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Original Research Article

Boron Removal from Produced Water Using Strontium Chloride-Mediated Chemical Oxo-Precipitation

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ABSTRACT

Produced water from oil and gas extraction poses a major environmental challenge due to its high boron content and associated risks to ecosystems and human health. Traditional boron removal methods suffer from high costs, limited efficiency, and the generation of secondary pollutants. This study presents a comprehensive assessment of strontium chloride as a precipitating agent in an optimised chemical oxo-precipitation process for removing boron from produced water. Through systematic variation of critical operational parameters, including pH, reagent dosages, and mixing speed, the treatment achieved nearly 85% boron removal under optimal conditions. Toxicity evaluation using *Lactuca sativa* L. lettuce seeds revealed a 133% increase in the median lethal dose after treatment, demonstrating substantial mitigation of ecological risk. The process embodies key principles of green chemistry by minimising hazardous byproducts, employing safer chemicals, and reducing sludge generation compared with barium-based methods, thereby improving safety for both workers and the environment. Therefore, this methodology directly contributes to the United Nations Sustainable Development Goals by advancing water quality improvement, promoting the reuse of treated water, minimising pollutant discharges, and supporting the protection of terrestrial ecosystems and public health through sustainable innovation.

KEYWORDS

Boron removal, Chemical oxo-precipitation, Phytotoxicity, Strontium chloride, Sustainable water treatment, Oxo-precipitation process.

INTRODUCTION

Water remains an indispensable resource for sustaining human, plant, and animal life [1]. In recent years, global attention has increasingly shifted toward the multifaceted challenges of climate change [2].

Boron is ubiquitous in the environment, occurring in the lithosphere, hydrosphere, and biosphere. In soils, total boron concentrations typically range between 5 and 30 parts per million (ppm), although only about 1–3% of the total boron is water-soluble and thus bioavailable for plant uptake [3], [4]. Weathering of borosilicate minerals – most notably tourmaline, but also minerals such as colemanite, borax, and kernite – liberates boron into the

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soil, where it predominantly occurs as uncharged boric acid under neutral to slightly acidic conditions [4], [5].

In aquatic environments, boron is primarily present as boric acid and borate ions. Seawater typically harbours around 4.6 mg/L of boron, and its concentration in fresh and groundwater can vary widely depending on factors such as soil composition, evaporation, and anthropogenic inputs [3], [4]. Additionally, boron may be associated with organic matter and colloidal fractions in both water and sediments, where interactions with humic substances and clay minerals significantly influence its mobility and bioavailability [3], [4]. Rapid population growth has intensified air and water pollution, driving an unprecedented demand for natural resources [6].

Boron is considered a critical micronutrient for a wide range of living organisms due to its unique biochemical properties. In plants, for instance, approximately 90% of boron is localised in cell walls where it forms borate diester bonds with pectic polysaccharides such as rhamnogalacturonan II (RG-II). This cross-linking is essential for maintaining cell wall integrity, ensuring proper cell-to-cell adhesion, and permitting regulated cell expansion during growth. Consequently, both boron deficiency and excess can result in severe developmental disruptions, ranging from impaired meristem function and reproductive failure to chlorosis and necrosis in tissues [5], [7].

The importance of boron as a micronutrient is underscored by the extremely narrow window between deficiency and toxicity. In plants, insufficient boron disrupts cell wall assembly and cellular signalling, resulting in symptoms such as deformed cell structures, reduced reproductive success (e.g., panicle sterility in rice), and overall stunted growth. Conversely, excess boron can rapidly lead to toxicity, manifesting as leaf chlorosis, dark brown spots, and eventual cell death, particularly under conditions where soil or irrigation water already contains high boron levels [2], [5]. This delicate balance necessitates precise management of boron in both natural and agricultural settings to avert the adverse impacts associated with either extreme [3].

Excess boron in drinking water poses significant health risks due to its narrow safety margin between essential physiological levels and toxic doses; even modest elevations above recommended guidelines (e.g., 1–2.4 mg/L) can trigger a cascade of adverse effects. In contrast, boron is necessary for processes such as bone health and immune function; its overconsumption has been linked to cellular injury and systemic toxicity [5], [6]. Acute exposure to high boron concentrations typically leads to gastrointestinal distress – including nausea, vomiting, abdominal pain, and diarrhoea – which has been documented in both controlled animal experiments and human poisoning incidents, where toxic doses have been reported to range from approximately 100 mg up to several grams, underscoring the element's potential for rapid toxicity upon ingestion [6].

The World Health Organization's (WHO) recommended maximum boron concentration in drinking water is 2400 µg/L. This guideline, established in 2011, was derived from a tolerable daily intake (TDI) of 0.17 mg/kg body mass per day [7]. In contrast, produced water, a byproduct of industrial and energy extraction activities, frequently exhibits boron concentrations that are orders of magnitude higher, ranging from tens to hundreds of milligrams per litre. This elevated boron content in produced water primarily results from natural geological sources: boron is leached from borosilicate minerals and borate-rich substrates via weathering processes and mobilised by geothermal and volcanic activities [8]. In addition, anthropogenic sources, such as municipal wastewater discharges, power plant effluents, and chemical landfill leachates, further contaminate produced water with high boron levels. The drastically higher boron levels in produced water, compared to the stringent WHO drinking water guideline, underscore the significant challenges in treatment processes – particularly for reverse osmosis systems (RO) – that must remove boron to meet safe water standards [8].

Current treatment technologies and limitations

Boron removal from produced water has been investigated using a wide range of technologies, including adsorption, ion exchange, membrane-based separations, electrocoagulation, and chemical precipitation methods [9]. Each of these approaches exploits different mechanisms to address the complexity of boron speciation, which exists mainly as neutral boric acid at low pH and as borate anions at higher pH.

