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A COMPARISON OF TECHNIQUES OF BORON REMOVAL FROM WATER AND WASTEWATER

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Abstract

Boron is a vital trace element required by plants, humans, and animals. It is also a significant element used in several industries. Along with the widespread usage of boron, boron waste progressively contaminates the potable water sources as well as causing a chain of environmental and health challenges to occur. This study reviews the techniques used for boron removal from aqueous solutions, including ion exchange, resin adsorption, reverse osmosis (RO), electrocoagulation, microfiltration, chemical coagulation, solvent extraction, electro dialytic, and hybrid processes. A review search was carried out from the databases Scopus, PubMed, Web of Knowledge, and Embase using the following key words: "Boron removal", "saline water", "wastewater", "desalination, "membrane", "adsorption", "seawater" "hybrid process", and "groundwater. Boron could be effectively eliminated using membrane treatments, such as RO, electrodialysis and microfiltration with elimination efficiency of 79-99.6%. Based on the findings of this study, the highest and lowest removal efficiency of boron using RO and resin techniques was 5.1-87% and 99.6%, respectively. The RO process is an appropriate technique for seawater desalination along with boron. Adsorption methods are only effective for aqueous solutions with low boron levels and mineral levels when the objective is to avoid repeated regeneration operations limitation. The highest concentration of boron in waters was found to be 25-100 mg/L in Poland, and the lowest concentration of 0.10-1.99 mg/L was found in Pakistan. These processes can be applied to future work to eliminate boron from saline water and wastewater in both experimental and real-world settings.

Keywords: Boron removal; Adsorption; Membrane; Hybrid process; Seawater; Water and wastewater.

1. Introduction

Boron is a widely distributed micronutrient in earth's hydrosphere (i.e. seawater and ground water) and lithosphere (i.e. soil or rocks) (Guan et al., 2016). The mean level of boron in the earth layer is 10 mg/L (Wolska & Bryjak, 2013). In soils, its mean level ranged between 10 and 20 mg/L. The content of boron in cliffs ranges from 5 mg/L in basalts to 100 mg/L in

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residuary shale. Seawater contains a mean boron value of 4.6 mg/L and boron concentration ranges from 0.5 to 9.6 mg/L.

Boron in fresh water ranges typically from below 0.01 mg/L to 1.5 mg/L and raises drastically in boron-enrichened soils in western regions of the U.S. and regions from the Mediterranean Sea to Kazakhstan (Wolska & Bryjak, 2013).There is a rising demand for boron application in various areas, such as agriculture (16%), glass (47%), detergent (2%), ceramic (16%), and other industries (19%) due to its valued raw material (Chruszcz-Lipska et al., 2021). Human-made sources of boron have become a severe challenge in the environment (Dolati et al., 2017). When released to earth, boron waste is *soluble* in rainwater. Boron composites transit into ground where they form some compounds with heavy metals (Dolati et al., 2017).

Therefore, the potential toxicity of heavy metals raises when compounds enter the groundwater, leading to severe health and environmental challenges (Ozyurt et al., 2019). Currently, the level of boron in groundwater raises clearly due to both natural and human-made reasons. Moreover, there has been a considerable raise in the level of boron in surface waters over recent years. Generally, impurities from industrial and municipal effluents, geochemical nature of the drain region, and being near to marine coastal areas affect the boron content in fresh water (Loizou et al., 2010). Boron is found in fruits, vegetables, nuts and wine (Wang et al., 2014). Humans can absorb adequate boron from common diet without going on a particular diet. The admissible daily intake is 0.3 mg boron/kg/day for animals and humans (Baldivia et al., 2016).

The harmful consequences of boron deficiency for plants, humans, and animals cannot be ignored, they are shown in Table 1. Boron pollution of water is a severe environmental challenge. Elimination of boron from water is difficult and can inhibitive be costly and infeasible. Techniques used for boron elimination in the past few decades and present include boron exploitation (Kabay et al., 2010), adsorption (Ahmadi et al., 2020; Guan et al., 2016), ion exchange (Darwish et al., 2015), reverse osmosis (RO) (Fadaei, 2021; Ruiz-García et al., 2019), electrodialysis (ED) (Kijański et al., 2013), ultrafiltration (Tang et al., 2016), electrocoagulation (EC) (Isa et al., 2014; Wang et al., 2017), chemical coagulation (Razavi et al., 2020; Yoshikawa et al., 2012), and hybrid process (Guan et al., 2016; Mohammadi et al., 2021; Samatya et al., 2015; Taie et al., 2021).

Each technique has its own advantages-disadvantages and works effectively under foremost conditions. Considering the harmful effects of boron on plants, animals, and humans, it is very vital to choose a suitable and efficient method to eliminate boron from water and wastewater. Thus, this study aims to present a comparative analysis of different techniques that have been applied to boron elimination from drinking water, wastewater, and seawater. This study is also aimed to present a holistic review of various methods for boron removal from water and wastewater.

