Journal of Ecohumanism
2024
Volume: 3, No: 7, pp. 3058 – 3073
ISSN: 2752-6798 (Print) | ISSN 2752-6801 (Online)
https://ecohumanism.co.uk/joe/ecohumanism
DOI: https://doi.org/10.62754/joe.v3i7.4704

A Review on Various Techniques for Boron Recovery: Focusing on Efficiency, Sustainability, Scalability, and Cost-Effectiveness

Muhammad Faseeh Memon[1], Zubair Ahmed Memon[2], Omar Shabbir Ahmed[3]

Abstract

Boron is a critical element extensively used across various industries—such as glass manufacturing, ceramics, agriculture, detergents, nuclear energy, and aerospace—due to its unique chemical and physical properties. However, its widespread industrial use has raised significant environmental concerns, particularly its accumulation in aquatic systems, posing risks to biodiversity, plant life, and human health. This review examines the impacts of boron pollution on aquatic organisms, plants, and humans, highlighting the necessity for effective recovery strategies. We provide a comprehensive analysis of boron recovery techniques—such as reverse osmosis, electrodialysis, nanofiltration, adsorption, membrane distillation, and leaching—focusing on their efficiency, sustainability, scalability, and cost-effectiveness. The evaluation compares each method's operational parameters, environmental impact, and economic feasibility. While methods like reverse osmosis and electrodialysis offer high removal efficiencies, they are often limited by operational costs and environmental drawbacks. Alternative methods like adsorption and nanofiltration present more sustainable and cost-effective options but may require optimization for large-scale applications. This review underscores the need for advanced, economically viable, and sustainable boron recovery technologies to mitigate environmental risks and comply with regulatory standards.

Keywords: *Boron Recovery, Wastewater Treatment, Reverse Osmosis, Electrodialysis, Nanofiltration, Adsorption, Membrane Distillation, Environmental Sustainability, Cost-Effectiveness, Scalability.*

Introduction

With the growing human population placing increasing demands on Earth's natural resources, issues like water pollution and contamination have become global concerns. Water, vital for humans, plants, and animals, is at the forefront of these challenges. Moreover, the global focus on climate change underscores the urgency of addressing environmental impacts caused by industrial activities (Siyal et al., 2021; Katar, 2022; Ghulam et al., 2022). Boron is a versatile element widely used in numerous industries, highlighting its importance in modern economies. As depicted in Figure 1, the demand for boron is experiencing significant growth across various sectors, particularly in waste management, energy storage, and the automotive industry, among others. (Aydin et al., 2020; Baskan & Atalay, 2014; Chang et al., 2008; K. Chen et al., 2015; Lu et al., 2018; Pan et al., 2009; G. Singh & Kumar, 2019; Smedskjær et al., 2011, 2015; Templeton et al., 2010; Woodring et al., 2010; Zhang et al., 2020). The utility of boron extends to industries such as glass manufacture, ceramics, fertilizers, and detergents, where it improves the qualities and performance of these materials. Boron plays a key role in nuclear energy, particularly in specialized industries, by functioning as a neutron absorber in reactors. This function is essential for managing nuclear fission processes. Boron Neutron Capture Therapy (BNCT) demonstrates this utilization, in which boron-based chemicals are specifically delivered into cancerous cells and then exposed to neutron radiation. This interaction produces alpha particles that specifically target and eliminate cancerous cells while preserving nearby healthy tissues, thus reducing unintended harm (J. Chen et al., 2019). In addition, boron fibers are employed in the aerospace sector to produce lightweight materials with great strength. These materials are crucial for enhancing the performance and efficiency of aircraft vehicles (Feng et al., 2022). Researchers are also investigating the potential of boron compounds in drug delivery systems, utilizing its distinctive chemical features to enhance targeted therapeutics (Al-Ejji, 2023a).

[1] Department of Civil and Environmental Engineering, Universiti Teknologi Petronas, 32610 Seri Iskandar, Perak, Malaysia, Email: muhammad_20001449@utp.edu.my.
[2] Professor, Department of Engineering Management, College of Engineering, Prince Sultan University, Riyadh, Saudi Arabia, Email: zamemon@psu.edu.sa, (Corresponding Author)
[3] Department of Engineering Management, College of Engineering, Prince Sultan University, Riyadh, Saudi Arabia, Email: Eoahmed@psu.edu.sa.

Journal of Ecohumanism
2024
Volume: 3, No: 7, pp. 3058 – 3073
ISSN: 2752-6798 (Print) | ISSN 2752-6801 (Online)
https://ecohumanism.co.uk/joe/ecohumanism
DOI: https://doi.org/10.62754/joe.v3i7.4704

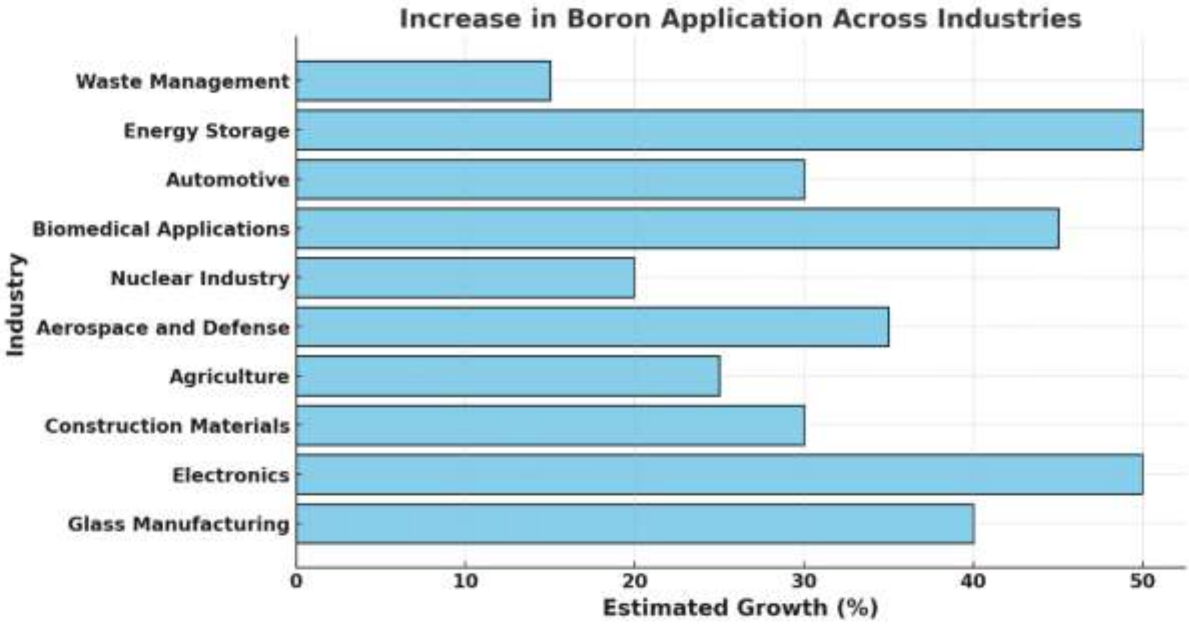

Figure 1: Increase in Boron Application Across Industries

Nevertheless, the ecological consequences of boron discharge are progressively becoming a subject of apprehension. Boron is mainly introduced into aquatic systems through anthropogenic activities, such as mining, glass and ceramics production, and detergent manufacturing. Wastewater with high levels of boric acid (H_3BO_3) or borates ($B(OH)_4^-$) is produced during the extraction and processing of borates. These compounds exhibit high solubility, enabling them to readily spread in water bodies. As a result, they can persist and accumulate over time, causing substantial environmental deterioration, especially in areas with intensive boron mining activities (X. Liu et al., 2022). The enduring presence of boron in aquatic systems presents a peril to biodiversity, as elevated levels can disturb the ecological equilibrium and inflict harm upon aquatic creatures (Srivastava & Wanjari, 2023).

Agriculture is a major contributor to boron pollution. Plant development is often improved by using fertilizers that contain boron, particularly in soils that lack this element. Although boron is necessary for the well-being of plants, excessive use or improper handling can lead to the leaching of boron into adjacent water bodies. In regions characterized by extensive irrigation methods, boron has the potential to move from the soil into groundwater sources, resulting in the buildup of boron that is difficult to address and resolve (Al-Ejji, 2023a). Excessive quantities of boron in water systems can have detrimental effects on aquatic life, causing harm to their health and ability to reproduce. Additionally, it can lead to a decline in soil fertility over time, ultimately affecting agricultural productivity (Khaliq et al., 2018).