Ion exchange resins and adsorption processes were among the earliest methods tested. Ion exchange resins provide high selectivity for boron removal and can achieve effective separation; however, they are often expensive, require complex regeneration procedures, and can be susceptible to interference from competing ions present in complex produced water matrices [9]. Similarly, adsorption using natural or synthetic adsorbents, such as activated carbon, has been demonstrated. Yet, these systems generally exhibit reduced adsorption capacity and face challenges with adsorbent exhaustion and regeneration over extended operational periods [10].

Membrane-based technologies, including RO, nanofiltration (NF), and electrodialysis (ED), have also been extensively explored. These processes can achieve high boron removal rates by operating at elevated pH to convert boric acid into borate ions, which are more effectively rejected by membranes; however, they come with significant drawbacks such as membrane fouling, scaling, high operational energy demands, and the necessity for multi-stage systems to meet stringent regulatory discharge limits [10], [11].

The electrocoagulation (EC) process has emerged as another promising option and works by applying an electrical current to sacrificial electrodes (commonly iron) to release metal hydroxide flocs that adsorb boron from solution. Under optimised conditions – typically at neutral pH with controlled current density and contact time – EC has been reported to achieve removal efficiencies exceeding 96%, and it benefits from relatively low energy consumption and minimal sludge production; nevertheless, its performance is sensitive to operational parameters and necessitates careful sludge disposal management [12].

Among the various methods examined, the chemical oxo-precipitation (COP) process has proven to be the most effective for boron removal from produced water. This method employs an oxidant, such as hydrogen peroxide, to transform boron species – converting inert boric acid into more reactive peroxoboron complexes – which can subsequently react with alkaline earth metals like barium to form stable, crystalline precipitates (e.g., barium borate) at room temperature and near-neutral to mildly alkaline pH, as discussed in [13] Chapter 8, and [14]. COP not only achieves near-total removal (up to 98.5%) but also offers significant operational advantages by reducing energy consumption, chemical input, and sludge generation. In addition, the precipitates formed are amenable to further processing for boron recovery, thereby enhancing resource sustainability. This combination of high efficiency, lower operating costs, and environmental friendliness establishes chemical oxo precipitation as the best technology from those tested for boron removal from produced water.

Precipitant Selection and Research Rationale

Chemical oxo-precipitation for boron removal routinely employs metal-based precipitants, with magnesium and barium compounds being the most common choices [15], [16]. Magnesium hydroxide, for instance, has been widely used owing to its low cost, abundance, and ability to efficiently adsorb boron when the pH is properly controlled [16]. In contrast, barium-based precipitants have demonstrated very high removal efficiencies by forming insoluble borate or perborate compounds under near-neutral conditions, often achieving recovery efficiencies exceeding 98% [15].

Notwithstanding their effectiveness, both magnesium and barium precipitants have notable drawbacks. Magnesium precipitates tend to exhibit reduced removal efficiency at low boron concentrations and require strict pH control, which may be challenging under variable

wastewater conditions [16]. Barium salts, while highly effective, raise severe environmental and health concerns due to their toxicity, as residual barium can be hazardous to both human and ecological receptors [17]. Moreover, both types of precipitants generate substantial volumes of co-precipitates or sludge that necessitate additional treatment and safe disposal, thereby increasing operational complexity and associated costs [17].

Strontium chloride, however, possesses several attributes that position it as an attractive alternative precipitant for boron removal. Its ionic characteristics are favourable for boron binding; strontium ions can interact with borate anions to form stable, low-solubility strontium borate complexes that may precipitate more selectively from produced water [15]. This mechanism is expected to reduce the risk of secondary pollution by lowering the overall volume and toxicity of the resulting sludge compared with barium-based systems [15]. In addition, the lower inherent toxicity of strontium relative to barium and its potential for operation under less stringent pH control could improve both safety and cost-effectiveness in practical applications [15]. Despite these promising attributes, strontium chloride has not been extensively tested in the context of produced water; hence, further investigation is needed to validate its performance and operational benefits.

Toxicity assessment is critically important in this context because produced water comprises a complex mixture of contaminants that may persist even after chemical treatment [18]. Conventional chemical analyses often overlook the biological impacts of residual byproducts, making it essential to evaluate toxicological endpoints through sensitive bioassays [19]. *Lactuca sativa* L., in particular, is an established model for acute phytotoxicity testing due to its rapid growth, sensitivity to chemical stressors, and ease of use under laboratory conditions [20].

Given these considerations and the identified knowledge gaps, this study was designed to systematically investigate the application of strontium chloride as a precipitant in the chemical oxo-precipitation process for boron recovery from produced water. The research encompasses comprehensive process optimisation by varying critical operational parameters, including pH, precipitant and oxidant dosages, and initial mixing speed, to maximise removal efficiency. Additionally, acute phytotoxicity was assessed using *Lactuca sativa* L. seeds as bioassays to evaluate the environmental safety of both produced water and treated effluent following chemical oxo-precipitation. This integrated approach addresses both the technical efficacy and environmental safety aspects of the proposed treatment technology, providing a comprehensive foundation for potential industrial implementation.

MATERIALS AND METHODS

This section presents the materials, experimental procedures, and design methodology used in this study. The investigation employed a comprehensive, multi-phase experimental approach to evaluate the performance of strontium chloride-mediated chemical oxo-precipitation for boron removal from produced water and to assess the ecological safety of treated effluent through phytotoxicity testing. The experimental protocol integrated systematic process optimisation and rigorous toxicity assessments, balancing both technical performance and environmental impacts. The workflow was structured in three interlinked domains: precipitant efficacy screening, operational parameter optimisation using a factorial design, and environmental evaluation via standardised plant bioassays. Synthetic produced water was used throughout to ensure reproducibility and eliminate variability arising from complex field matrices. This framework supports robust inter-comparisons with existing literature and subsequent pilot-scale validation.