Table .1. Effects of boron on plants, animals, and humans

Living beings	Effects of boron	Ref
Plants	Boron deficiency inhibits the growth of meristematic tissue, delays enzymatic reactions, leads to leaf thickening, bark cracking, poor budding, widely branching and decline of pullulating, yellow tips of leaves, defoliation, spots on fruits, decomposition of unripe fruit, prevention of photosynthesis	(Tang et al., 2017; Wolska & Bryjak, 2013)
Animals	Boron deficiency affects the combination and operation of many components of an animal's body, decreases absorption of calcium, magnesium and phosphorus, boron deficiency may also lead to malformations of fetus	(Guan et al., 2016; Wolska & Bryjak, 2013)
Humans	Changes blood composition, leads to neurological effects, physical disorders and mental development of children, affects functioning of many organs like cardio-vascular, coronary, nervous and reproductive, and alimentary systems, may cause nausea, vomiting and diarrhea, anorexia or weight loss	(Guan et al., 2016; Liu et al., 2022) ,

2. Methods

This study provides a review of the recent literature covering the period between 2010 and 2021. The last systematic search was carried out from April to June 2022. The review has principally focused on methods and processes. Databases like Google Scholar, Science Direct, and Web of Science were employed to retrieve several papers on the topic. Keywords, such as “Boron removal”, “saline water”, “wastewater”, “desalination, “membrane”, “adsorption”, “seawater” “hybrid process”, and “groundwater” were added to the above-mentioned methods to retrieve suitable papers. The inclusion criteria were access to the original article, English language, and using the type of aqueous solution investigated in this study, such as saline water, brackish water, seawater, geothermal water, and wastewater. The exclusion criteria were *unavailability of full text* of the article, review studies, book reviews, guidelines, protocols, letters-to-editors, articles submitted to conferences, theses, white papers, etc.

As shown in figure 1, a total of 150 peer reviewed publications were accessed based on the relevance of titles to the research. These were further screened to 80 after reading through their abstracts. In the present study, AM. F systematically investigated (2 times) title-abstract and full text to avoid bias. Then, data related to the removal method, type of environment, main findings, type of study, comment, and references was extracted. After screening the full text of the articles, 17 were used for this review, excluding the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) reference (Moher et al., 2009).

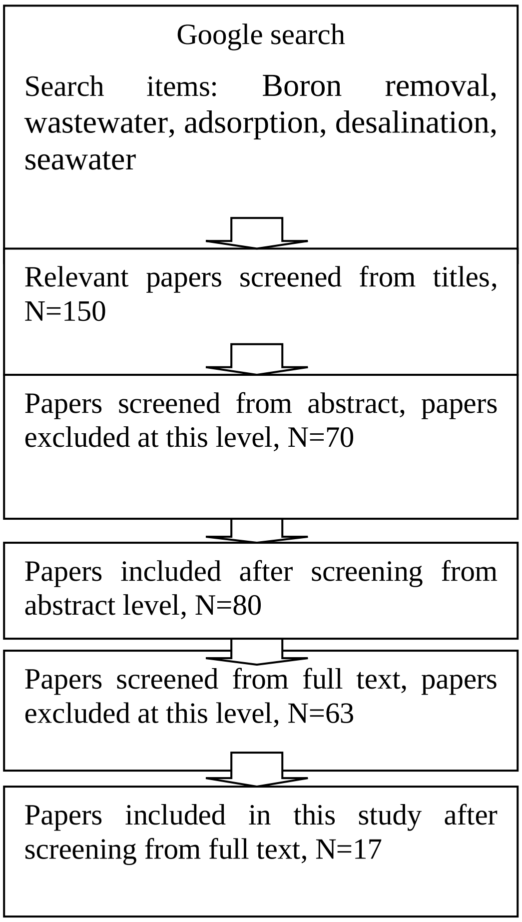

Figure.1. Chart presentation of the review process

3. Results and discussion

These articles were focused on various methods, including ion exchange resin (3) adsorption (4), reverse osmosis (RO) (3) EC (2), microfiltration (1), chemical coagulation (1), electrodialytic (1), ion exchange, adsorption, and RO (1), and mixed matrix membrane (1)

(See Table 2). Based on findings, the range of boron removal efficiency is found to be about 5.1 to 98 % and 92.84 to 99.6 % for resin and RO methods respectively (See Table 2). The boron level ranges from 0.00 to 100 mg/L were found in waters at different countries (See Table 4).