Furthermore, the wastewater produced by industrial processes, namely in the glass and ceramics industries, contains significant amounts of boron. These businesses employ boron to improve the mechanical and thermal characteristics of their products. However, the resulting wastewater often contains high levels of boron that traditional municipal treatment facilities find challenging to efficiently remove (X. Liu et al., 2022). Boron is commonly found in both household and industrial detergents, where it is used to reduce water hardness and improve cleaning effectiveness. The effluent from these sources exacerbates the enduring pollution of water systems, as current treatment procedures are insufficiently engineered to eliminate boron (Al-Ejji, 2023b). In order to protect the ecosystem and ensure its health, it is imperative to create sophisticated treatment techniques that can effectively deal with boron pollution in wastewater. The consequences of boron pollution are exacerbated by its interaction with other contaminants in the environment. For example, when boron is present in agricultural runoff, it can worsen the toxicity of other pollutants, resulting in combined effects that may increase the hazards to both human health and natural systems (Srivastava & Wanjari, 2023).

Journal of Ecohumanism
2024
Volume: 3, No: 7, pp. 3058 – 3073
ISSN: 2752-6798 (Print) | ISSN 2752-6801 (Online)
https://ecohumanism.co.uk/joe/ecohumanism
DOI: https://doi.org/10.62754/joe.v3i7.4704

In response to these environmental concerns, prominent regulatory bodies have enforced limits and limitations on the utilization and release of boron. The Environmental Protection Agency (EPA), a federal agency in the United States, has issued health advisories regarding boron, as part of its responsibility to regulate environmental contaminants and safeguard human health. The EPA advises that the content of boron in drinking water should not surpass 2.4 mg/L. Elevated amounts of boron may present health hazards, especially to vulnerable groups like children and pregnant women (Al-Ejji, 2023a). This recommendation is a component of the EPA's comprehensive initiative to guarantee the safety of drinking water and mitigate the ecological consequences of industrial and agricultural practices. In the European Union, the Registration, Evaluation, Authorization, and Restriction of Chemicals (REACH) is a regulatory framework that ensures chemical safety. It requires comprehensive safety assessments for boron and its compounds to evaluate their environmental and health effects before granting authorization for their use (Al-Ejji, 2023b). This framework ensures that the production and use of boron-containing products do not pose unacceptable risks to humans or the environment.

The Environmental Quality Act of 1974 is enforced by the Department of Environment (DOE) in Malaysia, which operates under the Ministry of Natural Resources and Environment. This legislation has provisions regarding the release of boron, specifically targeting sectors such as mining and processing. The DOE ensures adherence to environmental regulations in order to safeguard the nation's water resources against boron contamination (Al-Ejji, 2023a). The global regulatory measures emphasize the need to maintain a balance between the industrial applications of boron and its environmental consequences. The growing demand for boron in many industries highlights the importance of strict restrictions. This demand has resulted in increased attention to its environmental impact and the need for sustainable procedures in its extraction and utilization (Al-Ejji, 2023a).

Due to the peculiar chemical characteristics and solubility of boron, there is no straightforward or universally effective method for removing it from water and wastewater. Reverse Osmosis (RO), a frequently employed method, is typically inadequate due to the similarity in size between boron molecules and water molecules. This similarity allows boron molecules to flow through the RO membranes, leading to a decrease in removal effectiveness (X. Liu et al., 2022). The mean concentration of boron in seawater is approximately 5 mg/L; however, in certain geothermal waters, concentrations can reach up to 119 mg/L, underscoring the difficulty of efficiently eliminating boron from these sources (Lyu et al., 2017). Co-precipitation with metal hydroxides, as another technique, is inefficient and environmentally unsustainable due to its high reagent consumption and generation of substantial non-recyclable waste, which raises worries about secondary pollution. Conventional ion exchange methods encounter difficulties due to the presence of boron in non-ionic forms at normal pH values in the environment. This reduces the effectiveness of ion exchange resins in removing boron from water (X. Li et al., 2011).

Various supplementary techniques, including adsorption, membrane filtration (including nanofiltration and ultrafiltration), and electrodialysis, have been examined with different levels of achievement. The utilization of modified activated carbon and bio-based adsorbents for the process of adsorption has displayed promise, notably with substances such as chitosan and titanium dioxide, which have exhibited substantial capacities for boron adsorption (Gujar et al., 2022; Jaouadi, 2020). Nevertheless, the efficacy of these adsorbents may decline as temperatures rise, mostly due to alterations in viscosity and resin characteristics (Altınbaş et al., 2022). Membrane technologies and electrodialysis have the ability to efficiently eliminate boron in some circumstances. However, their extensive energy demands frequently hinder their economic viability for large-scale implementations (Soysüren et al., 2023). A recent study conducted by Altınbaş et al. (2022) has emphasized a new hybrid adsorption-electrodialysis technology that greatly improves the removal of boron from geothermal brine, especially when there are other ions present. Striking a balance between economic feasibility and environmental sustainability is a major hurdle, as numerous current approaches are either excessively costly or harmful to the environment (Akpinar et al., 2021; Soysüren et al., 2023).

Therefore, the objective of this review paper is twofold: first, to highlight the significance of boron recovery, and second, to conduct a comprehensive analysis of the various techniques currently employed for boron recovery, with a particular focus on their cost-effectiveness, sustainability and scalability.

Volume: 3, No: 7, pp. 3058 – 3073
ISSN: 2752-6798 (Print) | ISSN 2752-6801 (Online)
https://ecohumanism.co.uk/joe/ecohumanism
DOI: https://doi.org/10.62754/joe.v3i7.4704

Effects on Aquatic Life

Interaction of Boron with Aquatic Chemistry

Boron is an abundant element that has a vital function in the growth of plants, especially in minute quantities. Nevertheless, the level of toxicity of the substance escalates considerably at elevated concentrations, particularly in aquatic ecosystems. Industrial discharges, agricultural runoff, and mining operations are the main causes of boron contamination in water systems. These activities lead to the accumulation of boron in aquatic ecosystems. Once introduced into these ecosystems, boron persists as a contaminant because of its high solubility and capacity to stay floating in water, hence endangering aquatic creatures at different trophic levels. The toxicity of boron exhibits variability and is subject to multiple influencing factors, such as its chemical composition, ambient parameters like pH and temperature, and the varying tolerance thresholds of different aquatic species (X. Liu et al., 2022; Yeşilbudak, 2024).

In aquatic environments, boron is primarily found as boric acid (H_3BO_3), particularly at pH levels that are neutral or mildly acidic. However, at alkaline conditions, it undergoes dissociation, resulting in the formation of borate ions ($B(OH)_4^-$). The bioavailability and toxicity of water to aquatic species are greatly influenced by the specific type of boron it contains. For example, in less acidic conditions, organisms can absorb boric acid more easily, which results in higher levels of toxicity. Under alkaline or saline conditions, borate ions can form interactions with other ions or organic matter, leading to a decrease in the bioavailability of boron and, in certain situations, its overall toxicity (X. Liu et al., 2022; Mehanathan et al., 2022). Temperature and salinity are important environmental factors that significantly affect the behavior of boron in aquatic systems. Higher temperatures increase the solubility of boron, while elevated salinity promotes the formation of stable boron complexes, which in turn affects its bioavailability.

Algae and Microorganisms

Algae and microbes are essential parts of aquatic ecosystems, and their susceptibility to boron varies greatly. Although a little quantity of boron is essential for the growth of specific types of algae and cyanobacteria, higher levels can impede cellular activities and hinder growth. Studies have demonstrated that *Chlorella vulgaris*, a prevalent freshwater alga, undergoes oxidative stress and exhibits decreased growth when exposed to boron concentrations as low as 5 mg/L. Oxidative stress is linked to impaired nutritional absorption and elevated levels of malondialdehyde (MDA), a biomarker that indicates oxidative damage (Hasanein, 2024; Ramírez-Coronel et al., 2023). Similarly, cyanobacteria like *Spirulina platensis* and *Scenedesmus* sp. have suppressed photosynthesis and decreased nutritional absorption when subjected to boron levels ranging from 8 to 12 mg/L (Pratikno et al., 2019; Javed et al., 2021; Yeşilbudak, 2024).