Materials and Chemical Reagents

All reagents were of analytical grade. Boric acid (H_3BO_3, ≥99.5%) was used to formulate synthetic produced water. Strontium chloride hexahydrate ($SrCl_2 \cdot 6H_2O$, ≥99%) was selected as the precipitant due to its favourable ionic radius and divalent charge, which allow

effective boron binding via low-solubility complex formation similar to that of barium, but with far lower toxicity upon disposal. Strontium's chemical structure promotes a strong affinity for borate ions and facilitates robust precipitation under mild alkaline conditions, making it well-suited for sustainable water treatment processes. Barium compounds, although highly effective, pose serious toxicity concerns, and strontium chloride offers a lower-risk alternative [11], [21].

Hydrogen peroxide (H_2O_2, 30%) was used to convert boron into peroxoborate species, enhancing precipitation efficiency. Sodium hydroxide (NaOH, ≥98%) and hydrochloric acid (HCl, 37%) were used to adjust pH. Magnesium chloride hexahydrate ($MgCl_2 \cdot 6H_2O$, ≥99%) was used to prepare reconstituted hard water (RHW) for toxicity testing. *Lactuca sativa* seeds (lettuce), 75 mm laboratory-grade Whatman filter paper, and 100 mm sterile Petri dishes were employed for all bioassays. All glassware underwent acid washing and thorough rinsing with deionised water before use.

Synthetic Produced Water Preparation and Characterisation

A stock solution with 36 mg/L boron was prepared by dissolving 0.205 g boric acid in 1,000 mL of deionised water, then gently swirling in laboratory volumetric glassware until fully dissolved. The chosen concentration is representative of median boron levels in petroleum industry-produced waters, typically ranging from 10 to 200 mg/L. Employing a synthetic matrix reduces confounding variables and aligns with recommendations for accurately benchmarking boron removal technologies [21]. $SrCl_2 \cdot 6H_2O$ stock solutions of 540, 600, 750, and 900 mg/L were freshly prepared for each session. Dosage levels encompassed stoichiometric and excess regimes for boron-strontium precipitation, as reported in the literature. H_2O_2 in mixtures of 0.2, 0.4, 0.6, or 0.8 mL per 100 mL water was added immediately before the precipitant.

The pH was adjusted to 9–12 using NaOH, monitored with a calibrated laboratory pH electrode, and maintained within ±0.1 units. The set pH values accommodate optimal boron speciation and precipitation [22]. For mixing, a laboratory magnetic stirrer and uniform stir bars were employed, with speeds set at 100, 150, 200, or 300 revolutions per minute (rpm). Initial rapid mixing (5 min) was followed by gentle mixing for an additional 15 min to support flocculation without excessive shear, in accordance with recommended precipitation practices. The reaction mixture was allowed to settle for at least 1 h before clear supernatant was extracted for boron analysis [23].

Factorial Experimental Design

Optimisation experiments used a full factorial scheme, varying pH, precipitant dosage, oxidant dosage, and mixing speed across defined levels. Each combination was replicated to assess experimental reproducibility and generate statistically valid data. The parameter ranges and increments were determined based on thermodynamic and kinetic constraints reported for boron precipitation systems. Statistical significance of outcomes was determined using analysis of variance (ANOVA) with $p < 0.05$ set as the threshold [22].

Acute Phytotoxicity Assessment

This subsection presents the methodology used for acute phytotoxicity evaluation.

Bioassay organism and control preparation. *Lactuca sativa* seeds were chosen as the test organism due to their sensitivity, rapid germination, and wide use in regulatory toxicity tests. Seeds were placed (20 per dish) on moistened 75 mm filter paper in sterile dishes. RHW, prepared by dissolving 254 mg of $MgCl_2 \cdot 6H_2O$ in 1 L of deionised water, served as a controlled background for all bioassays, conforming to established standards for aquatic toxicity. Test solutions of produced water (PW) and effluent water (EW) were diluted in RHW to obtain serial concentrations of 1%, 3%, 10%, 30%, and 100% [3], [11].

Experimental setup. Each Petri dish received 5 mL test or control solution and was sealed in a plastic bag to minimise evaporation. Incubation proceeded at 22 ± 2°C in total darkness for 120 h to mimic standardised germination conditions. Controls (RHW only) accompanied each batch. Post-exposure, germination success was scored (radicle ≥2 mm was considered germinated, in accordance with OECD Test Guideline 208), and high-resolution digital images of each dish were taken against a uniform white background for length measurement.

Analytical methods and morphological measurement. Boron in supernatants was quantified using the curcumin-based colourimetric method, chosen for its specificity and suitability for aqueous environmental samples. To minimise matrix interference, all samples were diluted 30% before analysis, a procedure validated in previous studies for recovery and consistency. Spectrophotometry was performed with proper calibration, quality assurance and quality control (QA/QC) controls [21]. Root lengths of germinated seeds were measured from digital photographs using a custom Java-based image analysis program, calibrated to a size bar in each photo. This approach provides high accuracy in plant morphometrics and supports digital archiving and re-analysis.

Statistical analysis. All parameter-response data were processed by cubic spline interpolation to reveal trends and local optima, which were confirmed by quadratic regression. Probit regression of binary germination data (germinated/not) versus log concentration was used to calculate the median lethal dose (LD_{50}), while root growth inhibition (RGI) was calculated using eq. (1):

$$\mathrm{RGI} = \frac{L_\mathrm{c} - L_\mathrm{t}}{L_\mathrm{c}} \times 100 \tag{1}$$

where RGI is root growth inhibition [%], L_c is the mean root length of the control [cm], and L_t is the mean root length of the treatment [cm].

All findings were validated for statistical significance using ANOVA ($p < 0.05$), and any outlier measurements were identified by Grubbs' test.

RESULTS AND ANALYSIS

This comprehensive analysis presents a systematic optimisation of boron removal from produced water via chemical oxo-precipitation with strontium chloride hexahydrate ($SrCl_2 \cdot 6H_2O$) as the precipitant. The investigation examined four critical operational parameters across 16 experimental conditions to identify the most influential factors and establish optimal operating conditions for maximum boron recovery efficiency.