3.1. Adsorption

One of the most efficient techniques to eliminate boron from aqueous environments is adsorption because the process commitments are easy and can be applied to aqueous environments with low levels of boron (Wang et al., 2014). One study reported the use of olive bagasse for boron elimination, and found that the highest boron elimination was attained at initial pH=5.5 and the adsorption kinetics was found to conform to the pseudo-first-order reactions (Köse et al., 2011). Another study demonstrated that a clinoptilolite-type natural zeolite was modified using amorphous ZrO_2 and used for boron elimination; the best situation was found at pH=8, temperature 25°C, exposure time of 30 min, and adsorption percentage of 75% (Kluczka et al., 2013).

In a study, Ting et al. reported the maximum adsorption capability of 14.5 mg/g at pH 8 by using adsorbent (radiation induced grafting) (Ting et al., 2013). Another study reported that approximately 90% of boron sorption occurred within 8h at neutral pH by using chitosan sorbent (Wei et al., 2011). In another study, Al-Afy and Sereshti reported that the elimination efficiency of boron from tap, mineral and ground waters was 95–97% at pH 9.2, and exposure time of 14.8 min using adsorption (magnetic graphene oxide nanocomposite (GO/Fe_3O_4)) (Al-Afya & Sereshtia, 2019). A study by Al-Ithari et al. indicated that the efficiency of adsorption of date seeds for boron removal from seawater was about 71.10% at pH 7 and reaction time of 1440 min (Al-Ithari et al., 2011). In a study, Iizuka et al. reported that the adsorption capacity of waste concrete for boron removal from wastewater was about 90% within treatment time of 1440 min (Iizuka et al., 2014).

Another study reported that the highest capacity was found to be 16.14 mg/g and the highest maximum elimination obtained was around 97% by using adsorption capacity of fly ash for boron removal from an aqueous environment at pH 10.5 within 24 h (Ulatowska et al., 2020). In a study, Zohdi et al. demonstrated that the highest adsorption capacity of 1.97 mg/g was achieved at pH of 6.0 using multi-walled carbon nanotubes (MWCNTs) and enhanced with tartaric acid (Zohdi et al., 2014). Babiker et al. found that the adsorption capacity of waste tire rubber for boron elimination from aqueous solution was about 16.72 mg/g at pH 2 and with the contact time of 48 h (Babiker et al., 2019). A study by Fuchida et al. indicated that the adsorption efficiency of Calcined Ettringite for boron removal from wastewater was about 44% at reaction time of 60 min with ettringites calcinated at 55 and 65 °C (Fuchida et al., 2020). In a study by Chen et al. the adsorption capacity of magnetic magnetite (Fe_3O_4) nanoparticles for boron removal from aqueous environment was reported to be about 4.57 mmol/g at pH 7 and 45°C (Chen et al., 2020).

Another study demonstrated that the highest adsorption capability of nitrogen-doped graphene oxide for boron removal from seawater was found to be at 58.7 mg/ g (Chen et al., 2017). One study stated that the elimination efficiency of zeolite and limestone/coco peat wetlands was 12% and 17%, respectively for boron removal from acidic wastewater (Allende et al., 2014). A study showed that the value of the highest boron adsorption of MgO was 21.5 mmol/g at 30 °C after contact time of 24 h (Kameda et al., 2018). A study by Demey et al. indicated that the highest adsorption capacity of chitosan/Ni(OH)2-based sorbent for boron removal from aqueous solutions was obtained to be 61.4 mg/g at pH 12 (Demey et al., 2014). In another study by Abba et al., it is reported that the adsorption efficiency of synthesized nano-magnetite (Fe_3O_4) from industrial mill chips for removal of boron was 84% at pH 8, dose of 0.5 g, and exposure time of 180 min (Abba et al., 2021). One study found the maximum boron adsorption capacity to be 2.54 mmol/g after exposure time of 2 h using a high internal phase emulsion (Wang et al., 2021).

3.2. Membrane process

Membrane techniques are the mainly regular methods applied to desalination of seawater and any other saline waters. Even though this is the second technique to remove boron contamination, it has some usage restrictions.

3.3. Reverse osmosis method

As the main technique for seawater desalination, reverse osmosis (RO) method was adopted by various nations. It applies a semi-impermeable membrane which only allows water molecules to pass and maintains solute and microorganisms via this membrane. This is due to the high pressure of 50–75 bar to overcome the osmotic pressure of the water which is around 26–29 bar (Maddah et al., 2018). A study by Wang et al. reported the optimal separation performance of polyamide RO membranes to be 93.12% boron rejection, 44.17 $L/m^2.h$ water flux (Wang et al., 2018). One study reported approximately 50% raise in water flux and a minor raise in rejection using polyamide-based RO membrane via the interpolation of UiO-66 nanoparticles (Liu et al., 2019).

