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Chemical oxo-precipitation method: A Sustainable approach towards boron wastewater treatment

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ABSTRACT

High boron levels in water or wastewater poses an environmental threat. The extraction of boron from water or wastewater is crucial for environmental sustainability. There are various techniques for the removal and recovery of boron from wastewater, such as adsorption, membrane technology, and chemical precipitation. This review presents a concise evaluation of different technologies for boron removal. From the analysis, it is concluded that the chemical oxo precipitation method has several advantages, such as that it produces less volume of sludge and works at room temperature at alkaline pH, which reduces energy cost. However, barium salt chemical oxo precipitation may produce some toxic waste, but these effects can be overcome with the integration of technologies like chemical oxo precipitation with fluidized bed crystallization. Moreover, the method did not require solvent and costly membranes. Therefore, future studies may investigate the integration of technologies with chemical oxo precipitation, regeneration and recycling of precipitant, industrial application, and extensive techno chemical analysis for the green environment.

Key Words:

Boron removal, chemical oxo precipitation, environmental threat, integration, technology.

1. INTRODUCTION

The demand for boron compounds is rising worldwide, driven by the discovery of new uses for these materials. Numerous countries have specifically increased the use of boron chemicals to enhance economic development. The application of boron includes glass production, cosmetics, wire drawing, fireproofing textiles, and the production of leather and carpets. Boron-based composites are commonly utilized to enhance soil fertility, food preservation and surface cleaning because of its powerful fungicidal and bactericidal properties. Borax, commonly utilized in metal brazing and welding, is recognized for its efficiency. Borate compounds have shown their effectiveness across a range of applications, such as hand washing, detergents (which represent 17% of global borate usage), catalysts, high-energy fuels, and cutting fluids (Neal et al., 2010).

The global boron use in terms of B_2O_3 because of the large deposits of boron that can be mined and accessed from existing boron deposits (Korkut et al., 2012). The boron waste can be processed into borax and 90% of the waste can be converted into borax compounds. It is crucial to extract boron from wastewater to prevent from the potential hazards of water and land contamination such as the effluents from power plants in Pauzhetka, Russia, and Kizildere, Turkey, have boron levels of around 40 mg/L. This caused ecological disasters and permanent damage to Kamchatka rivers. The discharge of borax waste into the environment has been associated with elevated ecotoxicological effects, agricultural risks, and the need for more sanitary landfill sites. These issues demand significant investment and resources for effective management (Kim et al., 2023). Figure 1 depicts the global distribution resources of boron.

There are many methods for recovering and removing boron from wastewater such as precipitation (Siciliano et al., 2022), solvent extraction (Xu et al., 2021), ion exchange (Korkmaz & Günay, 2025), electrocoagulation (Rosadi et al., 2025) and membrane technology (Xie et al., 2025). Tsai and Lo (2015) investigated the recovery of boron from modified calcium hydroxide particles (calcium chloride-modified particles and calcium nitrate-modified particles). The results revealed boron recovery of 77.2% with calcium chloride-modified particles, with calcium nitrate-modified particles, and 67.2% with unmodified calcium hydroxide. A study showed the sustainable use of deep eutectic solvents (DES) for boron recovery. 2-methyl-2,4-pentanediol (MPD DES) was prepared with menthol and thymol. It was discovered that thymol based MPD DES achieved 90.1% boron recovery whereas menthol based MPD DES achieved 83.2% boron recovery (Almustafa et al., 2020).

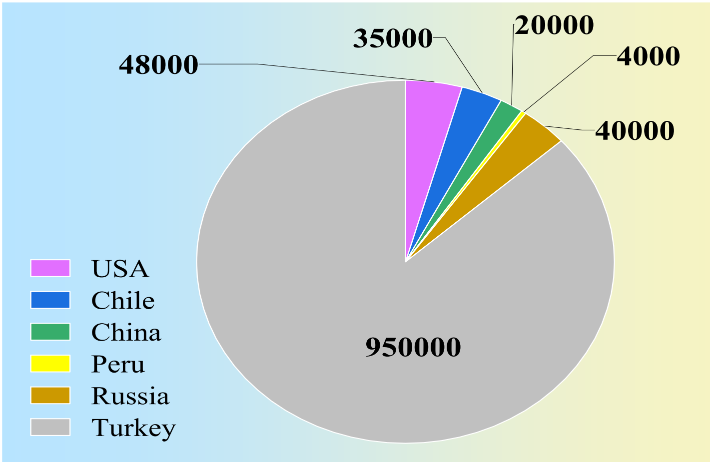

Figure 1. Global distribution of boron in tons (Brioche, 2025)

Shih and Chien (2023) investigated boron recovery from aqueous solution from electrocoagulation method. They formed combination of oxides from copper ferrite, nickel ferrite, and zinc ferrite. The results revealed that oxides formed from nickel and iron, and nickel and aluminum showed greater than 90% boron recovery in an hour with a current density of 12.5 mA/cm² from a 100 mg/L solution. Lou et al. (2023) designed an adsorbent named hierarchical alumina microspheres for boron removal. The process involved a co-precipitation method with the help of microwave radiation. The morphology of the adsorbent 'hierarchical alumina microspheres' was observed as dandelion type with 1.5 µm mean size. The results showed that the adsorption capacity of 'hierarchical alumina microspheres' was observed to be 51.6 mg/g whereas the theoretical adsorption capacity of 138.50 mg/g was obtained, which is consistent with Langmuir model. Moreover, this adsorbent may be efficient for removing boron, even in the presence of interfering ions. These results determine the importance of advanced methods and materials for boron recovery from boron contaminated wastewater.