Experimental Data and Factor Analysis

This subsection presents and analyses the experimental data. A combination of statistical techniques was applied to quantify the relative influence of operational parameters on boron recovery efficiency and to support process optimisation.

Data acquisition and structure. The experimental data were obtained from systematic investigations of four operational parameters, with each factor tested at four different levels while maintaining a constant initial boron concentration of 36 mg/L, as shown in **Table 1 – Table 4**. The data collection methodology ensured controlled conditions to isolate the individual effects of each parameter on boron recovery efficiency.

Table 1. Effect of pH on boron recovery

pH	Initial boron concentration [mg/L]	Final boron concentration [mg/L]	Boron recovery [%]
9.0	36	9.1	74.72
10.0	36	8.1	77.50
11.0	36	5.3	85.28
12.0	36	7.0	80.56

Table 2. Effect of precipitant dosage on boron recovery

Precipitant dosage [mg]	Initial boron concentration [mg/L]	Final boron concentration [mg/L]	Boron recovery [%]
450	36	10.1	71.94
600	36	8.7	75.83
750	36	8.3	76.94
900	36	8.8	75.56

Table 3. Effect of oxidant dosage on boron recovery

Oxidant dosage [mL]	Initial boron concentration [mg/L]	Final boron concentration [mg/L]	Boron recovery [%]
0.2	36	12.7	64.72
0.4	36	10.5	70.83
0.6	36	6.6	81.67
0.8	36	6.1	83.06

Table 4. Effect of mixing speed on boron recovery

Mixing speed [rpm]	Initial boron concentration [mg/L]	Final boron concentration [mg/L]	Boron recovery [%]
100	36	10.6	70.56
150	36	9.4	73.89
200	36	7.9	78.06
300	36	8.5	76.39

Multi-metric influence scoring system. The influence analysis employed a sophisticated multi-metric approach to quantify the impact of each parameter on boron recovery efficiency. The methodology incorporated four statistical measures: variance analysis (35% weight), range quantification (25% weight), coefficient of variation assessment (20% weight), and correlation strength evaluation (20% weight). This weighted composite scoring system provides a comprehensive assessment of factor influence that accounts for both the magnitude and consistency of each parameter's effect.

The variance analysis revealed substantial differences between factors, with oxidant dosage demonstrating the highest variance (77.50), indicating the greatest variability in recovery outcomes. This high variance translates directly to optimisation potential, as it demonstrates that small changes in oxidant dosage can produce significant differences in treatment efficacy. The range analysis further supported this finding, showing that oxidant dosage produced the largest spread in recovery rates (18.34 percentage points), ranging from 64.72% to 83.06%.

Correlation analysis and statistical significance. The Pearson correlation analysis revealed distinct patterns in the strength of the relationship between operational parameters and boron recovery efficiency. Oxidant dosage showed a strong correlation (r = 0.9658, p = 0.0342), representing the only statistically significant relationship among all tested factors. This near-perfect positive correlation indicates a highly predictable linear relationship between hydrogen peroxide dosage and recovery performance, with each 0.1 mL increase in oxidant dosage corresponding to approximately a 3.29 percentage-point improvement in boron recovery.

The remaining factors showed moderate to strong correlations but did not reach statistical significance: pH exhibited a correlation coefficient of 0.7221 (p = 0.2779), mixing speed showed r = 0.7474 (p = 0.2526), and precipitant dosage demonstrated r = 0.7125 (p = 0.2875). While these correlations suggest meaningful relationships, the lack of statistical significance ($p \geq 0.05$) indicates insufficient evidence to confidently attribute the observed variations to the tested parameter values rather than random experimental variation.

Analysis of variance results. The one-way ANOVA yielded an F-statistic of 0.7380 with a p-value of 0.5494, indicating no statistically significant differences in mean recovery rates across different factor groups. This finding suggests that the primary sources of variation lie within individual factor responses rather than between different types of factors. The ANOVA results reinforce the importance of optimising specific parameter values within each factor rather than simply selecting the "best" factor category.

Process optimisation and factor influence analysis. The systematic investigation of operational parameters revealed distinct hierarchical patterns in factor influence, shown in **Figure 1** (visualisation of factor influence scores and boron recovery scores).