Boron interferes with nitrogen fixation, a crucial mechanism for sustaining productivity in aquatic habitats, in cyanobacteria such as *Nostoc* sp. The disturbance can lead to a series of consequences on the process of nutrient cycling and the overall well-being of the ecosystem. Additionally, species that create toxic algal blooms, such as *Microcystis aeruginosa*, are highly sensitive to boron concentrations as low as 4 mg/L. This sensitivity can prevent the formation of blooms and consequently have a significant influence on ecosystems that depend on these species (Assunção et al., 2017; J. Liu et al., 2021). Boron toxicity has consequences that go beyond individual species, as it can impact community dynamics and the general functioning of aquatic ecosystems. This emphasizes the importance of conducting thorough studies of boron levels in these habitats. The varying sensitivity of different algal and microbial species to boron toxicity is summarized in Table 1, which presents the species or organisms affected, the boron concentration (mg/L), their tolerance or sensitivity levels, the observed effects, and relevant references, highlighting the need for targeted studies on boron levels in aquatic environments.

Journal of Ecohumanism
2024
Volume: 3, No: 7, pp. 3058 – 3073
ISSN: 2752-6798 (Print) | ISSN 2752-6801 (Online)
https://ecohumanism.co.uk/joe/ecohumanism
DOI: https://doi.org/10.62754/joe.v3i7.4704

Table 1: Boron Tolerance Limits and Impact Data for Algae and Microorganisms

Species/Organism	Boron Concentration (mg/L)	Tolerance/Sensitivity	Effects Observed	Reference
Chlorella vulgaris	5–10	Sensitive	Reduced growth, metabolic disruptions	Hasanein (2024); Ramírez-Coronel et al. (2023)
Spirulina platensis	8–12	Moderately sensitive	Growth inhibition, metabolic disturbances	Pratikno et al. (2019)
Scenedesmus sp.	10	Moderately sensitive	Disrupted chlorophyll production	Assunção et al. (2017)
Chlamydomonas reinhardtii	15	Moderately sensitive	Reduced respiration, decreased biomass	Simulation of the Suppressive Effect of Zinc on Cyanobacteria in Paper Mill Wastewater (2019)
Nostoc sp. (Cyanobacteria)	6–9	Sensitive	Impact on nitrogen fixation, reduced growth	Kondzior & Butarewicz (2018)
Microcystis aeruginosa	4–6	Highly sensitive	Inhibition of algal bloom formation	Assunção et al. (2017); J. Liu et al. (2021)

Impact of Boron on Fish Species by Habitat Type

Freshwater Fish

The study of boron's effects on fish species in several types of habitats, such as freshwater, brackish water, and saltwater, has gained attention due to its significant consequences for aquatic ecosystems. Boron contamination primarily originates from industrial discharges, agricultural runoff, and natural geological processes. The impact on aquatic life varies depending on the tolerance of different species and the prevailing environmental conditions (X. Liu et al., 2022).

Freshwater fish species, such as Rainbow Trout (*Oncorhynchus mykiss*), Goldfish (*Carassius auratus*), and Common Carp (*Cyprinus carpio*), are particularly sensitive to boron contamination. The sensitivity is mostly due to the neutral to slightly acidic pH values commonly found in freshwater habitats. In these situations, boron is primarily present as boric acid (H_3BO_3), which is more easily absorbed and harmful to aquatic organisms (Ball et al., 2012). Studies have shown that Rainbow Trout undergo considerable physiological stress when exposed to boron levels higher than 5 mg/L, leading to a decrease in red blood cell counts and impaired liver function (Juszczak et al., 2020; O. McGlade et al., 2021). Goldfish have shown reduced growth and reproductive success when exposed to boron levels as low as 4 mg/L, indicating their susceptibility to this pollutant (Brdar-Jokanović, 2020; Rani, 2023). Even though Common Carp exhibit a somewhat higher tolerance, they still experience physiological disturbances at concentrations of approximately 8 mg/L (Brdar-Jokanović, 2020; Rani, 2023).

Journal of Ecohumanism
2024
Volume: 3, No: 7, pp. 3058 – 3073
ISSN: 2752-6798 (Print) | ISSN 2752-6801 (Online)
https://ecohumanism.co.uk/joe/ecohumanism
DOI: https://doi.org/10.62754/joe.v3i7.4704

Brackish Water Fish

Fish species that live in brackish water habitats, including the Banded Killifish (*Fundulus diaphanus*) and Tilapia (*Oreochromis* spp.), are more resistant to boron contamination. Brackish habitats, which possess qualities of both freshwater and saltwater, have distinct attributes that can counteract the harmful effects of boron. Tilapia can withstand boron levels of up to 9 mg/L; however, extended exposure to such levels can cause metabolic strain and decrease reproductive capacity (Peterson, 2023; Rani, 2023). Similarly, *Fundulus diaphanus* has been observed to tolerate boron concentrations as high as 10 mg/L, but prolonged exposure leads to alterations in behavior and reduced survival rates (Brdar-Jokanović, 2020; Rani, 2023).

Saltwater Fish

Saltwater fish species such as Salmon (*Salmo* spp.) and Catfish (*Ictalurus* spp.) have varying levels of tolerance to boron pollution. The alkaline and saline characteristics of saltwater habitats decrease the bioavailability of boron, which predominantly occurs as borate ions ($B(OH)_4^-$), a less harmful form for aquatic organisms (X. Liu et al., 2022). Catfish have the ability to tolerate boron concentrations of up to 12 mg/L; however, prolonged exposure to these levels can compromise their immune systems and result in difficulties with reproduction (Dhamotharan et al., 2023; Rani, 2023). Salmon, although more resistant than their freshwater counterparts, still demonstrate indications of physiological strain and disturbances in metabolism at concentrations of 6 mg/L (Dhamotharan et al., 2023; Rani, 2023). Table 2 outlines the boron tolerance and environmental impact on various fish species, detailing the fish species affected, their water type, boron tolerance levels (mg/L), the observed effects, and the relevant references, providing insight into how boron contamination impacts aquatic life across different habitats.

Table 2: Boron Tolerance and Environmental Impact on Fish Species

Fish Species	Water Type	Boron Tolerance (mg/L)	Effects Observed	Reference
Rainbow Trout	Freshwater	5	Reduced red blood cells, impaired liver	Juszczak et al. (2020); O. McGlade et al. (2021)
Zebrafish	Freshwater	7	Developmental abnormalities	Peterson (2023); Rani (2023)
Goldfish	Freshwater	4	Impaired growth, reduced reproduction	Brdar-Jokanović (2020); Rani (2023)
Common Carp	Freshwater	8	Physiological stress, impaired immunity	Brdar-Jokanović (2020); Rani (2023)
Bluegill	Freshwater	11	Metabolic disruptions, decreased growth	Brdar-Jokanović (2020); Rani (2023)
Fundulus diaphanus	Brackish Water	10	Behavioral changes, lower survival	Brdar-Jokanović (2020); Rani (2023)
Tilapia	Freshwater/Brackish	9	Metabolic stress, impaired feeding	Peterson (2023); Rani (2023)
Salmon	Saltwater	6	Physiological stress, reduced growth	Dhamotharan et al. (2023); Rani (2023)
Catfish	Freshwater/Saltwater	12	Weakened immunity, reproductive challenges	Dhamotharan et al. (2023); Rani (2023)

Journal of Ecohumanism
2024
Volume: 3, No: 7, pp. 3058 – 3073
ISSN: 2752-6798 (Print) | ISSN 2752-6801 (Online)
https://ecohumanism.co.uk/joe/ecohumanism
DOI: https://doi.org/10.62754/joe.v3i7.4704

Fish Species	Water Type	Boron Tolerance (mg/L)	Effects Observed	Reference
Brown Trout	Freshwater	7	Reduced survival with prolonged exposure	Dhamotharan et al. (2023); Hessenauer & Wehrly (2022)

Figure 2 presents the relationship between increasing boron concentrations and the corresponding mortality rates observed in different fish species. The figure compares the boron sensitivity of species such as Rainbow Trout, Goldfish, Zebrafish, Tilapia, Common Carp, Fundulus diaphanus, and Salmon. The data, adapted from various studies (Aliem al., 2022; MacCormack et al., 2021; Yang, 2023), provides a comprehensive overview of the lethal effects of boron exposure across diverse aquatic environments. The x-axis denotes boron concentrations (mg/L), while the y-axis reflects the mortality rate (%) for each species at varying levels of exposure.