The chemical oxo-precipitation (COP) method is an efficient method of treating highly boron-contaminated water. COP method requires appropriate oxidizing agent (H_2O_2) to oxidize boron containing water, which then further reacts with metal salts to produce metal borates (Shih et al., 2014). Several researchers also advocate that the chemical oxo-precipitation method is a sustainable approach of treating boron-contaminated water (Khatoon et al., 2024; Lin et al., 2016; Mahasti et al., 2024; Mahasti et al., 2022). However, these studies are insufficient to fully explore the benefits of the process dynamics. Therefore, the objectives of the study are 1. To analyze and evaluate various methods for boron removal and recovery. 2. To compare existing methods with the chemical oxo-precipitation technique. 3. To identify the limitations of current boron removal systems and provide recommendations for future improvements.

2. Boron Recovery Technologies

2.1 Precipitation

The role of boron is crucial especially for the growth of plants and humans. The appropriate amount of dosage is important. Excessive amounts of boron can lead to negative environmental and health impacts as indicated by various studies (Chong et al., 2009; N. Hilal et al., 2011; Irawan et al., 2011; Kıpcak & Özdemir, 2012) such as higher level of boron can slow down the process of photosynthesis in plants, lower the chlorophyl levels and enhance lignin production that can impact on plant's health (Hilal et al., 2011). Studies on the harmful effects of boron on humans and animals are limited. Moreover, toxicity parameters depend on factors such as exposure frequency, duration, and severity, which make evaluation challenging (Hilal et al., 2011).The main precipitants involved in chemical precipitation of boron are calcium based minerals, calcium hydroxide, alum and ferric salts. The precipitation by alum and ferric salts may be called chemisorption where boron molecules bind strongly to the surface of the formed (Al(OH)3) and $Fe(OH)_3$ flocs (Lin et al., 2021b). These precipitants are effective in treating wastewater having low boron concentration (Lin et al., 2021b).However, high concentration of boron in wastewater can be treated using calcium hydroxide as a precipitant which allows the formation of parasibirskite ($Ca_2B_2O_5 \cdot H_2O$) (Lin et al., 2021b). Yilmaz et al. (2012) studied boron removal in aqueous solution from calcium hydroxide. The results revealed that 96 % boron removal efficiency was achieved at pH 1.0 and a stirring speed of 150 rpm. Table 1 shows the recent literature review for recovery/removal of boron .Tsai and Lo (2015) investigated boron recovery by utilizing modified calcium hydroxide particles namely calcium chloride-modified particles and calcium nitrate-modified particles. The results showed that boron recovery 77.2% (calcium chloride-modified particles), 76.3% (calcium nitrate-modified particles), and 67.2% (unmodified calcium hydroxide) were achieved at 95 °C in 1 hour.

Table 1: Recovery of boron via precipitation

Origin	Precipitating agent	Operating factors	Boron Recovery/Removal (%)	References
Boron containing solution	Ca $(OH)_2$	Initial boron conc:1000 mg/L, Stirring speed:150 rpm, pH:1.0, Temp. 353 K	>96 R	(Yilmaz et al., 2012)
Synthetic boron wastewater	Submicron from $CaCl_2$,Submicron with $Ca(NO_3)_2$, $Ca(OH)_2$	95°C, Reaction time: 1 hr.	77.2, 76.3, 67.2 Re	(Tsai & Lo, 2015)
Industrial wastewater	Ca $(OH)_2$, B_2O_3, $Al_2(SO_4)_3$.18 H_2O	$Ca(OH)_2$:2.01 g B_2O_3: 1 g, Initial pH:8.12, $Al_2(SO_4)_3$.18 H_2O:13.5 g/L	94.8 R	(Ozyurt et al., 2019)
Boron containing water	Calcined oyster shell	P/Ca <0.3, pH >12, Reaction time: 24 hr., Temp:25°C, Shaking speed:180 rpm	>90 R	(Yang 2021)
Oilfield produced water	Bottom ash leachate, $Ca(OH)_2$	pH_i=1, pH_f=11, temperature 40°C, Reaction time: 10 minutes	90 R	(Siciliano et al., 2022)
Boron containing wastewater	Ni(II) hydroxide	Initial boron concentration= 300 mg/L,Ni^{2+}/B=12:1, pH=9-10 at room temp	95.9 R	(Aisawa et al., 2023)

*R= boron removal, *R_e =boron recovery

Siciliano et al. (2022) investigated the utilization of acidic washing of combustion bottom ash (bottom ash leachate) with calcium hydroxide for boron removal from oilfield produced water. The process involves acidifying the water to pH 1, adding bottom ash leachate, and increasing the pH to 11 using calcium hydroxide. The operating conditions included an initial pH of 1, a final pH of 11, a bottom ash leachate dosage of 20 mL/L, and a temperature of 40°C. The results showed that a maximum boron removal of 90% was achieved. Similarly, Ozyurt et al. (2019) used the combined approach of chemical precipitation and coagulation to remove boron from industrial wastewater. Calcium hydroxide was used as precipitant and $Al_2(SO_4)_3{\cdot}18H_2O$ was used as coagulant. The optimized operating conditions were Ca $(OH)_2/B_2O_3$ ratio of 2.01, pH of 8.12, and 13.5 g/L of $Al_2(SO_4)_3{\cdot}18H_2O$ along with an initial boron concentration of 13.23 g/L. The 95% boron removal as B_2O_3 was obtained under these conditions. The use of calcium derived oyster shells is a sustainable approach for boron removal in the presence of phosphorous. The study revealed that pH>12 was beneficial for 90% boron removal as $[CaB(OH)_4]^+$ (Yang 2021) . Boron can also be recovered/remove from co-precipitation method. Aisawa et al. (2023) studied a co-precipitation method which deals with nickel and boron ions. The experimental results revealed that 95.9 % boron removal was achieved at pH (9-10) ,a Ni^{2+} to boron molar ratio of 12:1, and a temperature of 25°C.