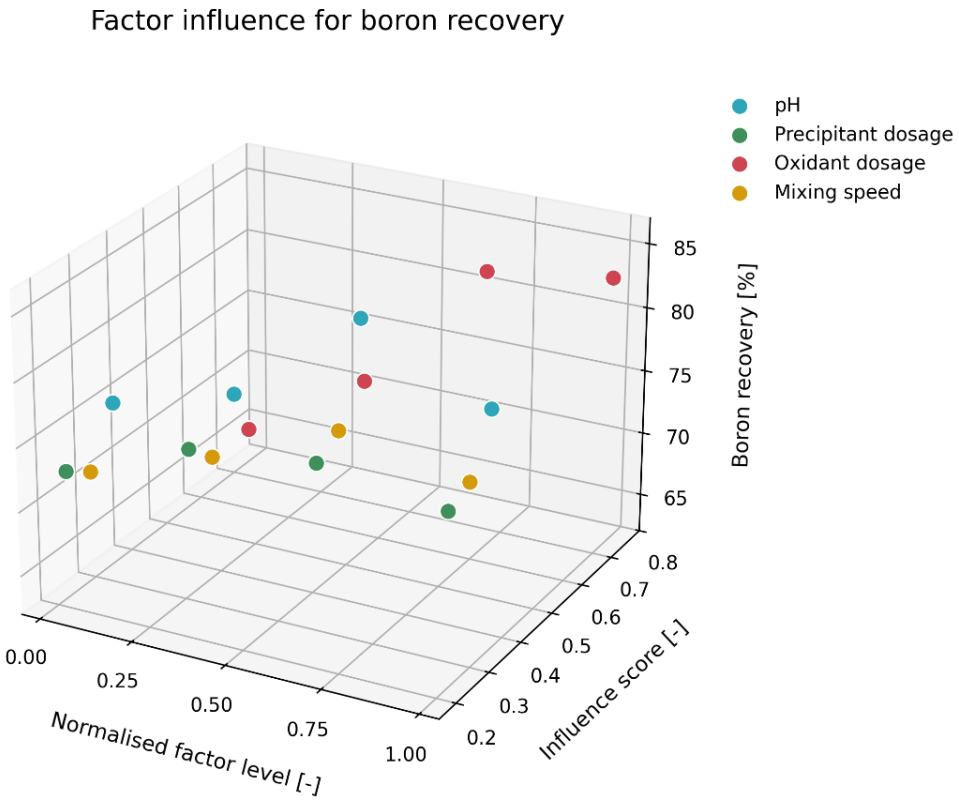

Figure 1. Three-dimensional factor influence analysis demonstrating operational parameter rankings and their impact on boron recovery efficiency

The comprehensive statistical analysis employed multifactorial evaluation metrics, including variance analysis, correlation coefficients, coefficient of variation, and influence

scoring to establish the relative importance of each operational parameter in determining treatment performance.

Primary Finding: Oxidant Dosage as the Dominant Control Parameter

The comprehensive factor influence analysis unequivocally establishes oxidant dosage as the predominant operational parameter, with an influence score of 0.7448 that substantially exceeds all other investigated factors. This dominance is substantiated by convergent statistical evidence, including the highest variance magnitude (77.50), the most extensive operational range (18.34%), an elevated coefficient of variation (0.1173), and the exclusive demonstration of statistically significant correlation with boron recovery efficiency (p = 0.0342). The mechanistic foundation underlying the influence of oxidant dosage relates directly to the critical role of hydrogen peroxide in enhancing precipitation kinetics through oxidative conditioning of the solution matrix, as demonstrated in previous studies on chemical oxo-precipitation systems.

The oxidative environment generated by hydrogen peroxide serves multiple synergistic functions during precipitation. Primarily, it promotes the conversion of recalcitrant boron species into forms more amenable to complexation with strontium ions, while simultaneously eliminating competing organic matter that could interfere with precipitation reactions. The robust linear relationship is expressed by eq. (2):

$$y = 32.93x + 58.61 \ (R^2 = 0.9328) \quad (2)$$

where y is boron recovery [%], x is oxidant dosage [mL], and R^2 is the coefficient of determination.

Equation (2) demonstrates that recovery efficiency increases predictably with increasing oxidant dosage, achieving optimal performance at a dosage level of 0.8 mL. This relationship suggests that the oxidative pretreatment fundamentally alters the boron speciation equilibrium, creating conditions favourable for enhanced strontium-boron complex formation.

Secondary Parameter Hierarchical Analysis

Solution pH emerges as the second most influential operational parameter with an influence score of 0.3562, demonstrating optimal performance at pH 11.0, where 85.28% boron recovery was achieved. The pH dependence reflects the fundamental acid-base speciation chemistry of boron in aqueous systems, where increasing alkalinity progressively promotes the formation of borate ions ($B(OH)_4^-$) that exhibit enhanced electrostatic affinity for strontium cations. The optimal pH of 11.0 represents a critical balance point that maximises borate ion availability while avoiding excessive hydroxide concentrations, which could destabilise strontium complexes through competitive complexation reactions.

Mixing speed ranks third in the hierarchical influence analysis with a score of 0.2928, achieving optimal performance at 200 rpm, and a recovery efficiency of 78.06%. The mixing-speed effect correlates directly with mass-transfer enhancement and uniform reactant distribution throughout the reaction medium, facilitating efficient molecular contact between boron and strontium species. However, the data reveal that excessive agitation beyond 200 rpm introduces detrimental hydrodynamic shear forces that disrupt precipitate formation and nucleation, thereby reducing recovery efficiency via particle breakage and redissolution.

Precipitant dosage has the lowest relative influence score, 0.2292, despite achieving a respectable maximum recovery of 76.94% at the 750 mg dosage level. The relatively stable performance across different strontium chloride dosage levels suggests that the stoichiometric requirements for precipitation are adequately satisfied across the tested concentration range, indicating minimal additional benefit from excess strontium availability beyond the optimal threshold. This finding implies that the process operates under strontium-sufficient conditions,

where boron speciation and solution chemistry, rather than precipitant availability, become the rate-limiting factors for enhanced recovery.

Optimal Operating Conditions and Performance Predictions

Based on the comprehensive statistical analysis and individual factor optimisation, the following conditions are recommended for maximum boron recovery efficiency:

- pH: 11.0 pH units
- Precipitant dosage: 750 mg strontium chloride hexahydrate
- Oxidant dosage: 0.8 mL hydrogen peroxide
- Mixing speed: 200 rpm.

Under the identified optimal conditions, the treatment system is predicted to achieve 80.84% boron recovery based on conservative averaging of individual factor maxima. This conservative estimate accounts for potential interactive effects between parameters that may prevent simple additive performance gains. The maximum individual recovery of 85.28% was achieved at pH = 11.0, representing the upper boundary of expected performance under optimal conditions.

The optimal conditions are projected to reduce boron concentrations from the initial 36 mg/L to a final range of 5.3–8.3 mg/L, representing a substantial removal efficiency that approaches regulatory compliance levels for industrial discharge standards. The treatment efficacy demonstrates the potential of chemical oxo-precipitation as an effective primary treatment technology for boron-contaminated produced water.

Process Control Priorities

The statistical analysis supports a hierarchical process control strategy prioritising parameters based on their influence scores and statistical significance. Oxidant dosage requires primary control attention due to its dominant influence and statistical significance, necessitating precise monitoring and adjustment capabilities. pH control represents the secondary priority, requiring maintenance within ±0.5 units of the optimal value to preserve maximum recovery potential.

