor Pressure (mm Hg)	Negligible at 20°C	Negligible at 20°C	Negligible at 20°C	Negligible at 20°C	0.0119 mm Hg @ 2140°C

V. BORON CHEMISTRY IN WATER

Boron chemistry in water is important because it can affect the quality of water for various purposes, including drinking, irrigation, and industrial uses. Boron can exist in different forms in water, including boric acid, borates, and complex boron species, depending on the pH and other water chemistry parameters [18].

Boric acid is the most common form of boron in water and is a weak acid that can dissociate to form borate anions. The dissociation of boric acid depends on the pH of the water, with higher pH resulting in a higher concentration of borate ions. Boric acid and borate ions are typically considered non-toxic at low concentrations, but high concentrations can be harmful to plants and animals [19].

The equation(1) and Fig. 2 illustrate the equilibrium reaction describing the dissociation of boric acid in water [2].

$$\mathbf{H_3BO_3 + H_2O \rightleftharpoons H^+ + B(OH)_4^-} \quad pK_a = 9.24 \quad (1)$$

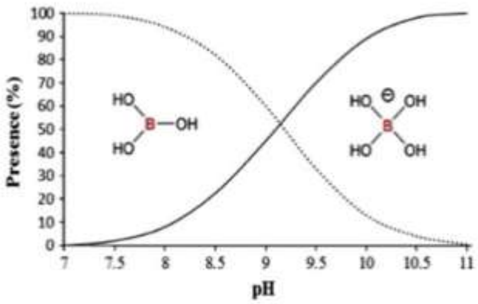

Figure 2: Dissociation of boric acid in water [2].

Borate $B(OH)_4^-$ carries a net negative charge, while boric acid (H_3BO_3) is neutral. These two forms are in chemical equilibrium with each other. This equilibrium is characterized by a low acid dissociation constant (Ka) of about 5.8 × 10^{-10} mol/L, which means that only a small fraction of boric acid molecules dissociates to produce hydrogen ions in water. Boric acid is therefore a very weak acid and has a pH of about 5.7 in water [20].

At neutral pH, the majority of the boron in solution is present as boric acid. As the pH increases, however, the concentration of the borate ion increases, and at pH values greater than 9.2, the predominant species is the borate ion [21].

Boron can also form complexes with other ions in water, such as calcium and magnesium, which can affect the solubility and mobility of boron in water. The formation of boron complexes with calcium and magnesium can lead to the precipitation of boron as borate minerals, such as borax. The solubility of boron in water is also influenced by the presence of other ions, such as sulfate and chloride, which can compete with boron for adsorption sites on clay particles and other surfaces in water [22].

VI. TOXICITY OF BORON

The toxicity of boron is an important consideration, particularly when it comes to monitoring and controlling its content in water, especially drinking water. Excessive exposure to boron has been associated with adverse health effects in humans and plants.

In terms of human health, the primary concern with boron toxicity is its potential impact on the reproductive system. High levels of boron exposure have been linked to impaired fertility, decreased sperm count, and increased risk of birth defects. Additionally, boron toxicity can affect the cardiovascular system, leading to changes in blood pressure and heart rate. Long-term consumption of boron-contaminated water or food can result in chronic boron toxicity in humans. Chronic boron toxicity occurs when individuals are exposed to high levels of boron over an extended period. According to a study conducted by [23], excessive boron intake has been associated with various adverse health effects.

Symptoms of chronic boron toxicity may include gastrointestinal issues such as nausea, vomiting, diarrhea, and abdominal pain. These symptoms can significantly impact an individual's quality of life and overall well-being. Furthermore, individuals exposed to high boron levels may experience dermatitis and respiratory irritation, as highlighted by a study published in the Journal of Environmental Science and Health, Part A [24].

VII. IMPACT OF BORON ON PLANTS

Boron is an essential micronutrient for plants, playing a crucial role in various physiological processes. However, excessive levels of boron can be toxic to plants and crops, leading to adverse effects on growth and development therefore, there is a small concentration range of boron between adequate level and toxic level for crops and plants.

Boron is absorbed by plant roots and transported through the xylem to various plant tissues. The uptake and transport mechanisms are tightly regulated to maintain optimal boron levels. However, when boron concentrations exceed the plant's tolerance level, toxicity can occur [25].

Boron toxicity symptoms vary among different plant species, but common signs include leaf chlorosis (yellowing), necrosis (tissue death), and stunted growth. Additionally, the toxicity can affect root development and lead to reduced water uptake [26].