From the above studies, it is clear that boron removal relies on the adopted method and operational conditions. Some studies showed 96% boron removal under optimized conditions, whereas sustainable approaches like using oyster shells also show promising results. However, the use of precipitants, pH, initial boron concentration, and temperature play important roles in the boron removal process, indicating that a tailored approach should be based on the specific source of boron.

2.2 Solvent Extraction

Solvent extraction method is one of the highly effective and globally used method for separating and purifying various elements such as lithium and boron. For boron extraction process, water immiscible alcohols having 8-9 carbon atoms are commonly utilized as solvents such as 2-ethylhexanol (Zhang et al., 2016), 2-ethyl-1,3-hexanediol (Liu et al., 2020), 2,2,4-trimethyl-1,3-pentanediol (Peng et al., 2021), and 2-butyl-2-ethyl-1,3-propanediol (Kwon et al., 2005).

Zhang et al. (2016) investigated the boron extraction from Salt Lake brine. The process involved the application of 2-ethylhexanol (an extractant), extraction thermodynamics, and process design to achieve maximum boron recovery. The studied parameters were magnesium concentration, time of extraction, and percentage of extractant used. The efficacy of the process was determined with logarithmic linear regression and thermodynamic analysis. It was observed that 0.7 average association constant was attained with logarithmic linear regression. Furthermore, the process favored exothermic reaction and enthalpy was considered as more important factor. The boron extraction efficiency was found to be 99.5% with 95.5% purity. Fan et al. (2018) proposed a solvent extraction method for boron recovery by employing continuous centrifugal technique, 2-ethyl-1,3-hexanediol and sulfonated kerosene. The findings showed that 98.46% extraction efficiency for boron was achieved with the help of 30% 2-ethyl-1,3-hexanediol 70% sulfonated kerosene, pH of 2.0–3.0, and organic to aqueous solvent ratio of 1:2. Similar findings were obtained in another research for boron extraction from Nd-Fe-B magnet waste. The extraction process composed of counter current extraction and usage of 30% 2-ethyl-1,3-hexanediol 70% sulfonated kerosene extracted 99.5 % boron recovery (Liu et al., 2020).

Table 2 described latest literature on boron recovery using the solvent extraction method. Guo et al. (2020) discovered the application of solvent extraction of boron involving 2,2,4-trimethyl-1,3-pentanediol, -ethylhexanol, and sulfonated kerosene. The process parameters were concentration of mixed alcohols, lithium, and solvent losses. The process showed that one molecule of 2,2,4-trimethyl-1,3-pentanediol reacted with one molecule of boric acid, together make up the complex of two C-O-B ester bonds. The results depicted the 99.95% boron extraction with 99.99 % stripping efficiency.

Deep eutectic solvents play great role in boron extraction for wastewater treatment. A study evaluated the boron extaction method by integrating hydrophobic deep eutectic solvent (thymol or menthol) with 2,2,4-trimethyl-1,3-pentanediol.The results indicated improved boron extraction properties and extraction efficiency of 98% was obtained at pH 2-8 (Almustafa et al., 2021).

Boron may be pressent in nuclear fuels in small amount especially those that are originated from uranium.To extract boron from these nuclear fuels, Saha et al. (2022) examined cloud point extraction technique and calorimetric methods. The methods employed in the extraction system include 2-ethyl hexane-1,3-diol (EHD) and curcumin, dispersed in the surfactant Triton X-114 and bromine water (surface modifier). The function of the surface modifier was to reduce the temperature from 80°C to about 42°C, which allowed >95% boron removal.

Lee et al. (2023) proposed an extraction system composed of 2,2,4-trimethyl-1,3-pentanediol (TMPD)and trioctyl/decylmethylammonium-bis(2,4,4-trimethilpentyl) phosphinate) (ALiCy), for boron recovery from brine.The TMPD was used in solvent extraction system wheras AliCy was employed in ionic liquid extraction system.The process of optimization consist of different factors such as TMPD and ALiCy concentration, ratio of ionic liquid to Aqueous, temperature, and time. The results showed a 93.8% boron recovery from TMPD system whereas AliCy system attained 72.3% boron recovery.

A study utilized a new method for extracting boron from natural brines. The various operating factors under study were pH, temperature, concentration of 2-butyl-1-octanol, and phase volume ratio. The samples of the natural brines were taken from salar de Hombre Muerto (Argentina) and simulated brines were also prepared for comparison.The results indicated an extra ordinary boron recovery from simulated brines (98.2%) and natural brines (94.2%), respectively.The optimized conditions were pH (5.5), temperature (25 °C), O/A (4), and 2-butyl-1-octanol (2 mol/L).Additionally, dual extraction of different ions such as Li, Mg, K, Na, and Ca were also minimum by adopting this extraction system (Kiemde et al., 2024) .

Huang et al. (2025) explored boron extraction from feebly alkaline Laguocuo Salt Lake, situated in China. The extraction systems composed of 2,2,4-trimethyl-1,3-pentanediol (TMPD), 2-butyl-1-octanol, and sulfonated kerosene. The single and multi-stage experiments were conducted for reverse flow boron extraction. The optimized operating conditions pH(8),O/A (1:1.5) and lesser temperatures were observed for boron recovery. The results indicated >83% boron recovery in single stage experiment, while 98.61% boron recovery was attained in multistage experiments.