Mixing speed and precipitant dosage warrant tertiary attention in process control systems, as their moderate influence scores suggest that reasonable variations from optimal values will not dramatically impact overall performance. This hierarchical approach enables efficient allocation of process monitoring resources while maintaining treatment effectiveness.

Statistical Validation and Significance Assessment

This subsection evaluates the statistical validity, robustness, and practical significance of the results through regression analysis, methodological assessment, and consideration of environmental, economic, and operational implications.

Regression model validation. The linear regression analysis provides quantitative validation of factor-recovery relationships, with oxidant dosage demonstrating superior model fit (R^2 = 0.9328) compared to other factors. The regression relationship for oxidant dosage is given by eq. (3):

$$y = 32.93x + 58.61 \quad (3)$$

where y is boron recovery [%] and x is oxidant dosage [mL].

Equation (3) indicates that each 0.1 mL increase in hydrogen peroxide dosage corresponds to a 3.29-percentage-point improvement in boron recovery, providing a practical basis for process optimisation calculations.

The statistical significance of the oxidant dosage relationship (p = 0.0342) provides confidence that the observed correlation represents a genuine cause-and-effect relationship rather than random experimental variation. This significance level exceeds the conventional α = 0.05 threshold, validating the mechanistic importance of oxidative conditioning in boron precipitation processes.

Methodological robustness. The experimental design ensured statistical validity through consistent initial conditions (a boron concentration of 36 mg/L), systematic variation of parameters, and replicated measurements across four levels per factor. The multi-metric influence scoring system reduces the risk of bias associated with single-parameter assessments, providing robust quantification of factor importance that accounts for multiple aspects of the strength of the statistical relationship.

The convergent evidence from correlation analysis, variance assessment, and ANOVA testing strengthens confidence in the identification of oxidant dosage as the most influential parameter. This methodological triangulation approach enhances the reliability of optimisation recommendations and supports their application in industrial-scale treatment systems.

Environmental and practical implications. The demonstrated boron recovery efficiency of 80–85% under optimal conditions represents a significant advancement in produced water treatment technology. The final boron concentrations achieved (5.3–8.3 mg/L) approach levels compatible with environmental discharge standards and beneficial reuse applications, addressing critical regulatory compliance challenges in the oil and gas industry.

The dominance of oxidant dosage as the controlling parameter offers practical advantages for industrial implementation, as hydrogen peroxide dosing systems are readily available and provide precise control capabilities. The strong linear relationship between dosage and recovery enables predictive process control that can adapt to varying influent conditions while maintaining consistent treatment performance.

Economic and operational considerations. The identification of optimal operating conditions provides a foundation for cost-effective treatment system design and operation. The moderate oxidant requirements (0.8 mL per treatment cycle) and standard pH adjustment suggest reasonable chemical consumption costs relative to the substantial environmental benefits achieved through effective boron removal.

The hierarchical control strategy enables efficient resource allocation for process monitoring and automation systems, focusing primary attention on the most influential parameters while maintaining adequate oversight of secondary factors. This approach maximises treatment reliability while minimising operational complexity and associated labour requirements.

Rationale for Phytotoxicity Bioassays

Assessing the acute phytotoxicity of both PW and EW using *Lactuca sativa* seedlings is a well-established approach in environmental toxicology due to the high sensitivity, ease of handling, and ecological relevance of this species [24]. Lettuce seeds germinate rapidly and respond predictably to pollutants, making them a model living sensor for both acute and chronic toxicity in water samples. These attributes have made *Lactuca sativa* bioassays a cornerstone in regulatory and academic studies on wastewater impact and agricultural risk assessment [25].

For ecotoxicity evaluation, two key endpoints were selected: seed germination rate/mortality and RGI. Germination success provides a binary, quantifiable acute endpoint that indicates whether exposure concentrations disrupt baseline cellular activity and development. RGI, by contrast, tracks subtler, sublethal impacts on energy allocation and development by measuring early radicle elongation. This dual assessment provides a broad

view of both organismal survival and fitness-related functional impacts, enabling meaningful comparison between untreated and treated water [26].

Probit regression analysis was employed to quantify LD_{50} values (the dose required to inhibit 50% of seeds). This method is widely utilised in environmental toxicology and is recommended by recent studies for linearising binary dose-response data to ensure comparability and predictive validity. RGI calculation as a percentage relative to controls is similarly standardised, capturing non-lethal but ecologically significant reductions in early root development – a sensitive indicator of chronic phytotoxicity and early plant stress [24] – [26].

By combining these methods, this study aims to clarify not only whether treated effluent is less acutely toxic than raw produced water, but also whether sublethal developmental effects remain key information for evaluating safe reuse or discharge.

Results and Interpretation

This subsection presents and interprets germination, mortality, LD_{50}, and root growth inhibition to assess the phytotoxicity of the produced and treated water.

Germination and mortality assessment. The germination response and mortality rates of *Lactuca sativa* L. seeds exposed to various concentrations of PW or treated EW are presented in Table 5. The results demonstrate a clear dose-dependent relationship between PW concentration and seed mortality, with the highest mortality rate, 60%, observed at 30% PW concentration. In contrast, the treated EW exhibits significantly reduced phytotoxic effects at intermediate and higher concentrations compared to untreated PW. However, some variability is observed at extreme dilutions, potentially attributable to experimental stochasticity inherent in biological systems. Notably, the 100% concentrations of both PW and EW showed identical mortality rates of 30%, suggesting that the treatment process effectively mitigates the acute toxicity associated with intermediate concentrations while maintaining consistent performance at full strength.