Excessive boron can disrupt various physiological processes in plants. It interferes with cell wall synthesis, leading to structural abnormalities and reduced plant strength. Boron toxicity can also impair membrane integrity, disrupt mineral nutrient uptake, and affect enzyme activities, ultimately affecting plant metabolism and growth [27]. In addition to its toxic effects, boron also plays a critical role in plant growth and development. According to a review by [28], boron is involved in various physiological processes in plants, including cell wall formation, carbohydrate metabolism, and hormone regulation. Boron deficiency can lead to stunted growth, reduced root and shoot development, and poor seed and fruit production in plants. Different crops exhibit varying levels of sensitivity to boron toxicity. For example, crops like soybean, beans, and cereals are generally more sensitive to high boron concentrations, while others such as sugar beet and sunflower are relatively tolerant. Understanding crop-specific boron tolerances is crucial for managing boron levels in agricultural systems [29].

Environmental factors can influence the severity of boron toxicity in plants. High soil pH, low organic matter content, and low soil moisture exacerbate boron toxicity, as they increase the availability and uptake of boron by plants. Proper soil management and irrigation practices can help mitigate boron toxicity risks [30].

In addition, extreme boron concentrations in soil can interfere with the uptake of other essential nutrients, such as calcium and magnesium, resulting in nutrient imbalances. This imbalance can lead to impaired plant growth, decreased flower and fruit production, and lower crop yields [31].

Some crops can show boron deficiency at a concentration that would be toxic to a different plant. Table 2.2 show the levels of many crops tolerance for boron concentration in irrigation water [32-34].

TABLE 2

Levels of crops tolerance for boron concentration in irrigation water [34].

Tolerance	Crops
Very sensitive (<0.5 mg/l)	Lemon , Blackberry
Moderate Sensitive (0.5-0.75) mg/l	Avocado, Grapefruit , Orange, Apricot, Peach, Cherry, Plum, Persimmon, Fig, kadota, Grape, Walnut, Pecan, Cowpea, Onion
Sensitive (0.75-1.0) mg/l	Garlic, Sweet potato, Wheat, Barley, Sunflower, Bean, mung, Sesame, Lupine, Strawberry, Artichoke- Jerusalem, Bean-kidney, Bean-lima, Groundnut-Peanut
Moderate sensitive (1.0-2.0) mg/l	Pepper- red, Pea, Carrot, Radish, Potato, Cucumber
Moderate tolerant (2.0-4.0) mg/l	Lettuce, Cabbage, Celery, Turnip, Bluegrass-Kentucky, Oats, Maize, Artichoke, Tobacco, Mustard, Clover-sweet, Squash, Muskmelon
Tolerant (4.0-6.0) mg/l	Sorghum, Tomato, Alfalfa, Vetch-purple, Parsley, Beet-red, Sugarbeet
Very tolerant (6.0-15.0) mg/l	Cotton, Asparagus

Excessive boron in soil can also affect crop production and quality. According to a study by [3], boron toxicity can lead to reduced crop yield and quality in crops such as wheat, barley, and sunflower. The study found that excessive boron in soil can lead to reduced shoot and root biomass, lower chlorophyll content, and decreased grain yield in wheat and barley. Similarly, in sunflower, excessive boron can lead to reduced seed weight and oil content. Fig.3 shows impact of boron on plant leaves and crops.

Figure3: Boron impact on leaves and crops

VIII. DIFFICULTY OF BORON REMOVAL FROM WATER

Removal of boron from water can be challenging due to several reasons. One reason for the difficulty of boron removal from water is its chemical properties. Boron has a high affinity for water and forms stable complexes with various ligands, making it difficult to remove by conventional water treatment methods such as coagulation and sedimentation. Additionally, boron can exist in different forms in water, including boric acid, borate ion, and boronate complexes, each with different chemical properties and reactivity. Therefore, the selection of an appropriate treatment method is essential for effective boron removal from water [35]. Another reason for the difficulty of boron removal is its low concentration in water. Boron typically occurs in water sources at concentrations ranging from 0.1 to 5 mg/L, which makes it difficult to remove using conventional treatment methods. In many cases, specialized treatment technologies such as reverse osmosis or ion exchange are required to achieve boron removal to acceptable levels [36].