Zhang et al. (2016) attaining 99.5% boron recovery, Huang et al. (2025) achieving 98.6%, and Guo et al. (2020) reaching 99.9%. The solvent extraction method demonstrated the higher recovery rates for boron, such as Zhang et al. (2016), Huang et al. (2025), Guo et al. (2020), who achieved 99.5%, 98.6%, and 99.9%, respectively. Extraction systems such as solvents like TMPD and 2-butyl-1-octanol were considered the most effective solvents. The extraction system can be environmentally friendly by utilizing deep eutectic solvents, and their optimization further enhances the boron recovery process. However, complexity, operational cost, and the accumulation of organic solvent in the environment are some of the challenges with this system. Therefore, there is a need for more sustainable techniques for boron removal and recovery.

Table 2: Recovery of boron via solvent extraction

Origin	Extraction system	Boron Recovery/Removal (%)	References
Salt Lake brine	2-ethylhexanol, Kerosene (diluent)	99.5 Re	(Zhang et al., 2016)
Concealed brine	2-ethyl-1,3-hexanediol, Sulfonated kerosene	98.4 Re	(Fan et al., 2018)
Concentrated brine	2,2,4-trimethyl-1,3-pentanediol, 2-ethylhexanol + sulfonated kerosene (diluent)	99.9 Re	(Guo et al., 2020)
Simulated brine	Trimethyl-1,3-pentanediol -based Deep Eutectic Solvents	90.1% (thymol) and 83.2% (menthol) Re	(Almustafa et al., 2021)
Boron containing water	2-Ethyl hexane-1,3-diol (EHD) with curcumin, N,N-dimethylformamide	95 R	(Saha et al., 2022)
Salt Lake brine	2,4-trimethyl-1,3-pentanediol	93.8 Re	(Lee et al., 2023)
Naturally occurring brine	2-ethylhexanol, Diluted kerosene (diluent)	94.2 R	(Kiemde et al., 2024)
Laguocuo Salt Lake	2,2,4-trimethyl-1,3-pentanediol, 2-butyl-1-octanol,sulfonated kerosene (diluent)	>83%(single stage process) and 98.61 %(multistage process) R	(Huang et al., 2025)

*R= boron removal, *R_e =boron recovery

2.3 Adsorption

In adsorption process, a substance known as adsorbent attach to the surface creating a thin film on another surface. This process is particular to the specific target for example, capturing specific element on the specific surface. The adsorbent has the ability to recycle many times to adsorb certain element again (Han et al., 2025). There are several mechanisms, such as hydrogen bonding, chelating properties, and electrostatic interactions in the adsorption method. The boron recovery from chelation mechanism can be seen in recent literature such as by Ju et al. (2025). Furthermore, different hydroxyl groups, acquired from polyhydroxy compounds may enhance the stability, reactivity , and substitution ability of the porous materials (Wang et al., 2023). Glucosamine (Luo et al., 2020), polyol-type materials (Quyen et al., 2025), and bisphenol hydroxyl (Khan et al., 2025) are some of the examples of these kinds of adsorbents. A magnetic hybrid adsorbent was crafted by Oladipo and Gazi (2016) for boron recovery. They modified the adsorbent by employing glycidol in it. The results showed that 70 %-93% boron can be removed from magnetic hybrid adsorbent. Table 3 illustrates some recent studies for boron recovery/removal from different sources. The advantage of the system is the regeneration of the adsorbent, cost effective and less or no interference of sodium and chromium competing ions.

Pinotti et al. (2022) grafted a magnetic composite comprising $CoFe_2O_4$ and MgO for boron removal from boron-contaminated wastewater. Orange juicewas used in the preparation of this magnetic composite material. From this process, 92% of boron was eliminated from a 20 mg/L boron concentration. It was also observed that this composite could remove about 6% more boron compared to magnesium oxide, and the proposed adsorbent can be recovered using a permanent magnet. Shao et al. (2023) studied an advanced system for treating and recovering boron from brine. They evaluated the adsorption and desorption mechanisms of the specific resin, N-methylglucamine resin (D403), for boron recovery. The cyclic process of adsorption and desorption consists of five steps: first, boron is adsorbed using the specific resin; then, the remaining brine is washed with water; next, boron is desorbed; followed by another water wash; and finally, the resin is regenerated and prepared for reuse.

A seven-column simulated moving bed system was also evaluated to improve efficiency. The experimental results showed that the system is effective for low boron concentrations in brine, even at 296.5 mg/L, and can achieve up to 96.8% boron recovery. A study evaluated the performance of DIAION™ CRB05 resin for boron recovery from boron containing water. They utilized Box-Behnken design for optimization of various parameters such as pH, adsorbent dose, boric acid concentration, and time. The results of optimization showed that 98% boron recovery was attained with a pH of 2, an adsorbent dosage of 2000 mg/L, time duration of 255 minutes and an initial boron concentration of 115 mg/L(Al-dhawi et al., 2023). Furthermore, Niu et al. (2024) evaluated the selectivity of boron by incorporating modifications in the structure of resin such as employing branched poly(ethylene imine) (PEI). This PEI then reacted with D-(+)-gluconic acid δ-lactone to enhance the capacity of the adsorbent. The results depicted that the adsorbing capacity of 39.6 mg/g was attained. This may be due to an increase in hydroxyl content because of PEI modification. The presence of coexisting ions did not significantly interfere with the results and the adsorption rate of 75% was achieved.