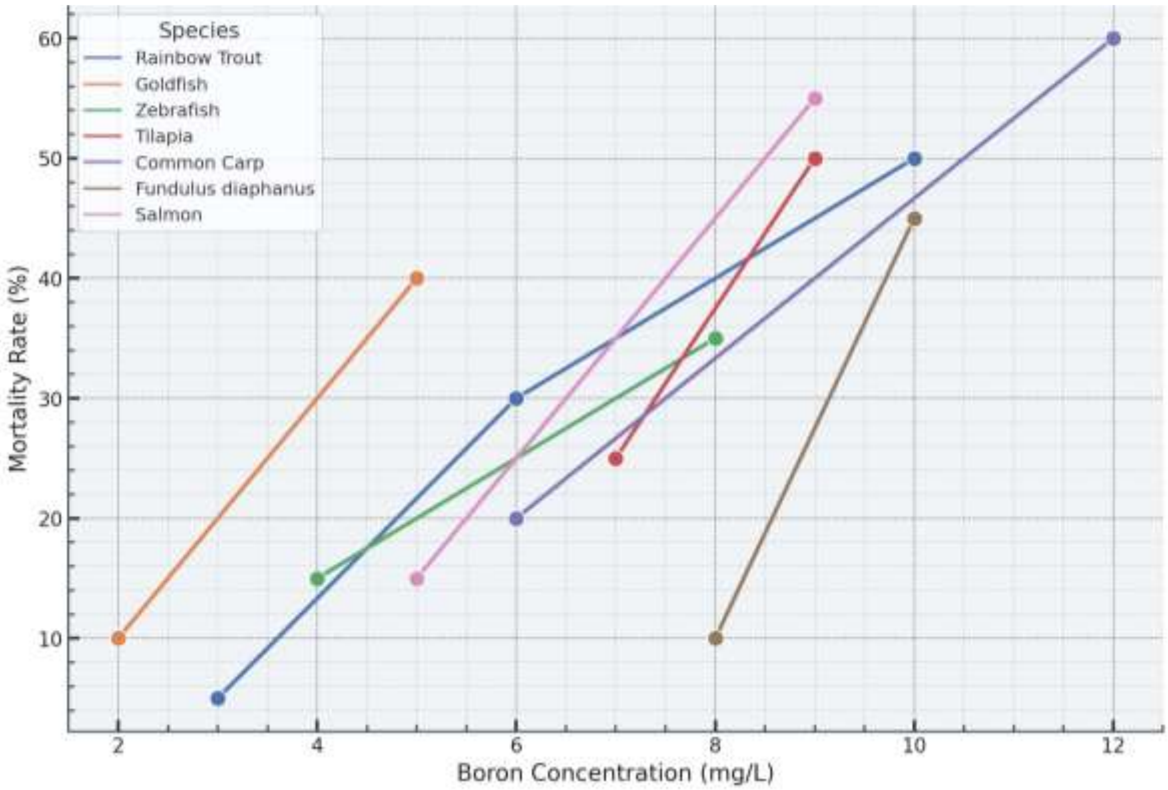

Figure 2: Impact of Boron Concentration on Mortality Rate Across Fish Species

It is evident from Figure 2 that an increase in boron concentration consistently results in elevated mortality rates among all species, although the sensitivity to boron varies. Goldfish emerge as the most sensitive species, with mortality rates climbing to 40% at a relatively low concentration of 5 mg/L. This heightened sensitivity is consistent with findings by Aliem al. (2022), who observed significant growth and reproductive impairments in Goldfish even at moderate boron levels. On the other hand, species like Tilapia and Fundulus diaphanus demonstrate higher tolerance, exhibiting significant mortality only after boron concentrations exceed 7-8 mg/L. Moreover, species such as Common Carp and Salmon display increased resilience at lower boron levels, but their mortality sharply rises once concentrations surpass 9 mg/L, suggesting that prolonged exposure to elevated boron concentrations remains harmful across species.

Impact of Boron on Plant Life

Journal of Ecohumanism
2024
Volume: 3, No: 7, pp. 3058 – 3073
ISSN: 2752-6798 (Print) | ISSN 2752-6801 (Online)
https://ecohumanism.co.uk/joe/ecohumanism
DOI: https://doi.org/10.62754/joe.v3i7.4704

Boron is acknowledged as a crucial element for the growth and development of plants, playing a central part in several physiological processes such as the creation of cell walls, transportation of sugars, and reproductive functions. It is essential for preserving the strength and stability of cell walls, aiding in the transportation of carbohydrates inside the plant, and guaranteeing the correct operation of reproductive organs including pollen tubes (Brdar-Jokanović, 2020; A. K. Singh et al., 2020). Boron is largely taken in the form of boric acid and plays a crucial role in several metabolic processes, such as nucleic acid and protein metabolism, as well as root growth and flower creation (Brdar-Jokanović, 2020; Ramírez Revilla, 2024). Nevertheless, it is crucial to meticulously regulate the levels of boron in soil and water, as plants necessitate it solely in minuscule quantities. Although low amounts of boron have positive effects, high levels can cause toxicity, which can have negative consequences on plant health and productivity (Brdar-Jokanović, 2020; Sagwal, 2023).

High levels of boron in soil can cause leaf damage, such as burning, yellowing, and death of tissue, especially at the edges of the leaves. Elevated concentrations of boron disturb cellular processes and hinder the absorption of vital nutrients by impeding the root systems' capacity to take in other critical elements (Güler, 2021). Plant species differ in their susceptibility to boron toxicity, with certain species being particularly susceptible while others have better tolerance. The variability is especially noticeable in dry places where irrigation water may have high levels of boron (Rani, 2023). For example, susceptible crops may display noticeable signs like leaf scorch and stunted growth. In more severe instances of boron toxicity, it can delay root development, affect the processes of flowering and fruiting, and eventually decrease agricultural yields (Güler, 2021; Ijaz et al., 2023).

The tolerance of a plant towards boron is mostly determined by its species, exhibiting significant variability in tolerance levels among different agricultural crops. Species that are tolerant to boron can endure larger concentrations without experiencing harm, but species that are sensitive to boron can be negatively impacted even by small increments in boron levels (Qu, 2024). Studies indicate that carrots can withstand boron levels of up to 4 mg/L, but oranges are susceptible to levels as low as 1 mg/L (Díaz, 2023). The need to choose suitable crop types for growing in boron-affected soils is emphasized by this differential tolerance. This is especially crucial in areas where boron accumulation is a concern because of irrigation methods (Νικολάου et al., 2020). Table 3 presents boron tolerance limits for different agricultural crops, categorized by tolerance levels, boron concentration (mg/L), and specific crop types, highlighting how varying boron concentrations affect crop sensitivity and agricultural productivity.

Table 3: Boron Tolerance Limits for Different Agricultural Crops (Ezechi et al., 2011)

Tolerance	**Boron Concentration (mg/L)**	**Agricultural Crops**
Extremely sensitive	< 0.5	Blackberry, Lemon
Very sensitive	0.5 - 0.75	Avocado, Grapefruit, Orange, Apricot, Peach, Cherry
Sensitive	0.75 - 1.0	Plum, Persimmon, Fig, Grape, Walnut, Pecan, Onion
Moderately sensitive	1.0 - 2.0	Garlic, Sweet Potato, Wheat, Sunflower, Bean varieties
Tolerant	4.0 - 6.0	Alfalfa, Parsley, Beet varieties, Tomato
Very tolerant	6.0 - 10.0	Sorghum, Cotton, Celery
Extremely tolerant	10.0 - 10.5	Asparagus

Impact of Boron in Drinking Water on Human Health

High concentrations of boron in drinking water can have significant adverse effects on human health. The World Health Organization (WHO) has established a guideline limit of 2.4 mg/L for boron in drinking water, with a more stringent recommendation of 0.5 mg/L due to potential health risks associated with higher concentrations (Akpinar et al., 2021; Baskan & Atalay, 2014; L. Li et al., 2022). Epidemiological

Journal of Ecohumanism
2024
Volume: 3, No: 7, pp. 3058 – 3073
ISSN: 2752-6798 (Print) | ISSN 2752-6801 (Online)
https://ecohumanism.co.uk/joe/ecohumanism
DOI: https://doi.org/10.62754/joe.v3i7.4704

studies have indicated that excessive boron exposure can lead to various health issues, including reproductive disorders, neurological impairments, and developmental toxicity (Baskan & Atalay, 2014; L. Li et al., 2022; Müezzinoğlu et al., 2011). For instance, studies have shown that boron levels exceeding 1 mg/L are associated with increased risks of infertility and low fetal weight (Baskan & Atalay, 2014; L. Li et al., 2022).