A third reason, the presence of other ions in water can also hinder boron removal. For example, high concentrations of chloride, sulfate, and bicarbonate ions can compete with boron for binding sites on treatment media, reducing the effectiveness of boron removal. Additionally, the presence of calcium and magnesium ions can cause scaling on treatment media, reducing the lifespan of the media and increasing operational costs [37].

A fourth reason, its small molecular size. Boron has a small atomic size, and its molecular weight is only 10.81 g/mol. This makes it difficult to remove boron from water using conventional methods such as reverse osmosis and nanofiltration, which are based on size exclusion mechanisms. According to a study by [38], the small size of boron molecules makes it difficult to remove using membrane-based methods.

A fifth reason, boron tends to exist in different forms depending on the pH and other chemical conditions of the water source. For example, at low pH levels, boron exists primarily in the form of boric acid, which is difficult to remove using conventional methods such as ion exchange or reverse osmosis [39]. At high pH levels, on the other hand, boron exists primarily in the form of borates, which are easier to remove using ion exchange and other methods. Furthermore, boron removal processes can be expensive and energy-intensive. For example, conventional methods such as reverse osmosis require significant energy inputs to operate and can be costly to maintain over time [40]. Other methods, such as adsorption using activated carbon or other materials, can also be expensive and may require frequent replacement or regeneration of the adsorbent material.

IX. TECHNOLOGIES FOR BORON REMOVAL FROM WATER

There are several methods available for the removal of boron from water, each with its own advantages and limitations. The common technologies for boron removal from aqueous solutions are chemical precipitation, reverse osmosis (RO), ion exchange, electrocoagulation and adsorption technique.

1. Chemical precipitation

Chemical precipitation is a widely employed method for boron removal from water sources. In this process, a precipitating agent added to the water, leading to the formation of insoluble boron compounds, which can then be separated from the liquid phase. One commonly used precipitant is calcium hydroxide Ca(OH)2, which reacted with boron to form calcium borate precipitates. The effectiveness of chemical precipitation in boron removal depends on factors such as pH, temperature, and the concentration of boron and precipitant in the water. This method can be effective for boron removal, but it may produce large volumes of sludge that require disposal [41].

In another study referenced in the paper by [42], involved the use of iron-based precipitants such as ferric chloride (FeCl3) or ferrous sulfate (Fe SO4), which added to the water, resulting in the formation of iron-boron compounds that precipitate out. The reaction between iron and boron is pH-dependent, with a lower pH typically favoring better boron removal. This method has been widely applied in both industrial and municipal wastewater treatment processes for efficient boron removal.

In a study by [43], it was found that adding lime to water with boron levels of 10 mg/L reduced boron concentrations to less than 2 mg/L, which is below the World Health Organization's recommended limit of 2.4 mg/L. In another study by [44], it was found that milk of magnesia was able to remove more than 90% of boron from water with concentrations of up to 25 mg/l.

2. Reverse Osmosis

Boron removal by Reverse Osmosis (RO) is a widely used and effective method for reducing boron concentrations in water sources. RO is a membrane-based water treatment process that utilizes a semipermeable membrane to separate dissolved solids, including boron, from the water. The membrane acts as a barrier, allowing only water molecules to pass through while rejecting contaminants.

According to a study conducted by [45], RO has demonstrated high efficiency in removing boron from various water sources. The researchers investigated the performance of RO membranes in treating boron-contaminated water and found that RO achieved boron removal rates ranging from 85% to 99%, depending on the operating conditions and membrane characteristics. The study also highlighted that RO was particularly effective in removing boron compared to other conventional treatment methods.

In another research article by [46], the authors investigated the influence of different operational parameters on boron removal efficiency using RO. The study focused on the impact of feed water pH, boron concentration, and operating pressure on the overall boron rejection rate. The results indicated that higher pH values, lower boron concentrations, and increased operating pressure favored enhanced boron removal. The findings emphasized the significance of optimizing these parameters to achieve efficient boron removal through RO processes.

Furthermore, a study conducted by [47], evaluated the performance of different types of RO membranes for boron removal. The researchers compared the boron rejection capabilities of cellulose acetate, polyamide thin-film composite, and polyamide thin-film nanocomposite membranes. The results showed that the polyamide thin-film composite and nanocomposite membranes exhibited superior boron rejection performance compared to cellulose acetate membranes.

3. Ion exchange

It is a process in which ions in a solution are replaced by other ions with the same charge from an ion exchange resin. Boron can be removed from water by ion exchange resins, such as strong acid cation exchange resin, weak acid cation exchange resin, and chelating resin. Strong acid cation exchange resin has been found to be effective in removing boron from water with a high concentration of salt. This method is effective for boron removal, but it may require frequent regeneration of the resin [48].