Younis and Mohamed (2024) designed a modified polyvinyl chloride resin, functionalized with N-methyl-D-glucamine using a methyl glycinate linker, for boron recovery from tourmaline ore from the Sikait area in Egypt, which contains 10.43% B_2O_3. The optimization results demonstrated that 25 mg/g adsorption capacity was achieved under operating conditions of initial boron concentration 150 ppm, pH 6, and time of agitation 10 minutes. Additionally, the purity of boric acid was measured by treating the sample with NaOH, and then adsorption experiments were conducted to get 98.56% pure boric acid having 17.23% of boron content. These results showed the potential of this system for industrial application. Han et al. (2025) developed an adsorbent named CNTs@PDA-PEI-NMDG by applying the Ouzo-effect method. Hollow dopamine nanospheres (HDN) were generated with carbon nanotubes (CNTs) under infrared light. The chelation of boron compounds with glucosamine-derived compounds has much importance; therefore, HDNs were further reacted with Cl-N-methyl-D-glucamine (Cl-NMDG) to absorb 31.09 mg/g within 50 minutes.

Table 3: Recovery of boron via adsorption

Origin	Adsorbent composition	Adsorbent Capacity/efficiency	References
Synthetic boron solution	Composite of $CoFe_2O_4$ and MgO	92 % R	(Pinotti et al., 2022)
Brines	N-Methylglucamine Resin	96.8% Re	(Shao et al., 2023)
Boron water	DIAION™ CRB05 Resin	98 % R	(Al-dhawi et al., 2023)
Salt Lake brine	Composite of chloromethyl polystyrene resin and branched poly(ethylene imine)	39.4 mg/g Re	(Niu et al., 2024)
Tourmaline ore	Composite of Polyvinyl chloride (PVC) ,N-methyl-D-glucamine (NMDG) , methyl glycinate linker	25 mg/g Re	(Younis & Mohamed, 2024)
Salt Lake brine	Composite of carbon nanotubes (CNT), Polydopamine (PDA), polyethyleneimine (PEI), Cl-N-methyl-D-glucamine (Cl-NMDG) formed CNTs@PDA-PEI-NMDG	31.09 mg /g Re	(Han et al., 2025)

*R= boron removal, *R_e =boron recovery

The adsorption studies demonstrated high selectivity and recyclability for boron recovery. Some systems achieved over 90% boron recovery, such as those developed by Oladipo and Gazi (2016), as well as Pinotti et al. (2022). Functionalization of materials with groups like hydroxyls enhances boron adsorption efficiency. Additionally, the desorption and regeneration processes showed high efficacy, with up to 96.8% recovery and stability over multiple cycles, demonstrating strong regenerative potential. The development of advanced materials, such as CNT-based adsorbents using photothermal methods, offers improved kinetics and higher capacities. However, the complexity of synthesizing such materials often requires significant capital, which presents challenges for large-scale applications. Future research should focus on operational constraints, potential environmental impacts, and addressing limited capacity and kinetic data.

2.4 Membrane Technology

Membrane technology involves the utilization of a semi-permeable membrane where a sample of wastewater passes through it and retains certain particles. The factors that impact the membrane technology are pressure, temperature, and electric fields. There are different methods involved in membrane technology, such as reverse osmosis (RO), ion exchange membrane processes like electrodialysis (ED) and Donnan dialysis (DD), forward osmosis (FO), and membrane distillation (MD) (Liu et al., 2022).

Reverse osmosis performs effectively under alkaline pH. The acidic condition badly affected the boron removal, and only 50% boron removal efficiency was obtained under neutral or acidic conditions. The reason is that at pH 7 or below, the boron molecules have the tendency to be ionized at acidic pH (Tu et al., 2010). There are some important factors that greatly impact the working of the RO system for boron removal and recovery, such as pH, salinity, recovery ratio, initial boron concentration, and lower temperature. The boron removal efficiency may be enhanced with the modification in the structure of the RO membrane, such as the integration of UiO-66 nanoparticles into polyamide (PA) nanocomposite membranes, resulting in a boron rejection rate of 11% (Liu et al., 2019), and the addition of 4-nitrobenzenesulfonyl chloride (NBS) into the polyamide (PA) layer of the membrane, resulting in a boron rejection rate of 93.10% (Li et al., 2020).

The table 4 shows boron removal/recovery from different sources. Hung et al. (2022) evaluated the membrane technology for the recovery of boron for meeting standards of Taiwan environmental agency. They used bipolar membrane electrodialysis in intermittent and continuous modes for boron removal/recovery. The factors examined were pH, current density and boron concentration. The findings revealed that at pH range (9.5-10.5), current density (6.36 A/m2), and voltage (12 V) removed 98.6% of boron, and attained 86.5% boron recovery. Moreover, batch experiment attained the similar results achieving 98.53% boron removal, and 81.2% boron recovery. Finally, <10 mg/L of residual boron was attained, which met the environmental regulations of Taiwan. Duan et al. (2022) developed a reverse osmosis membrane for boron removal composed of sulfonated groups, polyvinyl alcohol, and benzaldehyde disulfonic acid disodium salt. The mechanism involved the reaction between poly vinyl alcohol and boric acid, which formed complexes whereas sulfonate group helped to reduce sites of hydrogen bonding along with reduced diffusion rate of boron. This facilitates the boron removal. The results demonstrated 85.71% to 91.63% removal rate of boron, with 44.41 m^2/h elevated flux under sea water conditions.

