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

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ABSTRACT

Produced water from oil and gas extraction presents a major environmental challenge due to high boron content and toxicity risks for ecosystems and human health. Traditional boron removal methods suffer from high costs, limited efficiency, and generation of secondary pollutants. This study conducts a comprehensive assessment of strontium chloride as a precipitating agent in an optimized chemical oxo-precipitation process to remove boron from produced water. Through systematic variation of critical operational parameters including pH, reagent dosages, and mixing speed, the treatment achieved close to 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 minimizing hazardous byproducts, employing safer chemicals, and reducing sludge generation relative to barium-based methods, thus promoting improved safety for both workers and the environment. Therefore, this methodology contributes directly to the United Nations Sustainable Development Goals by advancing water quality improvement, promoting the reuse of treated water, minimizing pollutant discharge, 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].

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In recent years, global attention has increasingly shifted toward the multifaceted challenges of climate change [2].

Boron is distributed ubiquitously throughout the environment, appearing 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 soil solution, 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 harbors 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 pollution and the contamination of air and water, 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 localized 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 deficiency and excess of boron can result in severe developmental disruptions, ranging from impaired meristem function and reproductive failures 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 signaling, 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 in symptoms such as leaf chlorosis, dark brown spots, and eventual cell death, particularly under conditions where soil or irrigation water already contains substantial 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 by virtue of its narrow safety margin between essential physiological levels and toxic doses, as even modest elevations above recommended guidelines (e.g., 1–2.4 mg/L) can induce a cascade of adverse effects; while 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 diarrhea—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) value of 0.17 mg/kg body weight per day [7].

In contrast, produced water, which is a byproduct of industrial and energy extraction activities, frequently exhibits boron concentrations that are orders of magnitude higher, reaching tens to hundreds of milligrams per liter. 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 is mobilized by geothermal and volcanic activities [8]. In addition, anthropogenic contributions, such as municipal wastewater discharges, power plant effluents, and chemical landfill leachates, further contaminate produced water with high levels of boron. 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—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 (reverse osmosis, nanofiltration, and electrodialysis), 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 naturally derived or synthetic adsorbents such as activated carbon has been demonstrated, yet these systems generally exhibit reduced adsorption capacity and face challenges in adsorbent exhaustion and regeneration over extended operational periods [10].

Membrane-based technologies, including reverse osmosis (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].

Electrocoagulation (EC) 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 optimized 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 [13, Ch. 8], [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 suffer from a decline in removal efficiency at low boron concentrations and require strict control of pH conditions, 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 lower the risk of secondary pollution by reducing the overall volume and toxicity of the resultant 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 by-products, 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 optimization by varying critical operational parameters, including pH, precipitant and oxidant dosages, and initial mixing speed, to maximize removal efficiency. Additionally, acute phytotoxicity assessment using Lactuca sativa L. seeds as bioassays was conducted to evaluate the environmental safety of both produced water and treated effluent post-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.

Precipitant selection and research rationale

This 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 optimization and rigorous

toxicity assessments, balancing both technical performance and environmental impacts. The workflow was structured in three interlinked domains: precipitant efficacy screening, operational parameter optimization using a factorial design, and environmental evaluation via standardized 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 favorable 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 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, raise serious toxicity concerns, and strontium chloride offers an alternative with lower environmental risk [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 for pH adjustments. 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 deionized water prior to use.

Synthetic produced water preparation and characterization

A stock solution with 36 mg/L boron was prepared by dissolving 0.205 g boric acid in 1,000 mL deionized water, followed by gentle swirling in laboratory volumetric glassware until fully dissolved. The chosen concentration is representative of median boron levels in produced waters from petroleum industries, 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 (540, 600, 750, 900 mg/L) were freshly prepared for each session. Dosage levels encompassed stoichiometric and excess regimes for boron-strontium precipitation, as informed by literature. H_2O_2 (0.2, 0.4, 0.6, or 0.8 mL per 100 mL water) was added immediately prior to the precipitant.

The pH was adjusted in the range of 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 RPM. Initial rapid mixing (5 min) was followed by gentle mixing for an additional 15 min to support flocculation without excessive shear, based on recommended precipitation practice. The reaction mixture was allowed to settle for at least 1 h before clear supernatant was extracted for boron analysis [23].

Factorial experimental design

Optimization 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 by 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 $MgCl_2 \cdot 6H_2O$ in 1 L deionized water, supplied a controlled background for all bioassays, conforming to established standards for aquatic toxicity. Test solutions of PW and EW were diluted in RHW to obtain serial concentrations (1%, 3%, 10%, 30%, 100%) [3], [11].