In another research article by [49], the authors investigated that ion exchange is generally more effective at lower pH levels, as the boron ions are more likely to be in their uncharged form. The concentration of boron also affected the effectiveness of ion exchange, with higher concentrations requiring more frequent regeneration of the resin. Also they stated that the resins are usually made of organic polymers that have charged functional groups. When the resin is exposed to water containing boron, the boron ions are exchanged with ions on the resin. The process is reversible, meaning that the resin can be regenerated by exchanging the boron ions with other ions.

One challenge with ion exchange for boron removal is that other ions in the water can compete with boron for exchange sites on the resin. For example, if the water contains high levels of chloride ions, they may bind to the resin instead of boron ions, reducing the effectiveness of the ion exchange process. To address this issue, some researchers have explored the use of selective resins that preferentially bind to boron over other ions [50].

4. Electrocoagulation

Electrocoagulation has demonstrated its potential as an effective method for the removal of boron from water. The electrochemical process, facilitated by sacrificial electrodes, allows for the formation of coagulants that bind with boron particles, leading form larger agglomerates that can be easily separated from the water. One study conducted by [51], it investigated the effectiveness of electrocoagulation in removing boron from wastewater. The researchers used aluminum as the sacrificial electrode and tested various operational parameters such as current density, pH, and treatment time. They found that electrocoagulation achieved a high removal efficiency of boron, with removal rates ranging from 90% to 99% under different experimental conditions. The study concluded that electrocoagulation could be a viable and environmentally friendly approach for boron removal, but it is generally considered a high cost method in the water treatment.

In another research study, [52] investigated the removal of boron from synthetic wastewater using electrocoagulation with aluminum electrodes. The study examined the influence of different parameters such as current density, initial boron concentration, and electrolysis time on the removal efficiency. The results indicated that electrocoagulation effectively removed boron from the wastewater, achieving removal efficiencies above 99% under optimized conditions. The researchers also analyzed the effect of electrode aging and concluded that the performance of the electrocoagulation system remained stable over a considerable period of operation.

5. Adsorption Technologies

It is an effective approach for boron removal from aqueous solutions with very low concentrations. It is considered a commonly used method for boron removal from water due to its simplicity, low cost, and high efficiency when compared to other technologies. The basic principle of this process is to apply a solid material (adsorbent) to attract and hold onto molecules or ions from a liquid or gas (adsorbate) on its surface. This method has the advantage of producing less sludge than chemical precipitation, but it may require frequent replacement of the adsorbent material [53].

5.1 Adsorption Types

Adsorption mechanisms are broadly classified into physisorption, chemisorption, and biosorption, each with distinct characteristics and applications. Physisorption, mediated by weak van der Waals forces (10–100 kJ/mol), is a reversible process dominant at low temperatures and pressures, making it ideal for gas storage and purification using porous materials like activated carbon, silica gel, and zeolites [54]. In contrast, chemisorption involves stronger chemical bonding (100–800 kJ/mol), is typically irreversible, and requires higher energy inputs, rendering it suitable for catalytic processes and surface modifications employing metal oxides or carbon nanomaterials [55]. Biosorption leverages biological materials (e.g., algae, fungi) whose surface functional groups (e.g., carboxyl, amino) efficiently capture pollutants, offering an eco-friendly approach for wastewater treatment and metal recovery [56]. The choice of mechanism depends on the target adsorbate, operational conditions, and desired outcomes, with each method presenting unique advantages in environmental and industrial applications.

5.2 Adsorbents for boron removal

Several adsorbents have been tested for boron removal, including activated carbon, zeolite, modified chitosan, clays, fly ash, natural minerals, nanoparticles and other natural materials. Recently, researchers have become more focused on adsorbents with low cost, high and feasible regeneration, high adsorption rate and maximum capacity.

- **Activated carbon**

Activated carbon-based adsorbents have demonstrated high boron removal efficiencies (80–100%) across various experimental conditions [57]. Their exceptional performance stems from their large surface area and abundant active sites, which facilitate effective boron adsorption.

The adsorption capacity of activated carbon for boron is pH-dependent, with lower pH values favoring higher removal efficiencies. This trend occurs because the dominant boron species in acidic conditions are more readily adsorbed. Conversely, adsorption decreases at elevated pH levels due to less favorable boron speciation [57].