Table 5. Germination response and mortality rates of Lactuca sativa L. seeds exposed to produced water and effluent water at various concentrations

Treatment	Concentration [%]	Seeds germinated	Mortality [%]
Control	0	18	10
PW-1%	1	14	30
PW-3%	3	14	30
PW-10%	10	11	45
PW-30%	30	8	60
PW-100%	100	14	30
EW-1%	1	7	65
EW-3%	3	14	30
EW-10%	10	13	35
EW-30%	30	10	50
EW-100%	100	14	30

Probit regression and median lethal dose calculation. Probit analysis was systematically applied to transform mortality rates into quantifiable LD_{50} estimates, a statistical methodology particularly valuable for bioassay data characterised by binary response distributions. The transformation of mortality percentages into probit values, followed by regression against logarithmic concentrations of both PW and EW, yielded robust linear correlations with high statistical significance. The calculated LD_{50} values revealed substantial differences in acute

toxicity between untreated and treated water samples. For produced water, the LD_{50} was 14.73%, while the treated effluent water demonstrated a markedly elevated LD_{50} of 34.34%. This result represents a 133.1% increase in the median lethal dose, confirming the substantial reduction in acute phytotoxicity achieved by the strontium chloride-mediated oxo-precipitation treatment process.

The parallel regression lines observed in the probit analysis, as shown in **Figure 2**, provide crucial mechanistic insights into the detoxification process. The parallel slopes indicate that the treatment effect manifests as a rightward shift in the dose-response relationship rather than a fundamental alteration in the underlying toxicity mechanism. This finding suggests that although the potency of the toxic components has been reduced, their mode of action remains unchanged, supporting the hypothesis that boron removal is the primary driver of the reduction in toxicity rather than the introduction of novel protective compounds.

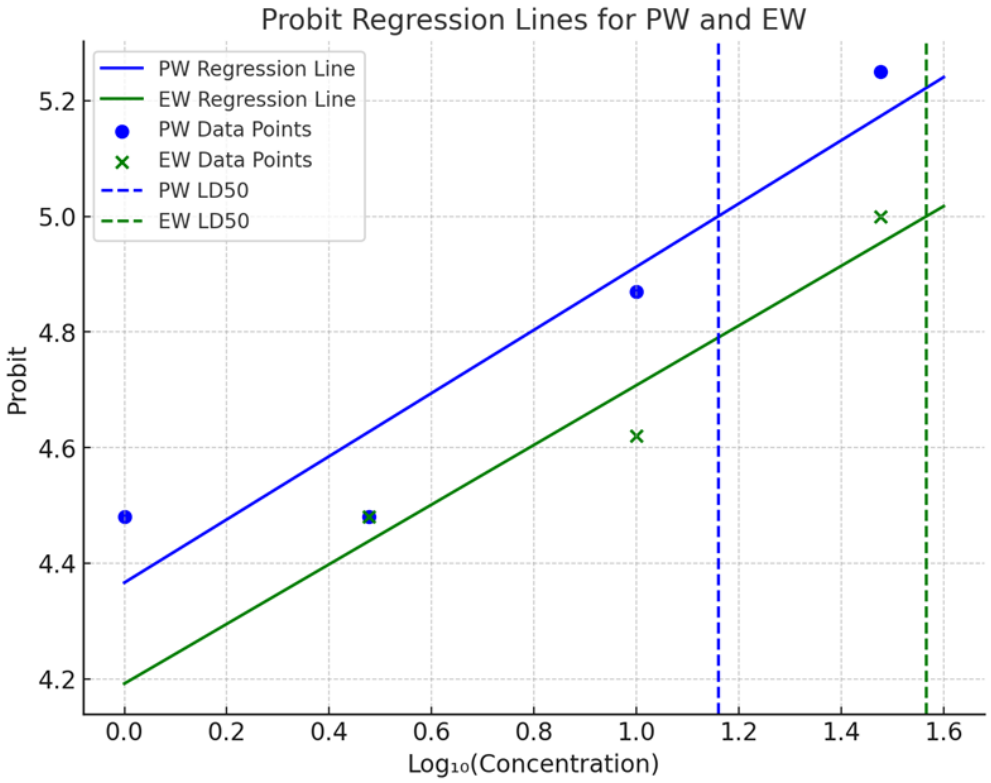

Figure 2. Probit regression lines for produced water and effluent water

Root growth inhibition assessment. Sublethal effects were comprehensively evaluated through RGI measurements, providing additional confirmation of treatment efficacy beyond mortality endpoints. The RGI data, presented in **Table 6**, revealed concentration-dependent inhibitory effects in both water types, with consistently lower inhibition rates in treated effluent water compared to produced water across most concentration ranges.

The RGI values increased progressively with concentration for both PW and EW, but the treated effluent consistently showed lower inhibition percentages than the untreated produced water. The differential effect was most pronounced at moderate concentrations, particularly in the 10–30% range, where the biological relevance of LD_{50} values is most significant for environmental risk assessment. At the highest concentration (100%), both treatments approached similar RGI values (59.85% for PW versus 56.17% for EW), suggesting that while treatment provides substantial protection at environmentally relevant concentrations, some residual toxicity persists at extreme exposure levels.

Table 6. Root growth inhibition response of Lactuca sativa L. seeds to produced water and effluent water at various concentrations

Treatment	Concentration [%]	Mean root [cm]	RGI [%]
Control	0	2.398	0.00
PW-1%	1	1.972	17.75
PW-3%	3	2.332	2.75
PW-10%	10	1.521	36.57
PW-30%	30	1.274	46.88
PW-100%	100	0.963	59.85
EW-1%	1	2.105	12.21
EW-3%	3	2.345	2.21
EW-10%	10	1.602	33.18
EW-30%	30	1.288	46.29
EW-100%	100	1.051	56.17

The graphical representation of RGI versus concentration in **Figure 3** clearly illustrates the dose-response relationships for both water types. The curves demonstrate typical sigmoid patterns characteristic of biological dose-response relationships, with steeper inhibition gradients observed at intermediate concentrations and plateau effects at higher exposures. Importantly, the consistent separation between PW and EW curves across the concentration range validates the treatment's effectiveness in reducing sublethal toxicity while preserving the fundamental dose-response characteristics of the system.