The chemistry and structure of the membrane may have a profound impact on boron removal. A recent study examined the effect of utilizing carbon nanotubes cellulose (CNTs), nanofibers (CNFs) and polyamide membrane (CNT–CNF–PA) on boron removal. A low-pressure system of 0.75 MPa was developed in reverse osmosis. The reverse osmosis filtration operation composed of the solution containing 500 ppm of sodium chloride, 5 ppm of boron, and pH of 7. After analysis, the results demonstrated that the integrated membrane CNT–CNF–PA achieved the high rejection rate of boron (74%). Furthermore, roughness of the surface facilitated the boron rejection mechanism whereas sodium chloride and boron rejections were related to pore structure (Fajardo-Diaz et al., 2023) .

The membrane distillation (MD) process is commonly used for removing boron from concentrated water. A study evaluated the performance of membrane distillation unit by introducing vacuum supported air gap unit for boron removal. Different recovery ratios were adopted for raw water and reverse osmosis concentrate. Furthermore, the operational parameters of the study were pressure, removal efficiencies, conductivity, and flow rates. The study observed concentrated boron crystals of 43.9% B_2O_3 (Mutlu-Salmanli et al., 2023) . Kim and Kim (2024) studied a novel approach for boron removal by the application of redox assisted electrodialysis with ion exchange method. This system did not require pH control due to the pH change produced by employing ion exchange resins locally. The results indicated a 99% boron removal efficiency at a very low energy usage of 0.09 kWh/m^3. Additionally, cost analysis displayed a 50% decrease in cost as compared to old electro deionization system. Zhao and Liang (2024) investigated the modification in membrane technology for enhancing boron removal. They integrated layered double hydroxides, N-methyl-d-glucamine polyols, and utilizing tannic acid as a binding agent. The membrane formed due to these integration may be called a thin film nano-composite membrane (TFN).The TFN membrane showed 78.6 % boron rejection rate, 99.4 % salt rejection, and 3.0 LMH /bar enhanced water permeance.

Xie et al. (2025) investigated the utilization of zinc-air battery(ZAB), assisted with bipolar membrane (BPM) technology for the removal of boron from wastewater. The mechanism of bipolar membrane showed that application of electric field formed OH^- ions. These ions react with boric acid to form $B(OH)^{4-}$. The zinc ions from anode reacts with $B(OH)^{4-}$ to form zinc borate. The factors of optimization include NaCl 3.0 g/L, 100 mg/L boron, zinc anode, and charcoal felt cathode, and 10 mL/min flow. The results indicated a 58.3 % boron recovery whereas two units of ZAM-BPM produced 60.8% boron recovery. The technology also had an additional advantage of self-sustained energy production.

The application of machine learning in the areas of boron recovery/removal process technologies may enhance the resource recovery and water quality. Recent literature showed that the integration of XGBoost model and particle swarm optimization may be used to enhance boron recovery optimization in forward osmosis process. The performance of the model was measured by evaluating different parameter such as , pH, boron concentration, and membrane orientation. The results indicated highest prediction accuracy of R^2 = 95.4% with highest boron rejection rate of 98.28% (Wang et al., 2025).

These studies demonstrated the effectiveness and versatility of membrane technologies such as electrodialysis, reverse osmosis, and membrane distillation techniques. Studies have described the recent literature on boron removal by membrane technology, observing a maximum boron rejection rate of >90% when optimizing factors. The integration of membrane technology with the other systems may enhance the boron removal efficiency, such as the utilization of bipolar membrane electrodialysis (BMED) and zinc-air batteries (ZAB). Moreover, membrane technology may be modified to enhance boron removal efficiency. Additionally, emerging technologies like XGBoost and particle swarm optimization may assist researchers in achieving accurate boron recovery from various resources. The limitations of membrane technology include specific pH conditions, fouling and stability issues, membrane costs, challenges in selective removal, and limited data on scalability and long-term operation

Table 4: Recovery of boron via membrane technology

Origin	Filtration mode	Boron recovery/Removal (%)	References
Boron containing wastewater	Electrodialysis	86.5 Re	(Hung et al., 2022)
Industrial wastewater	Membrane Technology	91 R	(Duan et al., 2022)
Boron containing water	Membrane technology	74% R	(Fajardo-Diaz et al., 2023)
Reverse osmosis concentrate water	Membrane distillation	43.9 R	(Mutlu-Salmanli et al., 2023)
Boron containing water	Electrodialysis	>98 R	(Kim & Kim, 2024)
Boron containing water	Nanofiltration	78.6 R	(Zhao & Liang, 2024)
Boron containing water	Electrodialysis	60.8 Re	(Xie et al., 2025)

*R= boron removal, *R_e =boron recovery

2.5 Chemical oxo-precipitation

Shih et al. (2014) define chemical oxo-precipitation as the process in which an oxidizing agent, such as hydrogen peroxide, first reacts with boron-contaminated wastewater and alters its pH to become alkaline. Subsequently, it reacts with metal salts to form boron precipitates at room temperature.In Eq-1 boric acid reacts with hydrogen peroxide (oxidizing agent) to form peroxyborate compound which then react with metal salts in Eq-2 to form metal borate (Lin, 2016).

$$H_3BO_3 + H_2O_2 \rightarrow H_2O + H_3BO_4 \quad (1)$$

$$H_3BO_4 + X^{m+} + OH^- \rightarrow X(BO_4)_n \quad (2)$$

Where

X^{m+} is the metal cation.

$X(BO_4)_n$is the metal borate.

Shih et al. (2014) developed a compelling alternative technique to traditional methods for the removal of boron from boron-containing water. The Chemical Oxo-Precipitation Method (COPM) reduced chemical and energy requirements by utilizing an oxidizing agent at room temperature. The results revealed that H_2O_2 showed excellent performance as oxidizing agent in boron removal as compared to Na_2O_2, $KMnO_4$, and $Na_2S_2O_8$ and $BaCl_2$

demonstrated unexceptional performance for boron removal as compared to $CaCl_2$, $MgCl_2$, and $SrCl_2$.Barium chloride achieved 98.5% boron removal under the operating factors of $[H_2O_2]/[B] = 2$ and $[Ba]/[B] = 1$.