The health impacts of boron exposure are particularly concerning in regions where drinking water boron concentrations are significantly elevated. For example, in some areas of Turkey, boron levels in drinking water have been reported as high as 29 mg/L, leading to increased incidences of reproductive health issues and neurological disorders (Kluczka et al., 2021). Furthermore, chronic exposure to boron has been linked to cardiovascular diseases and mental deficiencies (Baskan & Atalay, 2014; Müezzinoğlu et al., 2011). The toxicological effects of boron can manifest through symptoms such as nausea, vomiting, diarrhea, and dermatitis, which are indicative of boron poisoning (Cho et al., 2015).

To illustrate the relationship between boron concentration and associated health risks, the Figure 3 has been created using the facts and figures from the following studies Akpinar et al. (2021), Baskan & Atalay (2014), Cho et al. 2015, Kluczka et al. (2021), L. Li et al. (2022), Müezzinoğlu et al. (2011) and World Health Organization (2011)

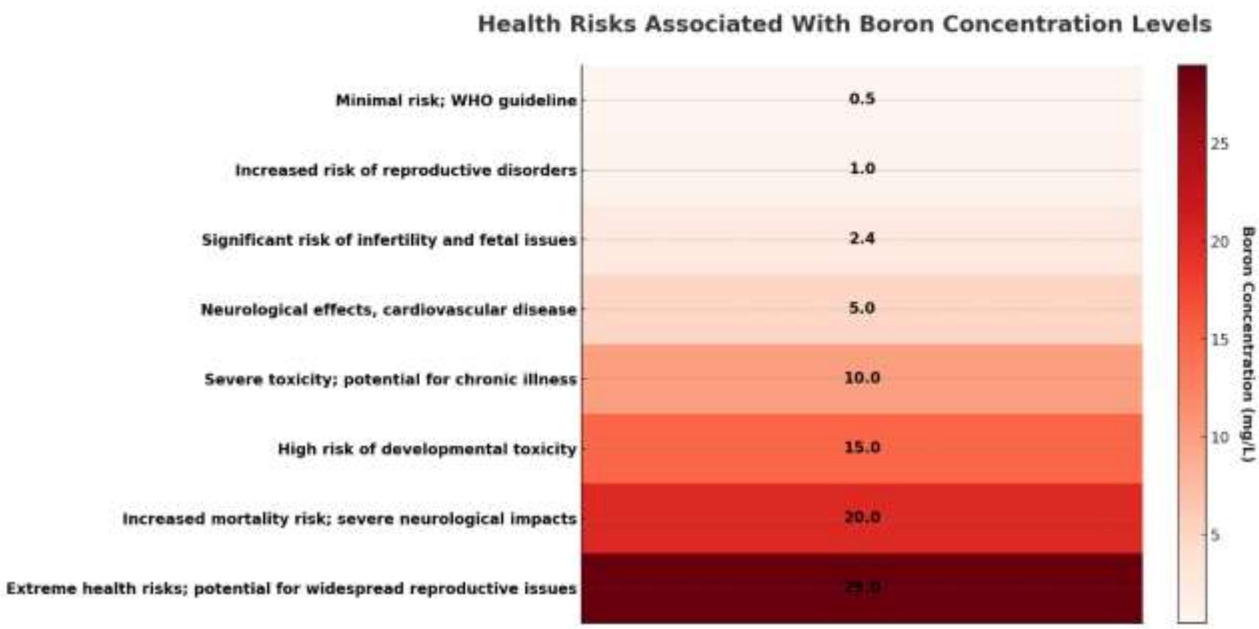

Figure 3: Relationship Between Boron Concentration in Drinking Water and Associated Health Risks

Review of Boron Recovery Techniques

A variety of techniques have been developed for boron recovery, each designed to address specific types of wastewater or industrial effluents. These methods range from more traditional approaches such as selective ion exchange and leaching to advanced technologies like membrane distillation and electrodialysis. Each technique offers unique advantages and faces particular challenges in terms of efficiency, cost, and sustainability. Table 4 provides an overview of the primary boron recovery techniques, highlighting their source applications, scalability, and relevant references.

Journal of Ecohumanism
2024
Volume: 3, No: 7, pp. 3058 – 3073
ISSN: 2752-6798 (Print) | ISSN 2752-6801 (Online)
https://ecohumanism.co.uk/joe/ecohumanism
DOI: https://doi.org/10.62754/joe.v3i7.4704

Table 4: Overview of the Primary Boron Recovery Techniques

Technology	Source	Scale	Reference
Reverse Osmosis (RO)	Produced water, Wastewater	Industrial	(Jeong et al., 2023; X. Liu et al., 2022; Sun et al., 2022)
Electrodialysis (ED)	Wastewater	Laboratory/Industrial	(Guesmi et al., 2020; Nagasawa et al., 2011)
Nanofiltration (NF)	Produced water	Industrial	(Jeong et al., 2023; Richards et al., 2010)
Adsorption	Wastewater	Laboratory/Industrial	(Baskan & Atalay, 2014; Ersan & Pinarbasi, 2011; Saleh Al-dhawi et al., 2023)
Membrane Distillation (MD)	Wastewater	Industrial	(Alkhudhiri et al., 2020)
Leaching	Wastewater	Laboratory	(Samatya et al., 2012; Tsai & Lo, 2013)

Reverse Osmosis (RO)

Reverse osmosis is widely used for boron removal from water through a semi-permeable membrane that applies pressure to overcome osmotic pressure. Despite its popularity, boron presents a challenge for conventional RO systems because boric acid ($B(OH)_3$), the dominant species at neutral pH, can pass through the membrane. To enhance boron rejection, system parameters such as pH adjustment are employed to convert boron into its negatively charged form, borate ions ($B(OH)_4^-$). This enhances membrane retention, but even with improvements, RO systems often require additional stages or hybrid approaches to achieve optimal boron removal rates.

Electrodialysis (ED)

Electrodialysis relies on an electric field to drive ions across ion-exchange membranes. With the use of bipolar membranes, ED can convert boron species into more easily removable forms. Studies have demonstrated ED's capacity to remove up to 90% of boron, making it suitable for industrial wastewater treatment. However, the efficiency of ED is influenced by the pH, boron concentration, and competing ions in the wastewater, which can affect its overall performance.

Nanofiltration (NF)

Nanofiltration sits between ultrafiltration and reverse osmosis in terms of selectivity, effectively removing divalent and larger monovalent ions while allowing smaller ions to pass. For boron recovery, NF is typically more effective at higher pH levels where boron exists as borate ions. Operational flexibility and lower energy requirements make NF an attractive option, although its efficiency can be enhanced when combined with other treatment techniques.

Adsorption

Adsorption involves the use of various materials like activated carbon and ion-exchange resins to capture boron from water. Adsorbents like DIAION™ CRB05 have been developed to selectively remove boron, making this process effective in both laboratory and industrial scales. The adsorption process is sensitive to factors such as pH and contact time, and while it offers significant potential for boron removal, the need for frequent adsorbent regeneration can raise operational costs.

Journal of Ecohumanism
2024
Volume: 3, No: 7, pp. 3058 – 3073
ISSN: 2752-6798 (Print) | ISSN 2752-6801 (Online)
https://ecohumanism.co.uk/joe/ecohumanism
DOI: https://doi.org/10.62754/joe.v3i7.4704

Membrane Distillation (MD)

Membrane distillation is a thermal separation process that uses hydrophobic membranes to allow water vapor to pass while rejecting liquid boron-containing water. MD works well at lower pressures and temperatures compared to conventional distillation, making it an energy-efficient option, especially when waste heat is available. However, membrane fouling and the need for pre-treatment can limit its widespread adoption.

Leaching

Leaching is a technique employed for extracting soluble boron from solids using solvents or acids. This method is commonly applied to polluted soils or solid waste materials. Parameters such as solvent choice, contact duration, and temperature play key roles in the efficiency of boron recovery. While effective, leaching carries risks related to environmental contamination if not properly managed.