Another study reported an increase in the boron rejection of the swelling-embedding-shrinking modified RO membranes from 82.12% to 93.10%, and showed that the salt refusal rate increased by 99.57% (Li et al., 2020). Wang et al. found the efficiency of boron removal from aqueous solution using RO to be above 93.12% at temperature 25◦C and pressure 1.2 Mbar (Wang et al., 2018). One study reported the efficiency of forward osmosis for boron removal from wastewater to be about 98.4% at pH 11 (Chang et al., 2020). A study by Tang et al. showed that boron rejection was 91% by using ultrafiltration 2, 3-dihydroxypropyl-hyper-branched polyethylenimine membrane (Tang et al., 2016). Another study by Sanchez et al. showed that boron retention capacity was in a range of 2-4 mg/g by using poly (glycidyl methacrylate-N-methyl-D-glucamine), P(GMA-NMG) and membrane polymer-enhanced ultrafiltration (Sánchez et al., 2016).

In a study by Yürüm et al. it was found that the maximum retention was 90.1% at pH 7-10 to remove aqueous boron using ultrafiltration (Yürüm et al., 2013). A study by Luo et al. reported the boron rejection up to 83.9% of double-skinned forward osmosis membranes designed for boron elimination from wastewater (Luo et al., 2016). Another study reported that RO with nanoporous graphene decreased boron levels with *a boron rejection rate* of 95% (Risplendi et al., 2019). A study by Ali et al. reported boron rejection performance with rejection rate up to 99% at pH 10 for boron elimination from saline water using polyamide thin-film composite osmosis membranes (Ali et al., 2019). Another study reported the boron elimination rate up to 90.6% under neutral status in a single stage using charge-aggregate induced RO membrane for boron elimination from seawater (Hu et al., 2016).

3.4. Ion exchange resin method

In this method, a set of synthetic ion exchangers are fixed on membrane matters containing cation-exchange membrane, anion-exchange membrane, and bipolar membranes. A study by Al Haddab et al. indicated that the efficiency of ion exchange **(**Amberlite IRA 743) for boron elimination from artificial seawater was about 85.1% at pH 8 (Darwish et al., 2015). Another study showed that the adsorption capacity levels were 6.27 mg/g by using ion exchange **(**Amberlite IRA-743) (Nasef et al., 2014). One study showed that the resin capability ranged from 4.4 to 3.1 mg/g at pH between 7 and 10 for boron elimination from salt groundwater (Hussain et al., 2019).

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A study by Kluczka et al. reported the efficiency of resin **(**Purolite A170 A) for boron elimination from water and wastewater to be about 98.5% at pH 9.5 (Kluczka et al., 2015). In a study by Kir et al. the Donnan dialysis technique was applied to eliminate boron from aqueous environment using plasma-modified and unmodified anion-exchange membranes and the highest values were found for plasma modified AFX membrane in comparison to the unmodified one (Kir et al., 2011).

3.5. Electrocoagulation (EC) method

As an emerging method used for water and wastewater treatment, EC combines the operations and benefits of traditional coagulation, flotation, and electrochemistry (Kuokkanen & Kuokkanen, 2013). In a study, Sari and Chellam reported that the elimination efficiency of boron from wastewater by using EC was above 90% at high Al/B ratios of above 70 (Sari & Chellam, 2015). Another study reported the optimal performance of 98% for boron removal from synthetic wastewater at pH 7, current density of 12.5 mA/cm^2, and contact time of 90 min (Ezechi et al., 2015). A study by Vasudevan et al. indicated that the optimum elimination performance for boron removal from water was 93.2% at pH 7, using EC (zinc anode) (Vasudevan et al., 2013).

The study by Yilmaz et al. has demonstrated that the highest boron elimination of 67% was attained at pH=6 using a continuous EC process (Massara et al., 2018). Dolati et al. reported the efficiency of EC for boron elimination from aqueous environments to be about 70% at pH 8 and contact time of 60 min (Dolati et al., 2017). In another study, Wided et al. reported that the *efficiency* of the EC method for boron elimination from natural water was about 33% at pH 8 and reaction time of 60 min (Wided et al., 2014). A study by Al Haddab et al. indicated that the efficiency of EC for boron removal from seawater was about 81% at pH 8 and contact time of 60 min (Khaoula et al., 2013). One study indicated that the efficiency of EC for boron elimination from synthetic seawater was about 96% at pH 8 (Zeboudji et al., 2013). A study by Chen et al. demonstrated that about 50% of the boron was eliminated from the river water with initial boron levels up to 10 mg/L in 2 h with a 0.2 A current, while about 80% of the boron was eliminated from produced water with initial boron levels up to 50 mg/L in 2 hours with 1.0 A current using the EC method (Chen et al., 2020).