Additionally, adsorption capacity increases with higher initial boron concentrations, as greater ion availability enhances uptake. Studies report maximum adsorption capacities of 9.81 mg/g for conventional activated carbon and 12.37 mg/g for modified variants [58], underscoring the potential of chemical modifications to improve performance.

- **Natural materials**

Zeolites are microporous aluminosilicate minerals characterized by a high surface area and a regular pore structure. The adsorption of boron by zeolites primarily occurs through ion exchange, where boron ions replace other cations (e.g., sodium or calcium) within the zeolite framework. Studies have shown that zeolite adsorption capacity for boron increases at lower pH levels, as the predominant boron species in solution become more adsorbable under acidic conditions [59].

A study by [60] investigated natural zeolite as an adsorbent for boron removal from aqueous solutions. The results demonstrated a high boron adsorption capacity of 7.5 mg/g, indicating its effectiveness in boron removal.

Similarly, [61] explored boron removal using natural peat, finding maximum efficiency within a pH range of 7–8. The authors concluded that peat is a viable, low-cost alternative to conventional boron removal methods.

Another study by [62] evaluated the efficacy of clay minerals, particularly bentonite, in boron removal. The results revealed that boron elimination occurred mainly through ion exchange and adsorption, with bentonite exhibiting the highest removal efficiency. The study suggested that clay minerals could serve as an economical solution for water treatment in boron-contaminated areas.

In a recent development, [63] synthesized a novel rice husk–magnetite composite for boron removal, achieving 90% efficiency. The enhanced performance was attributed to the synergistic interaction between rice husk and magnetite, highlighting the composite's potential for wastewater treatment applications.

- **Agricultural-based adsorbents**

Agricultural-based adsorbents present a sustainable solution for boron removal, offering multiple advantages including abundant availability, cost-effectiveness, and environmental benefits through waste valorization. These materials, often derived from agricultural byproducts that would otherwise contribute to pollution, can be regenerated and reused, enhancing their economic and ecological viability in water treatment systems [64]. Among these, biochar - a porous carbonaceous material produced via pyrolysis of wood chips, crop residues, or animal manure - has demonstrated particular promise due to its large surface area and effective boron adsorption capacity [65,66]. Further performance enhancements can be achieved through chemical modifications that introduce specific functional groups to increase boron affinity [67]. A notable example is corn straw ash, prepared by high-temperature combustion and fine grinding, which exhibited rapid adsorption kinetics (reaching equilibrium within 4 hours) and a substantial capacity of 12.56 mg/g at 50 mg/L initial boron concentration [68]. Optimal performance occurred at pH 6-8, with adsorption efficiency positively correlated to adsorbent dosage, confirming the practical potential of these modified agricultural materials for boron remediation applications.

- **Nanoparticles based adsorbents**

Nanoparticle-based adsorbents have shown exceptional potential for boron removal, leveraging their high surface area and reactivity. Iron oxide nanoparticles, for instance, achieve boron adsorption primarily through surface complexation and precipitation reactions, with enhanced capacity at lower pH levels due to their increasingly positive surface charge, which favors the uptake of negatively charged boron species [69]. Similarly, graphene oxide nanoparticles offer a highly effective two-dimensional structure rich in oxygen-containing functional groups, creating an optimal environment for boron adsorption [70]. Titanium dioxide nanoparticles (TiO_2 NPs) further demonstrate this capability, exhibiting a maximum adsorption capacity of 19.6 mg/g [71].

Magnetic nanoparticles, such as magnetite (Fe_3O_4), provide an additional advantage of facile separation via external magnetic fields. Studies report a remarkable adsorption capacity of 34.6 mg/g for boron removal, underscoring their practical utility [70]. Meanwhile, magnesium oxide (MgO)-based adsorbents have been extensively investigated for their boron affinity. The adsorption mechanism involves the formation of surface complexes between boron species and hydroxyl groups on MgO particles [72].

Recent advancements in MgO nanosynthesis have further improved performance. Ultrasonically synthesized MgO nanosheets, for example, exhibit significantly higher adsorption capacities compared to conventional MgO, attributed to their unique structure and increased surface area, which provide abundant active sites for boron binding [73]. Batch adsorption experiments confirm MgO's high efficiency, achieving up to 90% boron removal under optimized conditions (e.g., pH, contact time, and dosage) [74]. The adsorption mechanism, illustrated in Fig. 4, highlights the critical role of surface interactions in these processes.