Efficiency of Boron Recovery Techniques

As demonstrated in Figure 4, each method has a distinct range of efficiency, measured in terms of the percentage of boron removal. Reverse Osmosis (RO) exhibits the highest efficiency, with removal rates often exceeding 90%. This is followed closely by Electrodialysis (ED), which can achieve efficiencies up to 90% under optimal conditions. Nanofiltration (NF) and Adsorption techniques fall within the intermediate efficiency range of 60% to 85%, making them viable but slightly less effective options. Membrane Distillation (MD) and Leaching show the lowest maximum efficiency, typically around 70%, which may limit their utility for applications requiring high boron removal rates. The variation in efficiency underscores the importance of selecting the right technique based on the boron concentration in the effluent and the desired removal outcomes.

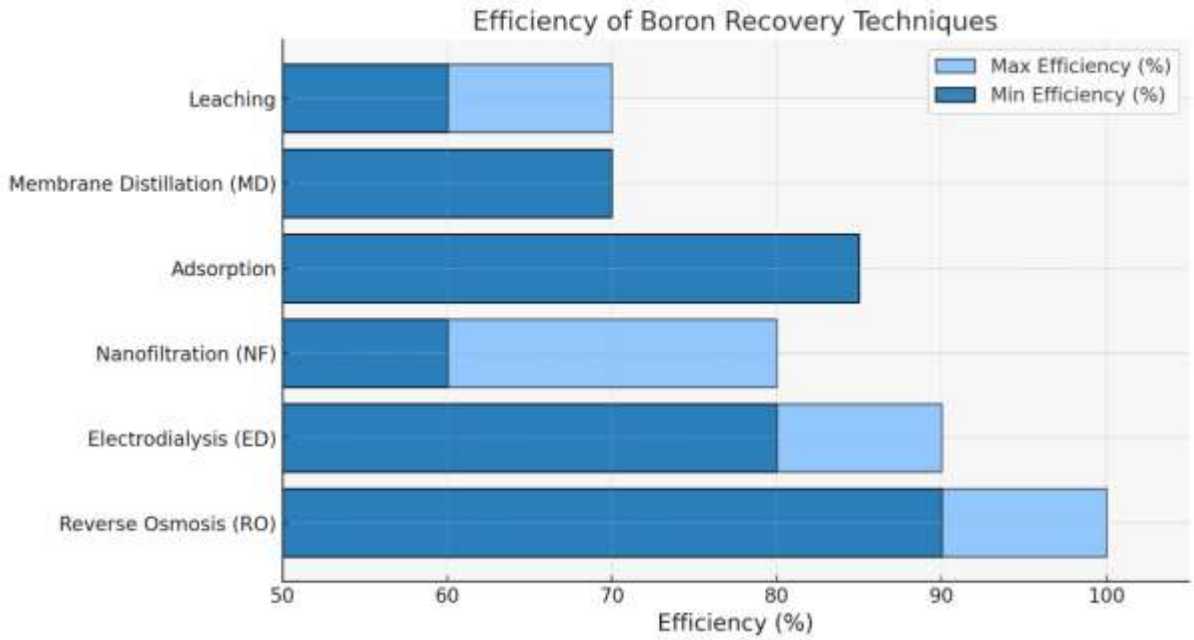

Figure 4: Efficiency of Various Boron Recovery Techniques

Cost-Effectiveness of Boron Recovery Techniques

The cost-effectiveness of these methods, as illustrated in **Figure 2** ("Cost-Effectiveness of Boron Recovery Techniques"), reveals a wide disparity in operational costs. Reverse Osmosis (RO), while highly efficient, incurs the highest costs, often exceeding $1,000 per cubic meter of treated water due to energy consumption

Journal of Ecohumanism
2024
Volume: 3, No: 7, pp. 3058 – 3073
ISSN: 2752-6798 (Print) | ISSN 2752-6801 (Online)
https://ecohumanism.co.uk/joe/ecohumanism
DOI: https://doi.org/10.62754/joe.v3i7.4704

and membrane replacement. Electrodialysis (ED), with an operational cost range of $500 to $800 per cubic meter, offers a more affordable alternative while maintaining high efficiency. Nanofiltration (NF) and Adsorption, both of which can achieve moderate efficiencies, demonstrate considerable cost advantages, with costs ranging from $200 to $600 per cubic meter, making them attractive for industrial applications where cost constraints are critical. Membrane Distillation (MD) presents a more nuanced case, with its cost varying significantly depending on the availability of waste heat, typically falling within the $400 to $700 range. Finally, Leaching emerges as the most cost-effective solution, with operational costs as low as $100 per cubic meter, but its lower efficiency makes it suitable only for specific applications, particularly where boron concentrations are not excessively high.

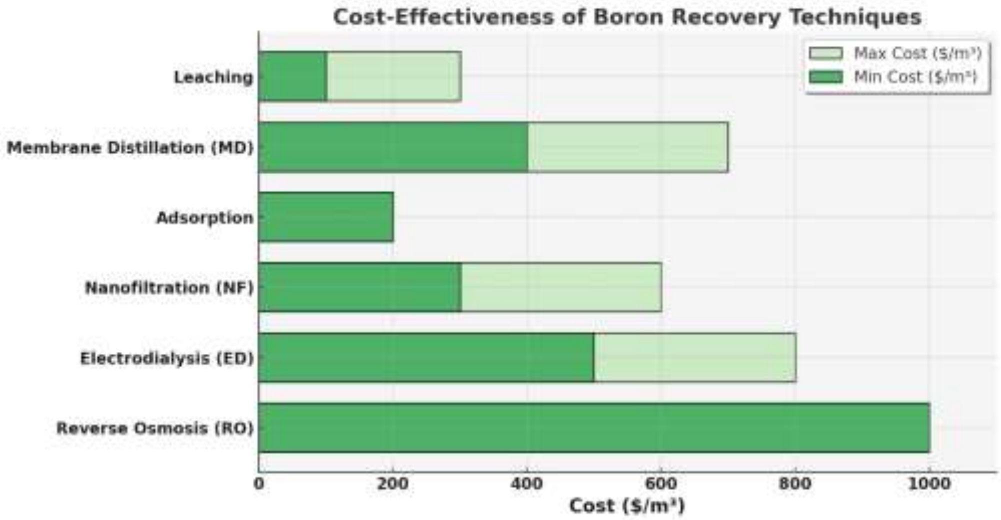

Figure 5: Cost-Effectiveness of Boron Recovery Techniques

Environmental Impact and Sustainability

Table 5 evaluates the environmental footprint of each method alongside sustainability considerations. Reverse Osmosis (RO) has significant environmental drawbacks, primarily due to its high brine disposal issues and the energy intensity required for its operation. These factors contribute to greenhouse gas emissions and make RO less sustainable in areas with limited energy resources. Electrodialysis (ED), though energy-efficient compared to RO, requires careful management of hazardous waste generated by ion-exchange membranes. Nanofiltration (NF) is a more environmentally friendly option due to minimal waste generation but faces challenges regarding membrane degradation over time.

Adsorption techniques are generally considered eco-friendly, with the main sustainability concern revolving around the disposal of spent adsorbents. The development of biodegradable or recyclable adsorbents is critical for enhancing the sustainability of this method. Membrane Distillation (MD) benefits from utilizing waste heat, which reduces its overall environmental impact. However, waste materials from the process still require careful management. Leaching, although cost-effective, poses environmental risks due to the potential for soil and water contamination, particularly from the use of acids in the process. However, when managed responsibly, leaching can contribute to a circular economy by recovering valuable materials from industrial waste.