Kartikaningsih et al. found that the efficiency of boron removal from wastewater was about 95% at pH 8, current 2.5 mA/ cm^2, and reaction time of 180 min by EC using aluminum as sacrificial anode (Kartikaningsih et al., 2016). A study by Ezechi et al. showed that the efficiency of EC for boron removal from synthetic wastewater was about 98% at pH 7, charge loading 2400 Ah/m^3, and reaction time of 90 min (Ezechi et al., 2014). A study by Isa et al. illustrated that the optimum removal efficiency of boron removal from wastewater was 99.7% at pH 6.3, current density 17.4 mA/cm^2, and time reaction of 89 min using EC (Isa et al., 2014).

3.5. Electrodialysis method

Electrodialysis (ED) is a membrane-based desalination technique for brackish water. Unlike other desalination techniques, it includes ions immigration via intercalation of anion and cation-exchange membranes when an electric field is produced due to difference in potential. Cation- and anion-exchange membranes are intermittently oriented between the anode and the cathode. By applying the potential difference in the system electrostatically, the cations are attracted to the cathode (negative pole) and anions membranes towards the anode (positive pole) (Folaranmi et al., 2020). One study showed that the efficiency of multi-step bipolar membrane ED for boron removal from wastewater was up to 90% at pH 7.3, and time of 60 min (Noguchi et al., 2018).

One study demonstrated that seawater and brackish water RO polyamide membranes have a boron rejection of 80-93% and 30-80% respectively (Shultz et al., 2018). A study by Nagasawa et al. showed that the efficiency of bipolar ED for boron elimination from aqueous solution was above 90% within 30 min (Nagasawa et al., 2008). Another study indicated that the efficiency of bipolar ED for boron elimination from saline solutions was about 72.3% at pH 12.25 and volume 0.5 L (Bunani et al., 2017). A study by Sun et al. reported the efficiency of bipolar membrane ED process (Graphene oxide modified porous P84 co-polyimide) for boron elimination from aqueous solutions to be up to 94.9%, contact time 3 h, and voltage 30 V (Sun et al., 2020).

3.6. Chemical coagulation method

Among different methods, chemical coagulation is well compatible for elimination of boron at high levels. One study reported that the highest *removal efficiency* of *boron* was 90% when Mg 30 mmol and Al 15 mmol at pH 10 were used during direct co-precipitation with Mg/Al layered *double hydroxide* (Kurashina et al., 2015). Another study reported boron elimination from geothermal water by co-precipitation with hydroxyapatite using magnesium ammonium phosphate (Sasaki et al., 2020). A study by Özyurt et al. demonstrated that boron removal from industrial wastewater was 95% using chemical precipitation and coagulation ($Ca(OH)_2$),and $Al_2(SO_4)_3 \cdot 18H_2O$) at pH 8.12 (Ozyurt et al., 2019). Another study reported that elimination of boron from an aqueous environment was 96% using chemical precipitation with calcium hydroxide within 25 min (Yilmaz et al., 2012).

A study by Lin et al. demonstrated that the removal of boron from aqueous solution was 95% using chemical precipitation with barium hydroxide ($Ba(OH)_2$) within 4 hours at pH 10.5 (Lin et al., 2016). One study indicated that the same coagulants (iron or aluminium) are necessary to remove about 80% boron from wastewaters (Chorghe et al., 2017). Another study reported the capacity of boron elimination from wastewater (boric acid solution) by chemical precipitation (calcium chloride) to vary from below 5% to 80% at room temperature (Shih et al., 2014). A study by Cao et al. reported the removal of boron from synthetic and field produced water by sodium silicate(Na_2SiO_3) to be 150 -30 mg/L (Cao et al., 2015).

One study reported that removal of boron from an aqueous solution was 85% using MgAlFe mixed oxides based on layered double hydroxides (Heredia et al., 2019). A study by Lin et al. demonstrated that elimination of boron from geothermal water was 95% using co-precipitation with hydroxyapatite within 1h (Sasaki et al., 2018). In another study, Irawan et al. demonstrated that elimination of boron from wastewater was 87% using precipitation with lime at 60°C (Irawan et al., 2011).

3.7. Solvent extraction method

A study by Xu et al. indicated that the recovery of boron by solvent extraction using aliphatic alcohol was about 97.79% at pH 3.5 (Xu et al., 2021). A study by Hoshina et al. illustrated that the boron chelating ability of about 18.3 mg/g was achieved within contact time of 4 h, at 40˚C (Hoshina et al., 2021). Another study demonstrated that the lime and soda ash softening treatment achieved 33% boron removal from brackish groundwater at pH 10 (Rioyo et al., 2018).

A study by Zhang et al. showed that the extraction of boron from saline water by solvent extraction using 2-ethylhexanol was about 99.5% with a purity of 95.5% (Zhang et al., 2016). In another study, Zhang et al. showed that the removal of boron from saline and aqueous solution was about 88.69% by flotation using sodium dodecyl benzene sulfonate and hydroxyl compounds as collector (Bai et al., 2018).