Lin (2016) instigated the perborates reaction and barium per borate re-precipitation in chemical oxo precipitation process, where barium hydroxide and hydrogen peroxide were used as precipitant and oxidant , respectively. The maximum boron recoveryof 99.7% was achieved under the operating conditions of pH 10.5, with $[H_2O_2]/[B] = 2$ and $[Ba]/[B] = 1$, within four hours. XRD analysis revealed the changing in the structure of boron precipitates (amorphous to crystalline). The boron compounds also showed migration such as $BaB(OH)_3OOB(OH)_3$, $Ba(B(OH)_3OOH)_2$, and ultimately $BaB(OH)_2(OO)_2B(OH)_2$. The study did not address the practical viability to real time boron contaminated wastewater. Similarly, the authors achieved the same boron removal efficiency of 99.7% by using barium chloride as precipitant and hydrogen per oxide as oxidant under operating conditions of H2O2]/[B] = 2, [Ba]/[B] = 0.8, pH= 10.5 within 20 minutes (Lin et al., 2016).

Tsai et al. (2019) developed a silica-based membrane known as mesoporous alumionsilicate (MAS). The membrane has a nanostructure of size 12.8 mm. The adsorption of barium ions (Ba^{2+}) was conducted through MAS and attained an adsorption capacity of 105 mg/g in a fluidized bed system. Subsequently, the chemical oxo precipitation method was employed to form barium peroxoborate precipitates. The precipitates are then subjected to a high temperature of 1050°C to produce barium borate. The process recovered 84.5% boron, and a 93.4% crystallization ratio was attained. The utilization of MAS, which was made up of waste material, demonstrated that the process was aligned with the circular economy principle. The study lacks regeneration of MAS and did not provide enough information for the usage of hydrogen peroxide and barium salt. Moreover, high temperature may incur additional energy and environmental costs.

Yu et al. (2022) studied the utilization of the chemical oxo precipitation method for sustainable practice in hydraulic fracturing systems. The precipitation system involves the use of barium chloride as a precipitant and hydrogen peroxide as an oxidant. The results revealed maximum boron removal efficiency of 95.5% at pH (pre-treatment) of 9, time of 30 minutes, pH (reaction) of 10, and reaction time of 360 minutes. The remaining boron concentration after the reaction was 6.76 mg/L. The study emphasized the importance of $[H_2O_2][B]$ and [Ba][B] for boron removal efficiency. The study lacks cost analysis, upscaling the project, and environmental issues related to the proposed technology.

A study addressed the problem of toxic waste produced by the use of barium salts in the oxo precipitation process. In this study, two types of systems, such as single-stage and multi-stage systems, were studied. Calcium chloride reacts with oxidized boric acid water to form calcium perborate, calcium carbonate, and calcium peroxide at pH 11. The reaction is followed by an adsorption reaction, and 97% and 99.5% boron removal efficiencies were achieved by single- and multistage systems, respectively. Moreover, a 45% reduction in cost was observed in the multistage system. In a single-stage process, calcium borates are fragmented and calcium is depleted. The study was not performed in real-time boron-containing wastewater, and the thermodynamics and kinetics of the adsorption process involved in this technology were not studied (Mahasti et al., 2022) .

Similarly, Lin et al. (2021a) developed a fluidized-bed-based crystallization system for boron removal. The aim of the study was to eliminate the environmental issues of the contaminated sludge and work beyond the limitation of the batch system. The chemical oxo precipitation process in the fluidized bed system enhanced the boron removal and achieved 85% boron removal efficiency and a crystallization ratio of 83%. The system observed a 95% confidence interval for crystallization ratio and boron removal efficiency. The system gave several advantages, such as cost-effectiveness, reduction in water content in the sludge, and sludge disposal. Mahasti established a multistage system for boron removal from the wastewater originating from power plants. The pH for the first two stages was 10.5, and the third stage has a pH of 11. The oxidant-to-boron ratio $[H_2O_2]$/ratio of 2 was taken for all three stages. Additionally, the molar ratio of calcium to boron [Ca] is a[B] ratio of 1.5:1 for all three stages. The system involving the chemical oxo precipitation process achieved 99.6% boron removal. The limitation of the system was the interference of the competing ions, such as sulphate and magnesium. Magnesium ions with Mg/B > 0.5 produced hindrance in boron removal. The system showed potential to be used in the industrial sector, whereas the system might need readjustment according to the type and requirement of the industry.

Chemical oxo-precipitation is also effective for treating acidic boron-containing wastewater. A study utilized this method to treat highly concentrated boron solution obtained from a desorption process using hydrochloric acid (HCl) after flue gas desulfurization. The process was optimized using central composite design, and the results revealed that a maximum boron recovery of 94% was achieved at H_2O_2/B and Ca/B ratios of 3.5, and at a pH of 9 at room temperature (Bok-Badura et al., 2025). Similarly, Khatoon et al. (2024) recovered 97% of boron from synthetic oilfield-produced water. This process was optimized using the Box-Behnken design, with optimal parameters being a pH of 10, a reaction time of 90 minutes, $ZrCl_4$/B ratio of 2, and H_2O_2/B ratio of 2.5. Future studies may require economic feasibility and actual industrial application.