Table 5. Environmental Impact and Sustainability Considerations of Boron Recovery Techniques

Technique	Environmental Impact	Sustainability Considerations
Reverse Osmosis (RO)	- High brine disposal issues - Energy-intensive, contributes to greenhouse gas emissions	- Significant environmental footprint - High operational costs

Journal of Ecohumanism
2024
Volume: 3, No: 7, pp. 3058 – 3073
ISSN: 2752-6798 (Print) | ISSN 2752-6801 (Online)
https://ecohumanism.co.uk/joe/ecohumanism
DOI: https://doi.org/10.62754/joe.v3i7.4704

Technique	Environmental Impact	Sustainability Considerations
Electrodialysis (ED)	- Lower energy use compared to RO - Potential hazardous waste from ion-exchange membranes	- More sustainable in terms of energy consumption - Waste management required
Nanofiltration (NF)	- Minimal waste generation - Concerns about membrane degradation	- Environmentally friendly option - Careful disposal and replacement strategies needed
Adsorption	- Generally eco-friendly - Disposal of spent adsorbents can be challenging	- Potential for using low-cost, eco-friendly materials - Development of biodegradable adsorbents needed
Membrane Distillation (MD)	- Utilizes waste heat, reducing environmental impact - Waste materials management required	- Lower overall footprint when integrated with waste heat recovery systems
Leaching	- Risk of soil and water contamination - Use of acids poses environmental risks	- Can contribute to circular economy if managed responsibly - Effective in waste material recovery

Scalability of Boron Recovery Techniques

Scalability is a crucial factor for industries seeking efficient and sustainable boron recovery processes, particularly as boron demand increases in agriculture, glass manufacturing, and electronics. Among the six methods reviewed—Reverse Osmosis (RO), Electrodialysis (ED), Nanofiltration (NF), Adsorption, Membrane Distillation (MD), and Leaching—each offers distinct scalability potential based on operational adaptability, cost-effectiveness, and environmental impact. RO, a popular choice for desalination, is highly scalable due to its modular design, making it suitable for both small- and large-scale applications (Figueira et al., 2022; Tu et al., 2010). However, its high operational costs, driven by energy consumption and the need for frequent membrane replacement, can limit feasibility in regions with economic constraints. Furthermore, the environmental challenges associated with brine disposal complicate its scalability and long-term viability (Jeong et al., 2023; X. Liu et al., 2022).

Electrodialysis (ED) provides an adaptable and energy-efficient alternative to RO, especially for treating brine and desalination processes. Its ability to adjust to various flow rates and concentrations makes it scalable for both small- and large-scale applications. However, the high capital costs of ED systems can be a significant barrier to widespread adoption, particularly in underdeveloped regions (Landsman et al., 2020; Nagasawa et al., 2011). Nanofiltration (NF) also presents a promising option, functioning efficiently at lower pressures and reducing energy expenses, which enhances its scalability potential (Attia et al., 2017; Tu et al., 2011). However, the durability of NF membranes and the need for regular maintenance may restrict widespread implementation, with its scalability relying on future advancements in membrane technology (Richards et al., 2010).

Adsorption techniques are notable for their simplicity and versatility, which facilitate easy scaling for large-scale operations. The use of cost-effective, eco-friendly adsorbents further improves their economic feasibility (Park, 2023; Saleh Al-dhawi et al., 2023). Nevertheless, the efficiency of adsorption can be influenced by boron concentration and the presence of competing ions, potentially limiting its applicability in certain conditions (Baskan & Atalay, 2014; Ersan & Pinarbasi, 2011). Membrane Distillation (MD) is currently in the development stage for large-scale applications, though its potential is encouraging, especially when integrated with waste heat recovery systems (Hussain et al., 2021; Kıpçak & Özdemir, 2012). Leaching can also be scaled effectively for extracting boron from industrial waste, but the environmental risks, particularly those related to soil and water contamination from acids, must be carefully managed (Chan & Wu, 2022; Ertan, 2020). Overall, while all methods show potential for scalability, each must be carefully

Volume: 3, No: 7, pp. 3058 – 3073
ISSN: 2752-6798 (Print) | ISSN 2752-6801 (Online)
https://ecohumanism.co.uk/joe/ecohumanism
DOI: https://doi.org/10.62754/joe.v3i7.4704

evaluated based on operational challenges, environmental impact, and economic feasibility to ensure sustainable implementation.

Conclusion

The increasing industrial utilization of boron has resulted in elevated levels of boron pollution in aquatic environments, leading to significant ecological, agricultural, and health concerns. Boron toxicity adversely affects aquatic life, causing physiological disruptions in algae, microorganisms, and various fish species, which can lead to reduced growth, metabolic disturbances, and increased mortality rates. Plant life is similarly impacted, with excessive boron causing toxicity symptoms that hinder growth and reduce agricultural yields. Human health risks associated with high boron intake from contaminated drinking water include reproductive disorders, neurological impairments, and developmental toxicity.

This review has critically analysed various boron recovery techniques, focusing on their efficiency, sustainability, scalability, and cost-effectiveness. High-efficiency methods like reverse osmosis and electrodialysis, while effective at removing boron, are often hindered by high energy consumption, operational costs, and environmental issues such as brine disposal. Alternative methods like adsorption and nanofiltration offer more sustainable and cost-effective solutions but may face challenges in terms of efficiency and scalability for industrial applications. Membrane distillation and leaching present additional options, but their environmental impacts and operational limitations require careful consideration.

The analysis highlights the necessity for innovative and integrated approaches that balance efficiency, cost, environmental impact, and scalability. Future research should focus on developing advanced materials for adsorption, enhancing membrane technologies, and creating hybrid systems that combine the strengths of different methods. Addressing the challenges of boron pollution is imperative to protect environmental health, preserve biodiversity, and ensure sustainable industrial practices. Implementing effective boron recovery techniques will not only mitigate environmental risks but also contribute to resource conservation and compliance with global regulatory standards.

Acknowledgments

The authors would like to acknowledge the support of Prince Sultan University for paying the Article Processing Charges (APC) of this publication. The author would like to thank Prince Sultan University for their support.

Conflicts of Interest

The authors declare no conflict of interest.

References

Akpinar, Ş., Koçyiğit, H., Gürbüz, F., & Odabaşı, M. (2021). Boron removal from aqueous solutions by polyethyleneimine-Fe3+ attached column adsorbents. Environmental Research and Technology. https://doi.org/10.35208/ert.913229

Al-Ejji, M. (2023a). Advanced membrane technology to remove boron from water and wastewater: A comprehensive study. ACS Applied Polymer Materials. https://doi.org/10.1021/acsapm.3c01177

Al-Ejji, M. (2023b). Advanced membrane technology to remove boron from water and wastewater: A comprehensive study. ACS Applied Polymer Materials. https://doi.org/10.1021/acsapm.3c01177

Aliem al., R. A. (2022). Toxicological effect of boric acid and cadmium chloride on the Nile tilapia, Oreochromis niloticus. Egyptian Journal of Aquatic Biology and Fisheries. https://doi.org/10.21608/ejabf.2022.264527

Alkhudhiri, A., Darwish, N. Bin, Hakami, M. W., Abdullah, A. S., Alsadun, A., & Homod, H. A. (2020). Boron removal by membrane distillation: A comparison study. Membranes. https://doi.org/10.3390/membranes10100263

Altınbaş, B. F., Orak, C., Ökten, H. E., & Yuksel, A. (2022). Novel hybrid adsorption-electrodialysis (AdED) system for removal of boron from geothermal brine. ACS Omega. https://doi.org/10.1021/acsomega.2c06046

Assunção, J., Batista, A. P., Manoel, J., da Silva, T. L., Marques, P., Reis, A., & Gouveia, L. (2017). CO_2 utilization in the production of biomass and biocompounds by three different microalgae. Engineering in Life Sciences. https://doi.org/10.1002/elsc.201700075

ISSN: 2752-6798 (Print) | ISSN 2752-6801 (Online)
https://ecohumanism.co.uk/joe/ecohumanism
DOI: https://doi.org/10.62754/joe.v3i7.4704
Attia, H. G., Alexander, S., Wright, C. J., & Hilal, N. (2017). Superhydrophobic electrospun membrane for heavy metals removal by air gap membrane distillation (AGMD). Desalination. https://doi.org/10.1016/j.desal.2017.07.022

Aydin, S., Terzi, E., Kartal, S. N., Pişkin, S., Depren, S. K., & Figen, A. K. (2020). New manufacturing methodology for boron-based rods for remedial treatments of wood: Solubilities and some physical and thermal properties of the rods. SN Applied Sciences. https://doi.org/10.1007/s42452-020-03593-2

Ball, R. W., Harrass, M. C., & Culver, B. D. (2012). Boron. Encyclopedia of Toxicology. https://doi.org/10.1002/0471435139.tox045.pub2

Baskan, M. B., & Atalay, N. (2014). Boron removal from aqueous solution by batch adsorption using Box–Behnken design. Desalination and Water Treatment. https://doi.org/10.1080/19443994.2014.929036

Brdar-Jokanović, M. (2020). Boron toxicity and deficiency in agricultural plants. International Journal of Molecular Sciences. https://doi.org/10.3390/ijms21041424