3.8. Hybrid process

Currently, hybrid membrane processes have been increasingly proposed to be used for water treatment. These processes relate membrane filtration (microfiltration (MF)), ultrafiltration (UF), and nanofiltration (NF) or RO to other methods, such as precipitation, ion exchange, sorption, etc, with the intention to elevate the dimension of the membrane, hybrid process dependence on feed water, objective concentration, and operation method (Alharati et al., 2017). One study showed that the ion exchange (resin Dowex XUS-43594.00)-UF hybrid system reduces the boron concentration of the geothermal water to below 1.0 mg/L (Kabay et al., 2013).

The parameters affecting hybrid process, including resin *concentration in suspension*, rate of fresh and saturated resin replacement, flow rate of infiltrate, and type of membrane, have been proposed to define the capacity of the hybrid process for boron elimination from seawater using RO with sorption-membrane filtration (MF or UF) hybrid process (Güler et al., 2011). In a study by Chieng and Chong, the highest capacity of palm oil mill boiler ash replete with several chemical materials for boron elimination from artificial wastewater was obtained to be 65.69% at pH 7.0, 25 °C, and reaction time of 12 h (Chieng & Chong, 2013). Another study showed that boron removal efficiency was about 80% by seawater forward osmosis (SWFO) and seawater reverse osmosis (SWRO) hybrid process (Ban et al., 2019). A study by Rioyo et al. demonstrated that by using lime and soda ash softening pretreatment for groundwater, regulating pH at 10.0, together with ED technique, a total boron elimination of 51 % was obtained (Rioyo et al., 2018).

A study by Kheriji et al. indicated the reduction of boron concentration in water to the admissible value by using RO and NF hybrid process (Kheriji et al., 2016). Another study showed that adsorption membrane filtration hybrid process has received considerable attention as an emerging technique for boron elimination with high efficiency and low operating expenditures (Hilal et al., 2011). One study indicated that using hybrid membrane inter-stage design for removal of boron from seawater saves up about 0.41 kWh/m^3 energy consumption (Raval et al., 2017). Regarding boron removal from seawater by using a microbial fuel cell equipped with anion exchange membrane, Ping et al. reported the maximum boron removal efficiency of about 80-90% at high pH (Ping et al., 2016). A study by Agashichev and Osman demonstrated that boron rejection from seawater was about 30–33% at pH < 8.6 and increased to 90% using low pressure RO (Agashichev & Osman, 2016).

Table 2. Comparing the boron removal methods

Removal method	Type of environment	Main findings	Type of study	Comment	Ref
Electro dialytic method	Aqueous environment (75-5000 mg/L of boron)	Electric current efficiency of 790% and 940% in the first and second steps, respectively	Original research	pH=11 -12, volumes=5 L, active area of each membrane was about 192.5 cm^2 and voltage drop 0.5 to 1.6 V	(Kijański et al., 2013)
Adsorption (Glycidol-functionalized macroporous polymer)	Aqueous solution	Maximum adsorption capacity= 29.2 mg/g	Original research	pH=9, initial concentration=1000 mg/L, adsorbent dose=5g/L, temperature 30 ◦C	(Luo et al., 2020)
Ion exchange, adsorption membrane filtration, and RO	Saline water	In RO the efficiency of elimination is enhanced at low temperature and low salinity, in ion exchange the elimination of boron enhances with an increase in H/D ratio and a reduction in flux	Review	-	(Hilal et al., 2011)
Resin	Aqueous solution	Loading capabilities of 2.9–4.0 mmol/g, removal efficiency up to76.3-97.5%	Original research	pH=4-8, boron released=2.76-3.90 mmol/g	(Ince et al., 2013)
Resin	Aqueous solution	Removal efficiency up to 5.1-87%	Review	The highest boron flow rate was reported at pH = 9.5, while for a diluted	(Dydo & Turek, 2013)

Removal method	Type of environment	Main findings	Type of study	Comment	Ref
				solution (0.001 mol/L) it was obtained at pH=11.5	
Resin	Aqueous solution	The highest adsorption capacity of resin was 4.54 mg/g at 25 °C	Original research	pH=3.4 to 10.9 contact time = 12 h, pseudo-second-order reaction	(Wang et al., 2014)
Microfiltration	Aqueous solution	Feed pH significantly increases the membrane flux, the membrane flux decreases as the operating pressure increases	Original research	Polyvinylidene fluoride membranes of various pore size (0.1, 0.22 and 0.45)	(Darwis et al., 2017)
Electrocoagulation	Synthetic wastewater	Boron removal up to 98%	Original research	Optimum conditions: initial concentration=10 mg/L, contact time =90 min, pH=7, current density 12.5 mA/cm^2	(Isa et al., 2014)
Electrocoagulation	Synthetic wastewater	The optimum situation for boron elimination pH 7, charge loading 2400 Ah/m^3, contact time 90 min, and removal efficiency98%	Original research	Operational conditions: pH 3–11, charge loading 1200–3600 Ah/m^3, reaction time 15–90 min and level 10–30 mg/L	(Ezechi et al., 2014)
Membrane (mixed matrix)	Aqueous solution	Removal efficiency above 97.6%	Original research	Flux rate of 25 L/m^2·h, initial concentration=5 mg/L, effective	(Wang et al., 2017)