Figure 4: Schematic diagram of boron adsorption and hydration of MgO [75].

Layered double hydroxides (LDHs) have emerged as highly effective adsorbents for boron removal, with their performance tunable through compositional and thermal modifications. In a study by [76], three distinct LDHs—comprising magnesium/aluminum (Mg/Al), magnesium/zinc (Mg/Zn), and magnesium/nickel (Mg/Ni) cations—were synthesized and calcined at varying temperatures to remove interlayer anions and generate oxide materials. The results revealed that calcination significantly enhanced boron sorption capacity across all LDH types, attributed to increased surface area and pore volume at higher temperatures.

The choice of divalent metal cation critically influenced adsorption performance. The Mg/Al LDH exhibited the highest boron uptake, followed by Mg/Ni and Mg/Zn variants, highlighting the role of cation-dependent surface properties in governing sorption behavior. This systematic comparison underscores the potential of tailored LDHs for efficient boron removal, with calcination temperature and cation selection serving as key optimization parameters.

- **Chelating synthetic resins**

Synthetic resins are widely regarded as one of the most effective and selective methods for boron removal from aqueous solutions, owing to their high efficiency and specificity. These resins consist of polymeric matrices functionalized with groups capable of complexing with boron ions, with the three primary types being anion exchange resins, chelating resins, and hybrid resins (which combine both mechanisms) [77]. Anion exchange resins operate through ionic exchange, utilizing functional groups such as strong base (quaternary ammonium) or weak base (tertiary amine) moieties to selectively capture boron species [78]. Chelating resins, including iminodiacetic acid (IDA), aminophosphonic acid (APA), and carboxymethylated varieties, employ covalent bonding for highly effective boron removal [79]. Of these, IDA resins have demonstrated particular promise due to their strong boron affinity, making them especially valuable for wastewater treatment and desalination applications [81,82]. Hybrid resins merge the advantages of both approaches, exhibiting superior selectivity and faster removal kinetics compared to single-mechanism resins, which has led to their widespread industrial adoption [80]. The versatility and tunability of these synthetic resins, achieved through careful selection of functional groups, make them indispensable for addressing boron contamination across diverse water treatment scenarios.

- **Clay materials**

Clay minerals possess negatively charged surfaces that effectively attract positively charged boron ions, with their adsorption capacity strongly dependent on surface area and porosity characteristics [83]. These properties make clay minerals particularly valuable for addressing boron contamination, which poses significant health and environmental risks when present at elevated concentrations in water sources [83]. Among the various clay minerals investigated—including montmorillonite, kaolinite, and bentonite—montmorillonite demonstrates superior boron adsorption performance due to its exceptional surface area and cation exchange capacity [83].

The adsorption mechanism primarily involves ion exchange between boron species and exchangeable cations present on clay surfaces, with process efficiency being highly pH-dependent [84]. Optimal boron removal typically occurs under acidic conditions (lower pH values), where the clay surface chemistry favors boron adsorption [84]. Beyond natural clays, research has shown that modified clay composites offer enhanced performance. Organo-clay modifications, for instance, significantly improve boron removal through increased surface interactions and expanded surface area [85].

The relationship between clay mineral properties and boron removal efficiency was thoroughly investigated by [86], demonstrating that increased surface area and porosity directly enhance adsorption capacity, with montmorillonite showing particular promise due to its expansive surface characteristics. Building on these findings, [87] specifically examined bentonite clay, revealing its exceptional boron adsorption capability through a unique intercalation mechanism where boron ions penetrate the clay's interlayer spaces, facilitated by its 2:1 layered structure and exchangeable cations. Further research by [88] on kaolinite clay identified surface hydroxyl groups as the primary active sites for boron complexation, with optimal adsorption occurring at near-neutral pH conditions where these hydroxyl groups are most reactive. Most significantly, [89] achieved remarkable improvements in boron removal by chemically modifying vermiculite and perlite clays with hexadecyltrimethylammonium (HDTMA) and glutamic acid (GA), which synergistically expanded the surface area while introducing new functional groups that enhanced both adsorption capacity and kinetics, as clearly illustrated in Fig. 5. These studies collectively establish that both natural and modified clay minerals, through their versatile surface chemistry and modifiable structures, represent highly effective and economically viable solutions for boron removal from contaminated water sources.