Chang, P. C., Yeh, P.-C., & Yang, J. (2008). Fatigue crack growth in hybrid boron/glass/aluminium fibre metal laminates. Fatigue & Fracture of Engineering Materials & Structures. https://doi.org/10.1111/j.1460-2695.2008.01288.x

Chen, J., Yang, Q., Liu, M., Lin, M.-T., Wang, T., Zhang, Z., Zhong, X., Guo, N., Lu, Y., Xu, J., Wang, C., Han, M., & Wei, Q. (2019). Remarkable boron delivery of iRGD-modified polymeric nanoparticles for boron neutron capture therapy. International Journal of Nanomedicine. https://doi.org/10.2147/ijn.s214224

Chen, K., Liu, S.-S., Guagliardo, P., Kilburn, M. R., & Koyama, M. (2015). A fundamental study of boron deposition and poisoning of $La_{0.8}Sr_{0.2}MnO_3$ cathode of solid oxide fuel cells under accelerated conditions. Journal of the Electrochemical Society. https://doi.org/10.1149/2.0141512jes

Cho, B. Y., Kim, H. W., & Shin, Y. S. (2015). A study on boron removal for seawater desalination using the combination process of mineral cluster and RO membrane system. Environmental Engineering Research. https://doi.org/10.4491/eer.2014.0083

Dhamotharan, K., Roh, H., Morton, H. C., Vossgård, A., Hansen, T., Fjelldal, P. G., Karlsbakk, E., Fiksdal, I. U., Dahle, M. K., Berg-Rolness, H., Mæhle, S., Berhe, G. D., Nordbø, J., Patel, S., Madhun, A. S., Grove, S., & Kvamme, B. (2023). Experimental transmission of Piscine orthoreovirus-1 (PRV-1) in different life stages of Atlantic salmon (Salmo salar) and brown trout (Salmo trutta). Frontiers in Marine Science. https://doi.org/10.3389/fmars.2023.1151577

Díaz, L. A. (2023). Potential use of agricultural waste—Carob kibbles (Ceratonia siliqua L.) as a biosorbent for removing boron from wastewater. Separations. https://doi.org/10.3390/separations10090464

Ersan, H. Y., & Pinarbasi, S. (2011). Boron removal by glucamine-functionalized hydrogel beads in batch fashion. Journal of Applied Polymer Science. https://doi.org/10.1002/app.33723

Figueira, M., Reig, M., de Labastida, M. F., Cortina, J. L., & Valderrama, C. (2022). Boron recovery from desalination seawater brines by selective ion exchange resins. Journal of Environmental Management. https://doi.org/10.1016/j.jenvman.2022.114984

Feng, L., Wei, P., Song, Q., Zhang, J., Fu, Q., Jia, X., Yang, J., Shao, D., Li, Y., Wang, S., Xia, Q., & Song, H. (2022). Superelastic, highly conductive, superhydrophobic, and powerful electromagnetic shielding hybrid aerogels built from orthogonal graphene and boron nitride nanoribbons. ACS Nano. https://doi.org/10.1021/acsnano.2c07187

Ghulam, A. N., dos Santos, O. A. L., Hazeem, L., Backx, B. P., Bououdina, M., & Bellucci, S. (2022). Graphene oxide (GO) materials—applications and toxicity on living organisms and environment. Journal of Functional Biomaterials, 13(2), 77. https://doi.org/10.3390/jfb13020077

Gujar, J., Haddadi, E., & Sonawane, S. S. (2022). Kinetics and isotherm studies for the adsorption of boron from water using titanium dioxide. The Canadian Journal of Chemical Engineering. https://doi.org/10.1002/cjce.24429

Güler, E. (2021). Effect of feed water composition and pretreatment on the irrigation water for boron-sensitive crops. Journal of Boron. https://doi.org/10.30728/boron.843259

Jaouadi, M. (2020). Characterization of activated carbon, wood sawdust and their application for boron adsorption from water. International Wood Products Journal. https://doi.org/10.1080/20426445.2020.1785605

Jeong, N., Wiltse, M. E., Boyd, A., Blewett, T. A., Park, S., Broeckling, C. D., & Tong, T. (2023). Efficacy of nanofiltration and reverse osmosis for the treatment of oil-field produced water intended for beneficial reuse. ACS ES&T Engineering. https://doi.org/10.1021/acsestengg.3c00138

Juszczak, M., Sawicki, T., Szymczak, M., & Kamiński, P. (2020). Ichthyology, breeding and economic importance of rainbow trout in Poland. Folia Pomeranae Universitatis Technologiae Stetinensis Agricultura Alimentaria Piscaria Et Zootechnica. https://doi.org/10.21005/aapz2019.52.4.02

Khaliq, H., Zhong, J., & Peng, K. (2018). The physiological role of boron on health. Biological Trace Element Research. https://doi.org/10.1007/s12011-018-1284-3

Kondzior, P., & Butarewicz, A. (2018). Effect of heavy metals (Cu and Zn) on the content of photosynthetic pigments in the cells of algae Chlorella vulgaris. Journal of Ecological Engineering. https://doi.org/10.12911/22998993/85375

Katar, I. (2022). Promoting pedestrian ecomobility in Riyadh City for sustainable urban development. Scientific Reports, 12(1), 14808. https://doi.org/10.1038/s41598-022-18183-y

Liu, X., Xu, C., Chen, P., Li, K., Zhou, Q., Ye, M., Zhang, L., & Lu, Y. (2022). Advances in technologies for boron removal from water: A comprehensive review. International Journal of Environmental Research and Public Health. https://doi.org/10.3390/ijerph191710671

Pan, H., Zhao, X. L., Zhang, X., Zhang, K. B., Li, L., Li, Z. Y., Lam, W., Lu, W. W., Wang, D. P., Huang, W., Lin, K., & Chang, J. (2009). Strontium borate glass: Potential biomaterial for bone regeneration. Journal of the Royal Society Interface. https://doi.org/10.1098/rsif.2009.0504

Pratikno, H., Titah, H. S., Handayanu, & Mahardhika, G. R. (2019). Impressed current anti-fouling (ICAF) to reduce population of Chlorella vulgaris cause bio-corrosion on AH36 steel in marine environment. E3S Web of Conferences. https://doi.org/10.1051/e3sconf/201912506001

Journal of Ecohumanism
2024
Volume: 3, No: 7, pp. 3058 – 3073
ISSN: 2752-6798 (Print) | ISSN 2752-6801 (Online)
https://ecohumanism.co.uk/joe/ecohumanism
DOI: https://doi.org/10.62754/joe.v3i7.4704

Rani, A. (2023). Insight of oxidative stress, ultrastructural transformations, and elemental variations in rice seedlings exposed to boron toxicity: Unraveling the role of Fe-Sod in boron tolerance. Asian Journal of Research in Biochemistry. https://doi.org/10.9734/ajrb/2023/v13i4269

Richards, L. A., Vuachère, M., & Schäfer, A. I. (2010). Impact of pH on the removal of fluoride, nitrate and boron by nanofiltration/reverse osmosis. Desalination. https://doi.org/10.1016/j.desal.2010.06.025

Siyal, A. A., Shamsuddin, M. R., Khahro, S. H., Low, A., & Ayoub, M. (2021). Optimization of synthesis of geopolymer adsorbent for the effective removal of anionic surfactant from aqueous solution. Journal of Environmental Chemical Engineering, 9(1), 104949. https://doi.org/10.1016/j.jece.2020.104949

Smedskjær, M. M., Mauro, J. C., Youngman, R. E., Hogue, C. L., Potužák, M., & Yue, Y. (2011). Topological principles of borosilicate glass chemistry. The Journal of Physical Chemistry B. https://doi.org/10.1021/jp208796b

Soysüren, G., İpek, İ. Y., Arda, M., & Arar, Ö. (2023). Polymer-enhanced ultrafiltration–electrodeionization hybrid system for the removal of boron. Environmental Science Water Research & Technology. https://doi.org/10.1039/d3ew00041a

Srivastava, T., & Wanjari, N. (2023). Boron isotopic systematics and its significance in natural processes: An overview. Nature Environment and Pollution Technology. https://doi.org/10.46488/nept.2023.v22i02.007

Zhang, C., Gao, X., & Yilmaz, B. (2020). Development of FTIR spectroscopy methodology for characterization of boron species in FCC catalysts. Catalysts. https://doi.org/10.3390/catal10111327.