Removal method	Type of environment	Main findings	Type of study	Comment	Ref
				area 1.76 cm^2	
RO membrane (polyamide layer)	Aqueous solution	Boron rejection with mannitol was 97.81% at 400 psig, and 92.84% with methyl salicylate	Original research	Feed water including 10 mg/L boron at pH 10, effective area 19.25 cm^2, feed water pressure 120 and 400 psi	(Raval et al., 2017)
RO (polyamide membrane)	Brackish water	Maximum rejection of 99.6% at pH=10	Original research	FT-30-type membranes, 15.5 bar,2000 mg/L NaCL	(Ali et al., 2019)
Adsorption (Steelmaking slag)	*Water*	Maximum adsorption capacity= 145 mg/g	Original research	Contact time=24 h, initial concentration=500 mg/L, adsorbent dose=2g/L, temperature 25 ◦C	(Balidakis & Matsi, 2020)
Adsorption (zeolite synthesized from fly ash)	Aqueous solution	Percentage removal up to 93%, adsorption capacity 50 mg B/L, pH=7	Original research	Adsorbent 0.1–5 g, solution concentration of 5 to 200 mg B/ L, pH = 4.0–12.5, temperature=25, 50, and 75˚C, for 2–240 min	(Kluczka et al., 2015)
Chemical coagulation(hydroxyapatite)	Wastewater	Efficiency of boron removal 99.4%, the boron removal rate reduced in the presence of a coexisting ion	Original research	Synthetic wastewater 50 mL, contact time 20 min, pH=12	(Yoshikawa et al., 2012)
Reverse osmosis	Simulated seawater	Boron removal rate 93.10%	Original research	Temperature 25°C, pH=8,	(Li et al.,

Removal method	Type of environment	Main findings	Type of study	Comment	Ref
(sulfonyl membrane				simulated seawater containing 32000 mg/L NaCl and 153 mg/L B,55 bar	2020)

3.9. Boron from global perspective

According to findings of the present study, the highest boron concentration of 25-100 mg/L was found in the waters in Poland, and the lowest concentration of 0.10–1.99 mg/L was found in Pakistan, and the concentration of boron reported in Geothermal waters was higher than surface and ground waters (Table 4 and Figure 2). The WHO and United States guideline value was set at 2.4, and 0.6- 1 mg/L, respectively (Table 3). One study reported that the mean boron value in seawater is 4.5 mg/L, but it can be more than 9 mg/L in many districts such as the Mediterranean Sea (Najid et al., 2021).

Another study reported that the boron concentration of DaQaidam saline lake in China to be above 600 mg/L, while the boron concentration of the hot spring water ranges from 39.8 to 49.5 mg/L (Yu et al., 2018). Loizou et al. reported that boron concentration in ground water ranges from above 0.3 to below 100 mg/L (Loizou et al., 2010). The level of boron concentration in potable water varies extensively based on the source of the potable water. However, it ranges from 0.1 to 0.3 mg/L for most of the world regions (Kmiecik et al., 2016). In seawater, the boron level ranges from 0.5 to 9.6 mg/L, and its mean level varies from 4.5 mg/L to 4.6 mg/L. High boron concentration is also a popular specification of geothermal water sources (Tomaszewska & Szczepański, 2014), particularly when TDS is above 1000 mg/L.