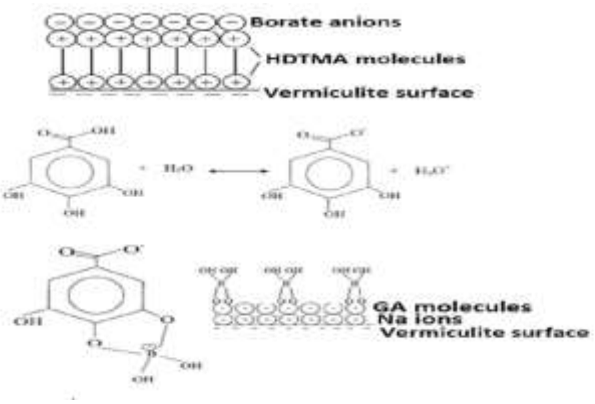

Figure 5: Boron adsorption on vermiculite using HDTMA and GA as the adsorption agent [89].

Table 3 summarizes the boron adsorption capacities of various adsorbents reported in recent literature. The compiled data demonstrate significant variations in performance across different material classes, including activated carbons, clay minerals, and synthetic resins. Isotherm analysis reveals that modified adsorbents typically exhibit enhanced capacities compared to their unmodified counterparts. The table particularly highlights the superior adsorption capabilities of specialty resins and nanostructured materials. These comparative results provide valuable insights for selecting optimal adsorbents based on specific water treatment requirements. The data underscore the importance of both material composition and surface functionalization in determining boron removal efficiency.

TABLE 3

Adsorption isotherms of boron for various adsorbents

Adsorbent	**Experimental Conditions**	**Equilibrium[a] / Maximum[b] Adsorption Capacity**	**Ref.**
CTAB-kaolin	Ci = 16.5 mg/L, pH = 2, time = 3 h, adsorbent dose = 2 g/L, T = 25°C	[a] 3.12 mg·g^{-1}	[90]
Bare TiO2	Ci = 16.50 mg/L, pH = 4, time = 4 h, adsorbent dose = 10 g/L, T = 45°C	[a] 0.672 mg·g^{-1}	[91]
CTAB-TiO2	Ci = 16.50 mg/L, pH = 4, time = 3.5 h, adsorbent dose = 6 g/L, T = 25°C	[a] 1.60 mg·g^{-1}	[91]
Bentonite	Ci = 120 mg/L, pH = 9, time=24 h, adsorbent dose = 50 g/L, T=25°C	[b] 0.51 mg·g^{-1}	[92]
Bentonite-FeCl3	Ci = 120 mg/L, pH = 9, time=24 h, adsorbent dose = 50 g/L, T=25°C	[b] 0.83 mg·g^{-1}	[92]
Kaolinite	Ci = 120 mg/L, pH = 9, time=24 h, adsorbent dose = 50 g/L, 25°C	[b] 0.60 mg·g^{-1}	[92]
Kaolinite-FeCl3	Ci = 120 mg/L, pH = 9, time=24 h, adsorbent dose = 50 g/L, T=25°C	[b] 0.80 mg·g^{-1}	[92]
Waste calcite	Ci = 120 mg/L, pH = 9, time=24 h, adsorbent dose = 50 g/L, T=25°C	[b] 1.05 mg·g^{-1}	[92]
Waste calcite-FeCl3	Ci = 120 mg/L, pH = 9, time=24 h, adsorbent dose = 50 g/L, T=25°C	[b] 1.60 mg·g^{-1}	[92]
Zeolite	Ci = 120 mg/L, pH = 9, time=24 h, adsorbent dose = 50 g/L, T=25°C	[b] 0.53 mg·g^{-1}	[92]
Zeolite-FeCl3	Ci = 120 mg/L, pH = 9, time=24 h, adsorbent dose = 50 g/L, T= 25°C	[b] 0.76 mg·g^{-1}	[92]
Magnesite and bentonite clay composite	Ci = 20 mg/L, pH = 11, time=30 min, adsorbent dose = 2 g/L, T=26 ◦C	[b] 4 mg·g^{-1}	[93]
Fly ash zeolite	Ci = 50 mg/L, pH = 7, time=0.5 h, adsorbent dose = 20 g/L, T=25 ◦C	[a] 2.3 mg·g^{-1}	[94]