Table 5: Recent studies on boron removal using chemical oxo precipitation method

Origin	Precipitating agent	Oxidizing agents	Operating factors	Boron Recovery/boron removal (%)	References
Boron containing water	$BaCl_2$	H_2O_2	$[H_2O_2]/[B] = 2$ and $[Ba]/[B] = 1$	98.5 R	(Shih et al., 2014)
Boron containing water	Ba $(OH)_2$	H_2O_2	pH=10.5,$[H_2O_2]/[B] = 2$ and $[Ba]/[B] = 1$	99.7 Re	(Lin, 2016)
Boron containing water	$BaCl_2$	H_2O_2	pH=10.5,$[H_2O_2]/[B] = 2$ and $[Ba]/[B] = 0.8$, time=20 minutes	99.7R	(Lin et al., 2016)
Boron wastewater	Ba^{+2} ions	H_2O_2	pH=10.5,$[H_2O_2]/[B] = 2$ and $[Ba]/[B] = 1$	84.5 R_e	(Tsai et al., 2019)
Fracturing wastewater	$BaCl_2$	H_2O_2	$[H_2O_2]/[B] = 4$ and $[Ba]/[B] = 2$, pH_t=9 (30 min), pH_R=10 (360 min)	95.5 R	(Yu et al., 2022)
Boron wastewater	$CaCl_2$	H_2O_2	pH=11,$[H_2O_2]/[B] = 3$ and $[Ca]/[B] = 1.5$, time=15 minutes (single stage process0	97 R	(Mahasti et al., 2022)
Boron wastewater	$BaCl_2$	H_2O_2	pH=10,$[H_2O_2]/[B] = 1.5$, $[Ba]/[B]$ =0.8, barium per borate granules as fluidized medium,	85 R	(Lin et al., 2021a)
Coal fired power plant wastewater	$CaCl_2$	H_2O_2	$pH_1 = pH_2 = 10.5$, $pH_3 = 11.0$, $[H_2O_2]/ [B]$(for all stages) = 2, $[Ca] /[B] = 1.5:1$(for all stages)	99.6 R	(Mahasti et al., 2024)
Synthetic produced water	$ZrCl_4$	H_2O_2	pH=10,$[H_2O_2]/[B] = 2.5$, $[Zr Cl_4]/[B] = 2$ and time=90 min	97 R_e	(Khatoon et al., 2024)
FGD wastewater	$CaCl_2$	H_2O_2	pH=9,$[H_2O_2]/[B] = 3.5$ and $[Ca]/[B] = 3.5$	96.8 Re	(Bok-Badura et al., 2025)

*H_2O_2 Hydrogen peroxide, *Na_2O_2 sodium peroxide, *$KMnO_4$ per manganite, *$Na_2S_2O_8$ peroxydisulfate, *$CaCl_2$ calcium chloride, *$MgCl_2$ magnesium chloride, *$BaCl_2$ Barium Chloride, *$SrCl_2$ strontium chloride, *Ba $(OH)_2$ Barium hydroxide, *pH_t pretreatment pH,* pH_R reaction pH, *R boron removal, *R_e boron recovery, *FGD flue gas desulfurization

3. Comparison of Chemical oxo precipitation with other methods

Table 6 shows a comparison of different extraction methods in relation to the chemical oxo-precipitation approach for recovering boron. There is less sludge produced by chemical oxo-precipitation for boron recovery as compared to traditional chemical precipitation procedures since the oxidant is so important in promoting the precipitation reaction. Solvent extraction method demonstrate high efficiency, careful pH control and solvent management whereas chemical oxo precipitation operations are simple, cost effective, and environment friendly (Khatoon et al., 2024). Although membrane methods like nanofiltration and reverse osmosis are quite effective at removing boron, they may be rather expensive to operate and need a lot of energy (Najid et al., 2024). Furthermore, fouling is a common problem with membrane systems, which means that replacement and maintenance are needed regularly to keep them running well (Najid et al., 2024). Unlike adsorption and membrane technology, which need adsorbents or membrane materials, chemical oxo-precipitation doesn't require these, making it a more cost-effective choice in that regard.

Table 6: Comparison of boron recovery techniques versus the chemical oxo-precipitation method.

Boron recovery techniques		**Chemical-oxo-precipitation method**
Chemical Precipitation	High sludge volume.	Less sludge volume
Solvent Extraction	Environmental risks associated with the use of organic solvents.	No organic solvent is used
Adsorption	Limited capacity to remove contaminants..	That issue does not exist.
Membrane Technology	Membrane fouling and expensive membranes	That issue does not exist.

4. Future Perspective

Future studies for boron recovery may include the following

1. Machine learning and the use of artificial intelligence in optimizing parameters for maximum boron
2. removal/recovery with the chemical oxo-precipitation method may enhance the full potential of this method.
3. The chemical ox-precipitation for the boron removal method has been tested at laboratory scale, so the effectiveness of this method at a larger scale should be evaluated.
4. The combination of various technologies such as adsorption, membrane technology and solvent extraction with chemical oxo-precipitation method may enhance the efficiency of the boron removal from wastewater.
5. For larger-scale applications, cost analysis of the method should be conducted.
6. The method of regeneration of precipitating agents after the chemical oxo precipitation method may be evaluated for future studies.

5. CONCLUSION

Boron removal and recovery have paramount importance because its recovery not only benefits the environment but also becomes a valuable resource and can be used in different industries such as glass, ceramics, fire extinguishers, and many other applications. Among various methods of boron removal and recovery, chemical oxo-precipitation is recognized as the most efficient and sustainable method. Future studies may include integration of technologies and machine learning applications with the chemical oxo precipitation method for sustainable recovery of boron.

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CONFLICT OF INTEREST

There is no conflict of interest between all the authors

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