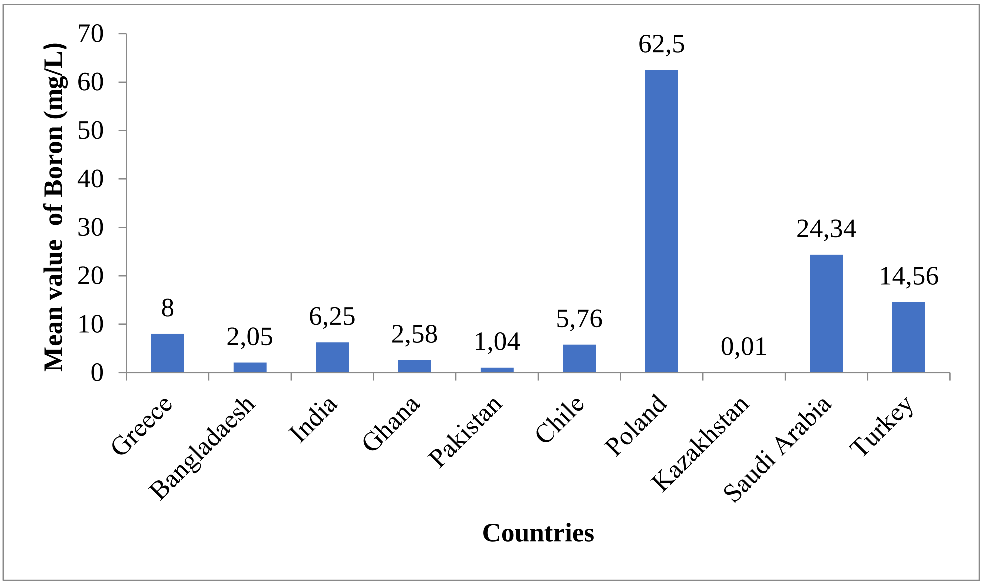

Figure 2. Mean value of boron in groundwater of various countries

Table 4. Water quality criteria for boron

Country/Organization	Concentration (mg /L)	Ref
World Health Organization	2.4	(Edition, 2011)
United States Environmental Protection Agency	NA	(Sasaki et al., 2018)
Canada	5	(Wolska & Bryjak, 2013)
Australia	4	(Wolska & Bryjak, 2013)
United States	0.6-1	(Wolska & Bryjak, 2013)
New Zealand	1.4	(Wolska & Bryjak, 2013)
Brazil	5	(Guan et al., 2016)
Spain	1	(Ruiz-García et al., 2019)
Iraq	0.1	(Najid et al., 2021)
Saudi Arabia	0.5	(Najid et al., 2021)
China	0.5	(Hu et al., 2016)

Country/Organization	Concentration (mg /L)	Ref
Iran	5	(IoSaIRo, 2010)

Table 5. Boron concentration in surface and ground waters from several countries

Regions/countries	Boron concentration (mg/L)	Ref
Greece	8	(Yilmaz et al., 2006)
Bangladesh (Coastal belt)	0 - 4.10	(Rahman et al., 2021)
India (Pune district)	0.10–12.40	(Kadam et al., 2020)
Ghana (NE region)	0.03–5.13	(Zango et al., 2019)
Pakistan (Punjab Province)	0.10–1.99	(Hassan & Nawaz, 2014)
Chile (North)	0.22 - 11.30	(Cortes et al., 2011)
Poland	25-100	(Chruszcz-Lipska et al., 2021)
Kazakhstan (Ilek river)	0.012-0.024	(Pavlichenko et al., 2018)
Saudi Arabia (Jeddah)	3.70-44.98	(Rehman & Cheema, 2017)
Turkey (Balcova)	Surface water 0.02-9.49, Geothermal water 7.8-21.33	(Aksoy et al., 2009)

4. Conclusions

The presence of boron in seawater and geothermal water is the issue of special global attention owing to its toxicity and potential effect on humans, plants, and animals' health. As a result, several techniques, such as solvent extraction, adsorption, ion exchange resin, chemical coagulation, membrane processes, and hybrid processes have been suggested for boron elimination from seawater and geothermal water. Boron elimination by using membrane process (i.e. RO, MF, and ED) is very effective with elimination efficiency of 79-99.6%. Among disadvantages of these processes are pH pre-adjustment, scaling, and generation of salt waste. Chemical coagulation with hydroxyapatite, lime, and aluminium sulphate with removal efficiency of 99.4% is also used for boron removal. Disadvantages of these processes include waste generation, high price, and problem with ultimate disposal. Ion exchange resin is one of the most effective, widely used techniques with boron elimination efficiency of 5.1-97.5%.

Among limitations of this technology are the challenge of waste disposal, high-cost regeneration, and clogging. Adsorption is one of the most efficient techniques for boron removal from water and wastewater. Further, its elimination efficiency has been reported to be more than 93%. Boron removal is mainly dependent on high pH and high temperature. The elimination of boron by EC is very effective, and the removal efficiency of this technique has been reported to be about 98%. Generally, it is difficult to choose the best treatment that permits a good removal of boron. Each method has its own advantages and disadvantages.

Nevertheless, it is worthy to note that using a hybrid system might be more economically and ecologically beneficial, as well as promising due to the above-mentioned benefits. Future studies should be focused on obtaining this composition with continuous stirred-tank reactor from bench scale to full scale application of renewable energies. Sum, at present, most studies only discussed the effect of a single factor or lack of depth studies. Hence, further evaluation is needed to describe all factors effects and mechanism techniques.

Authors' contributions

Abdolmajid Fadaei was responsible for the conceptualization, design of the study, and interpretation of data, and drafted the article. Author read and approved the final manuscript.

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