Experimental setup

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

Analytical methods and morphological measurement

Boron in supernatants was quantified using the curcumin-based colorimetric method, selected for its specificity and suitability in aqueous environmental samples. To minimize 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 and 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 LD_{50} (median lethal dose). RGI was calculated as $\text{RGI}\ (\%) = [(\text{Lc} - \text{Lt})/\text{Lc}] \times 100$, comparing control and treatment mean root lengths. All findings were validated for significance via ANOVA ($p < 0.05$), and any outlier measurements were identified by Grubbs' test.

RESULTS AND ANALYSIS

This comprehensive analysis presents the systematic optimization of boron removal from produced water using 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 analyzes the experimental data.

Data acquisition and structure

The experimental data was obtained from systematic investigations of four operational parameters, with each factor tested at four different levels while maintaining constant initial boron concentration of 36 mg/L as shown in Table 1, Table 2, Table 3 and Table 4, respectively.

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

Statistical methodology and influence quantification

This section applies a combination of statistical techniques to quantify the relative influence of operational parameters on boron recovery efficiency and to support process optimization.

Multi-metric influence scoring system

The influence analysis employed a sophisticated multi-metric approach to quantify each parameter's impact 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 optimization 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), spanning from 64.72% to 83.06% recovery.

Correlation analysis and statistical significance

The Pearson correlation analysis revealed distinct patterns of relationship strength between operational parameters and boron recovery efficiency. Oxidant dosage demonstrated exceptional correlation strength ($r = 0.9658$, $p = 0.0342$), 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 3.29 percentage points improvement in boron recovery.

The remaining factors showed moderate to strong correlations but failed to achieve 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 analysis yielded an F-statistic of 0.7380 with a p-value of 0.5494, indicating no statistically significant differences between the mean recovery rates of 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 optimizing specific parameter values within each factor rather than simply selecting the "best" factor category.

Process optimization and factor influence analysis

The systematic investigation of operational parameters revealed distinct hierarchical patterns in factor influence, as presented in Figure 1, which illustrates the three-dimensional visualization of factor influence scores and their relationship to 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.