F400 + xylitol	Ci = 60 mg/L, pH = 7, time= 4 h, adsorbent dose = 20 g/L, T=25 °C	^{a} 1.45 mg·g^{-1}	[95]
F400 + sodium gluconate	Ci = 60 mg/L, pH = 7, time= 4 h, adsorbent dose = 20 g/L, T=25 °C	^{a} 1.04 mg·g^{-1}	[95]
Cur-AC	Ci = 1000 mg/L, pH = 5.5, time=2 h, adsorbent dose = 40 g/L, T=25 °C	^{b} 5.0 mg·g^{-1}	[96]
CWZ-30	Ci= 30 mg/L, pH = 6, time= 2 h, adsorbent dose = 20 g/L, T=20 °C	^{a} 0.294 mg·g^{-1}	[97]

Overall, this review has highlighted critical knowledge gaps and practical challenges in the development and implementation of boron removal technologies. Although extensive laboratory-scale research has demonstrated the efficiency of various adsorbents, particularly bio-based and nanostructured materials, there remains a noticeable lack of pilot- and industrial-scale studies. This gap restricts the practical deployment of promising technologies and limits our understanding of real-world performance under variable water conditions, including high salinity and the presence of competing ions. Furthermore, many studies emphasize removal efficiency while overlooking essential parameters such as adsorbent regeneration, selectivity, and long-term stability factors that are vital for real-world applications.

Another major shortcoming is the absence of comprehensive comparative analysis between adsorption and non-adsorptive boron removal methods such as membrane filtration, ion exchange, and electrocoagulation. Each of these alternatives presents distinct advantages and limitations, and their comparison with adsorption could offer deeper insights into the most suitable technology for specific water treatment contexts. Reverse osmosis, for instance, shows high boron rejection but is energy-intensive and costly; ion exchange is selective but susceptible to fouling; and electrocoagulation shows promise but generates sludge and requires process optimization. Future studies should incorporate such comparisons to contextualize adsorption's position within the broader technological landscape.

Additionally, the economic feasibility and environmental sustainability of adsorbents are seldom addressed in depth. While some materials show excellent performance in lab settings, their scalability, production costs, energy demands, and environmental impacts are often unclear. High-performing nanomaterials may carry environmental risks due to toxic precursors or non-renewable inputs. Sustainable development of adsorbents should therefore prioritize raw materials that are abundant, low-cost, and environmentally benign. Life cycle assessments, cost-benefit analyses, and energy evaluations are necessary to ensure long-term applicability.

In summary, bridging the gap between laboratory research and real-world implementation requires interdisciplinary collaboration, inclusion of environmental and economic metrics, and increased emphasis on scale-up validation. Addressing these areas will be key to advancing boron removal technologies from theoretical exploration to practical, impactful water treatment solutions.

X. CONCLUSION

Boron contamination in water poses significant risks to human health and the environment, necessitating the development of efficient and scalable removal technologies. This review has explored various adsorbents and their mechanisms for removing boron from aqueous solutions, categorizing them by material type and performance characteristics. Among the techniques reviewed, adsorption remains one of the most promising due to its operational simplicity, potential cost-effectiveness, and adaptability to different water matrices. However, the current literature still lacks consistency in reporting adsorption capacities under comparable conditions, which hampers benchmarking across materials. Furthermore, despite the emergence of high-performing adsorbents such as modified biochars, metal oxides, and nanocomposites, their long-term stability, regeneration potential, and environmental impact require further validation. Most studies are limited to laboratory experiments, with little emphasis on real-world application or integration with existing water treatment infrastructure. Ultimately, while progress has been made in developing new adsorbent materials, translating these findings into scalable, sustainable, and economically viable solutions remains a central challenge that future research must address.

XI. RECOMMENDATIONS

Future research should prioritize the development of adsorbents that are not only effective but also sustainable and economically feasible. Special attention must be given to adsorbents derived from low-cost, abundant, and renewable resources, such as agricultural waste or industrial byproducts. Additionally, researchers should focus on enhancing regeneration performance and assessing adsorbent durability across multiple treatment cycles. Studies should also investigate the removal of boron under complex conditions, such as high-salinity environments or the presence of competing ions, to better simulate real-world scenarios. Incorporating economic analyses and life cycle assessments into experimental design will help determine the true viability of various materials. Pilot-scale and field-scale studies should be encouraged to evaluate operational challenges and maintenance needs. Moreover, future work should include systematic comparisons between adsorption and alternative technologies to provide a holistic view of their respective strengths and limitations. Establishing standardized testing protocols and reporting formats will also improve data comparability and foster collaboration across disciplines. These steps are essential for transitioning boron removal technologies from laboratory research to industrial implementation.

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