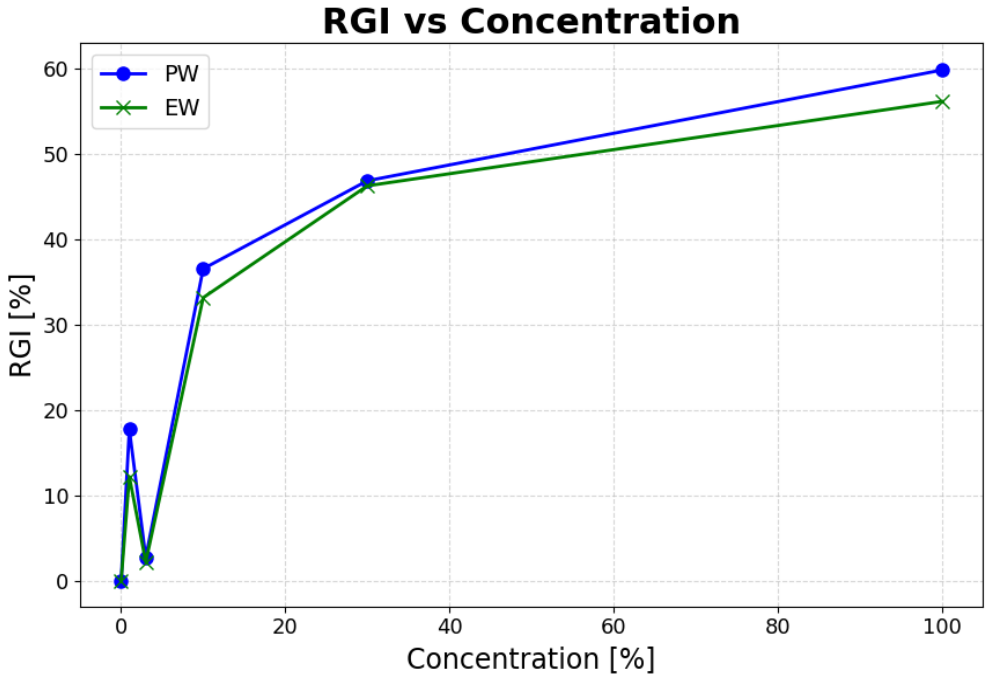

Figure 3. Root growth inhibition versus concentration for produced water and effluent water

Ecological and regulatory implications. The convergence of higher LD_{50} and lower RGI values for EW demonstrates the success of boron removal and confirms the suitability of these paired methods for risk characterisation. While the acute hazard is greatly reduced in EW, the persistence of >50% root inhibition at 100% concentration suggests that, while much safer, even optimally treated effluent should be further diluted or monitored before unrestricted agricultural discharge.

CONCLUSION

This research successfully demonstrates that strontium chloride-mediated chemical oxo-precipitation represents a significant advancement in sustainable boron removal from produced water, achieving up to 85.28% removal efficiency under optimal conditions. The systematic optimisation revealed oxidant dosage as the most influential parameter, with a strong linear correlation (r = 0.9658, p = 0.0342) enabling predictable process control for industrial applications. The substantial reduction in ecological toxicity, evidenced by a 133% increase in the median lethal dose for treated effluent compared to untreated produced water, validates the environmental safety benefits of this approach. This methodology exemplifies green chemistry principles by minimising hazardous byproducts, utilising safer reagents than conventional barium-based systems, and reducing overall sludge generation while maintaining high treatment efficacy.

The integration of rigorous toxicity assessment with process optimisation demonstrates that effective boron removal can be achieved without compromising environmental safety, thereby directly supporting United Nations Sustainable Development Goals through improved water quality, reduced pollutant discharges, and enhanced protection of terrestrial ecosystems. The hierarchical process control strategy identified through statistical analysis provides a practical framework for industrial implementation, prioritising oxidant dosage control while maintaining operational simplicity and cost-effectiveness. Future research should focus on repeating these experiments on produced water collected from various industries and oil fields, as this will allow for validation of process robustness across diverse compositional matrices, assessment of treatment efficiency under varying salinity and contaminant profiles, and establishment of universal operational parameters that can accommodate the wide geographical and geological variability inherent in produced water characteristics. Such comprehensive validation would strengthen the technology's commercial viability and provide critical data for regulatory approval across different jurisdictions, ultimately establishing strontium chloride-mediated oxo-precipitation as a reliable, sustainable solution for global produced water management challenges.

AUTHOR CONTRIBUTIONS

Muhammad Faseeh Memon: contributed to the conceptualisation of the study, developed the research methodology, conducted the investigation, curated and analysed the data, and prepared the original draft of the manuscript. **Muhammad Raza Ul Mustafa:** provided supervision throughout the research project, ensured the scientific rigour of the work, validated the research findings, and contributed to the critical review and editing of the manuscript. **Zubair Ahmed Memon:** offered substantial guidance and supervision, assisted in validating the methodology and findings, and participated in reviewing and refining the manuscript to ensure clarity, coherence, and adherence to academic standards.

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CONFLICTS OF INTEREST

The authors declare no conflicts of interest.

NOMENCLATURE

Symbols

L	mean root length	[cm]
p	probability value	[–]
pH	potential of hydrogen	[–]
r	Pearson correlation coefficient	[–]
R^2	coefficient of determination	[–]
x	oxidant dosage	[mL]
y	boron recovery	[%]

Greek letters

α	significance level	[–]

Subscripts and superscripts

c	control
t	treatment

Abbreviations

ANOVA	Analysis of Variance
COP	Chemical Oxo-Precipitation
EC	Electrocoagulation
ED	Electrodialysis
EW	Effluent Water
LD_{50}	Median Lethal Dose
NF	Nanofiltration
OECD	Organisation for Economic Co-operation and Development
PW	Produced Water
RGI	Root Growth Inhibition
RHW	Reconstituted Hard Water
RO	Reverse Osmosis
WHO	World Health Organization

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