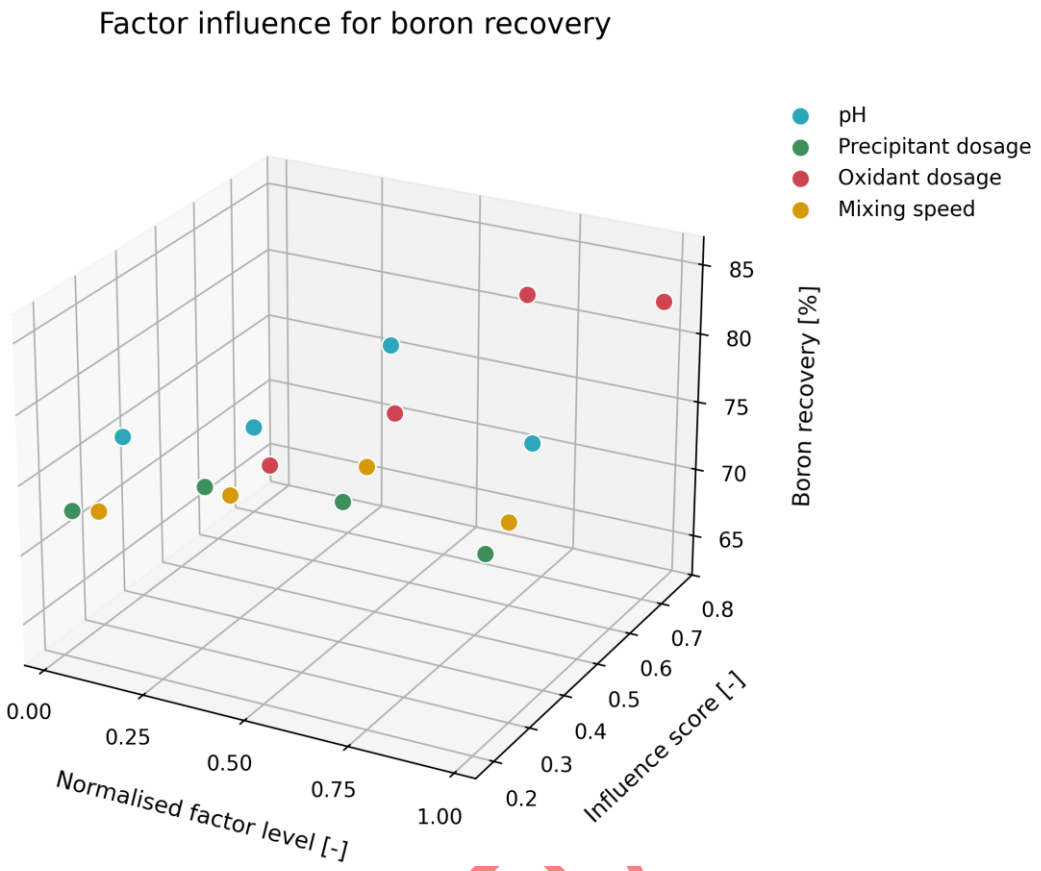

Figure 1. Three-dimensional factor influence analysis demonstrating operational parameter rankings and their impact on boron recovery efficiency

Primary finding: oxidant dosage as the dominant control parameter

The comprehensive factor influence analysis unequivocally establishes oxidant dosage as the predominant operational parameter, exhibiting an influence score of 0.7448 that substantially exceeds all other investigated factors. This dominance is substantiated through convergent statistical evidence encompassing 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 oxidant dosage influence 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 facilitated by hydrogen peroxide serves multiple synergistic functions in the precipitation process. 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 expressed by eq. (1):

$$y = 32.93x + 58.61 \ (R^2 = 0.9328) \quad (1)$$

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 favorable 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 maximizes borate ion availability while avoiding excessive hydroxide concentrations that could destabilize 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 with 78.06% recovery efficiency. 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 reveals that excessive agitation beyond 200 RPM introduces detrimental hydrodynamic shear forces that disrupt precipitate formation and nucleation processes, consequently leading to decreased recovery efficiency through particle breakage and redissolution phenomena.

Precipitant dosage demonstrates the lowest relative influence score of 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 optimization, 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 substantial removal efficiency that approaches regulatory compliance levels for industrial discharge standards. The treatment efficacy demonstrates the potential for chemical oxo-precipitation to serve as an effective primary treatment technology for boron-contaminated produced water.

Process control priorities

The statistical analysis supports a hierarchical process control strategy prioritizing 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 section 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 equation for oxidant dosage ($Y = 32.93x + 58.61$) 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 optimization calculations.

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

Methodological robustness

The experimental design ensured statistical validity through consistent initial conditions (36 mg/L boron concentration), systematic parameter variation, 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 statistical relationship strength.

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 optimization 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 need 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 maximizes treatment reliability while minimizing operational complexity and associated labor requirements.

Rationale for phytotoxicity bioassays

Assessing the acute phytotoxicity of both produced water (PW) and effluent water (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: (1) seed germination rate/mortality, and (2) root growth inhibition (RGI). Germination success provides a binary, quantifiable acute endpoint, indicating 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 for the quantification of LD_{50} values (the dose required to inhibit 50% of seeds). This method is widely utilized in environmental toxicology and is recommended by recent studies for linearizing binary dose-response data, ensuring comparability and predictive validity. RGI calculation as a percentage relative to controls is similarly standardized, capturing non-lethal but ecologically significant reductions in early root development—a sensitive indicator for chronic phytotoxicity and early plant stress [24], [25], [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 results to assess the phytotoxicity of produced and treated water.

Germination and mortality assessment

The germination response and mortality rates of Lactuca sativa L. seeds exposed to various concentrations of produced water (PW) and treated effluent water (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 of 60% observed at 30% PW concentration. In contrast, the treated effluent water (EW) exhibits significantly reduced phytotoxic effects at intermediate and higher concentrations compared to untreated PW, though 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	Conc. (%)	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 characterized 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 determined to be 14.73%, while the treated effluent water demonstrated a markedly elevated LD_{50} of 34.34%. This represents a 133.1% increase in the median lethal dose, confirming the substantial reduction in acute phytotoxicity achieved through the strontium chloride-mediated oxo-precipitation treatment process.

The parallel nature of the regression lines observed in the probit analysis as shown in Figure 2 provides 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 while 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 toxicity reduction rather than the introduction of novel protective compounds.

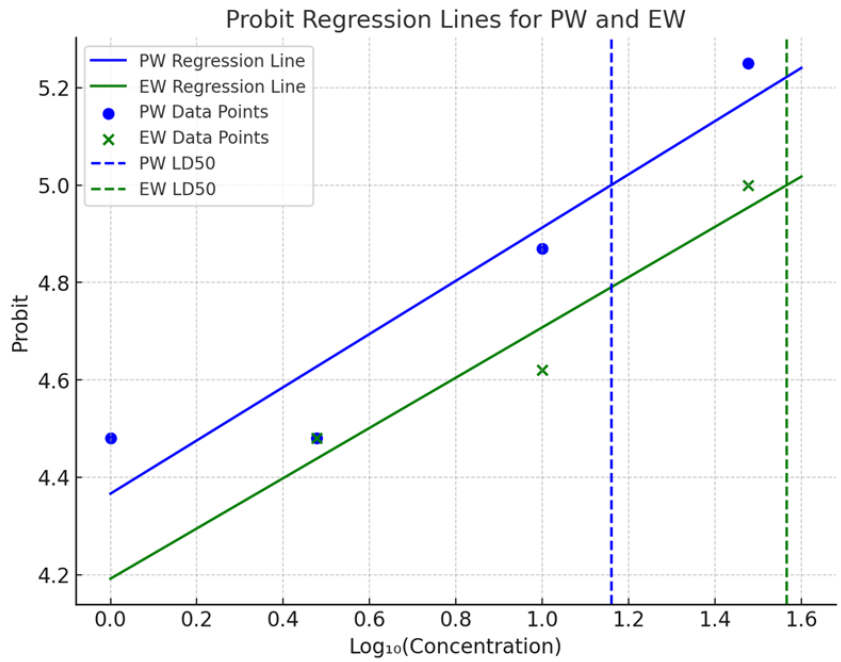

Figure 2. Probit regression lines for produced water and effluent water

Root growth inhibition assessment

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

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

Treatment	Conc. (%)	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 RGI values demonstrated progressive increases with concentration for both PW and EW, but the treated effluent consistently yielded equal or lower inhibition percentages compared to 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.

The graphical representation of RGI versus concentration as shown 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 maintaining the fundamental dose-response characteristics of the system.

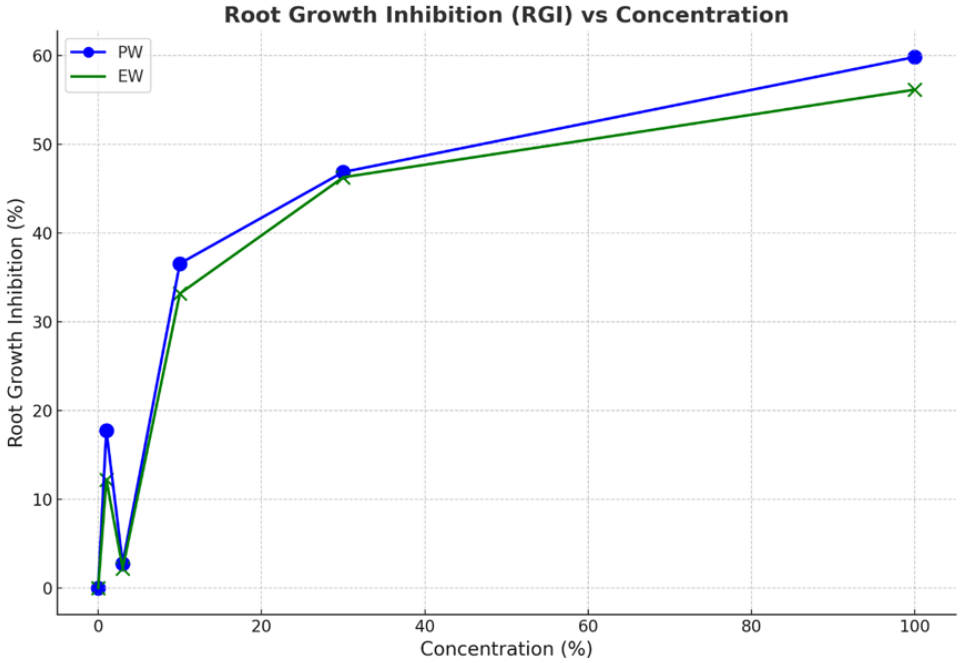

Figure 3. Root growth inhibition versus concentration for produced water and effluent water

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 characterization. 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 optimization 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 minimizing hazardous byproducts, utilizing 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 optimization demonstrates that effective boron removal can be achieved without compromising environmental safety, directly supporting United Nations Sustainable Development Goals through improved water quality, reduced pollution discharge, and enhanced protection of terrestrial ecosystems. The hierarchical process control strategy identified through statistical analysis provides a practical framework for industrial implementation, prioritizing 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 conceptualization 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 rigor 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.

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