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Salt Tolerance of *Phragmites australis* and Effect of Combing It with Topsoil Filters on Biofiltration of CaCl_2 Contaminated Soil

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Abstract: De-icing salt used for safe winter driving can have negative impacts on local water quality, vegetation, and soils. This study aimed to evaluate the salt tolerance of reeds (*Phragmites australis*) against calcium chloride (CaCl_2) and the biofiltration effect of combining it with topsoil biofilters for desalination in roadside ditches. Two experiments were conducted in a controlled environmental greenhouse over a period of 150 days. For the first experiment, the salt tolerance of *P. australis* was examined after treating reeds with five different concentrations of de-icing salt: 0, 1, 2, 5, and $10 \text{ g} \cdot \text{L}^{-1}$. In a second experiment, the effect of combining two topsoil filters (expanded clay and activated carbon), each planted with and without reeds, was investigated under a high CaCl_2 concentration of $10 \text{ g} \cdot \text{L}^{-1}$. As the CaCl_2 concentration increased, the electrical conductivity (EC) of soil leachate and the level of salt exchangeable cations (K^+ , Ca^{2+} , Na^+ , and Mg^{2+}) significantly increased whereas the acidity (pH) significantly decreased (all $p \leq 0.05$). No statistical difference was observed in leaf length or width, while plant height, number of leaves, and both fresh and dry weights were significantly increased with increasing CaCl_2 concentrations ($p \leq 0.05$). Treatments using topsoil filters, particularly those with activated carbon and reeds, showed the greatest reduction in leachate EC and total exchange cations values. These results suggest that combining *P. australis* with topsoil filters can assist biofiltration effectively, demonstrating its applicability even in roadside soils subject to extreme levels of de-icing salts.

Keywords: de-icing salt; halophytes; roadside plants; salt tolerance; phytodesalinization; phytomanagement; *Phragmites australis*



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1. Introduction

Maintaining safe driving conditions in areas affected by winter snow and ice necessitates the use of de-icing salts [1]. These salts are predominantly composed of sodium chloride (NaCl) and calcium chloride (CaCl_2). They can prevent and remove ice accumulation on roads, with CaCl_2 serving as an alternative to NaCl for road de-icing [2]. It can elevate concentrations of chloride, sodium, and calcium, adversely affecting local water quality, vegetation, and soils [3].

Due to their low ecological and economic impacts, using high-salt accumulating plants for phytoremediation of chloride-rich soils, wastewater, and wastes is of great interest [4]. Therefore, phytoremediation of saline environments exhibits unique characteristics. It necessitates the use of plant species capable of surviving and adapting to excessive salt ions. It also needs the management of salt ion concentrations through various mechanisms [5]. The only plants that thrive in saline conditions are halophytes, which represent 1% of the world's flora. They are widely used for phytodesalinization or salt phytoremediation [6]. Halophytes are salt-tolerant, owing to various adaptation mechanisms, such as their ability to exclude excess salt ions at the root, uptake and sequester these ions in aerial parts, or excrete ions from leaf surfaces [7]. These species can tolerate high salinity levels and achieve optimal growth at NaCl concentrations between 200 and 1000 mM [4].

Vegetative cover can enhance the chemical and biological properties of contaminated soil by increasing organic matter, nutrient levels, cation exchange capacity, and biological activity, thereby creating a self-sustaining ecosystem [8]. The stabilization of de-icing salts can be integrated with phytodesalinization to address physicochemical limitations and establish green cover. Furthermore, when selecting species, native plants are preferred due to their ability to tolerate local environmental conditions and their roles in natural ecological restoration [9].

Phragmites australis, a widely distributed wetland grass from the Poaceae family, can grow rapidly and produce a significant amount of biomass quickly [10]. Additionally, *Phragmites* colonies are found in areas with both high and low salt concentrations, yet species abundance does not correlate strongly with elevated salt levels [4]. In this context, extensive research has assessed salt tolerance and the mechanisms to counter NaCl salt stress. It has been shown that *P. australis* can tolerate saline conditions. When it is grown in water with a NaCl concentration of $200 \text{ mmol} \cdot \text{L}^{-1}$, it can accumulate substantial amounts of Na^+ and Cl^- [11]. *P. australis* displays a specific range of salinity resistance. It is well-adapted to saline substrates with low chloride phytoextraction potential. It can also tolerate salinity environments of up to 23% NaCl and 6% salinity with high above-ground biomass ranging from 1 to $5.5 \text{ kg} \cdot \text{m}^{-2}$ [10]. However, few studies have explored the growth responses of these reeds to CaCl_2 concentrations typical of de-icing salts, necessitating an evaluation of the plant's survival and tolerance under specific salinity conditions in soils.

Biofiltration systems are stormwater control measures specifically designed to reduce pollutant concentrations of pollutants discharged into urban waterways [12]. Their general design includes a topsoil filter layer that supports vegetation while promoting mechanical and chemical processes for pollutant removal. Thus, they play a crucial role in removing pollutants [13]. While most contaminants are physically removed by filter media, dissolved forms such as de-icing salts can be eliminated through various processes including adsorption and precipitation [14]. The use of activated carbon adsorption is commonly implemented in groundwater remediation, municipal water filtration, and removal of volatile organic compounds. Activated carbon is also valuable for remediating contaminated soil, particularly in urban areas [15]. Although much research has focused on the influence of topsoil filters on plant growth, only limited studies have explored methods to mitigate soil salinization [16].

Therefore, this study aimed to evaluate *P. australis*'s tolerance to de-icing salt (CaCl_2), assess phytodesalinization, and investigate the effects of combining reed plantings with two biofilters (activated carbon and expanded clay) under conditions of high de-icing salinity on biofiltration of CaCl_2 contaminated soil.

2. Materials and Methods

The experiments were conducted in a controlled environmental greenhouse at Konkuk University, Chungju, Chungcheongbuk-do, South Korea, over a period of 150 days from April to August 2018. During this time, the cultivation environment was monitored using a HOBO data logger (UX100-003, Onset, Melbourne, Australia), recording an average illuminance of 21,947 Lux, a temperature of 19.8°C , and a relative humidity of 66.2%.

2.1. Experimental Soil and Plant Materials

This study utilized a lightweight horticulture substrate (Hanpanseung, SGtech, Anyang, Republic of Korea) consisting of 74.84% coco peat, 15% vermiculite, 5% biotite, 5% perlite, 0.158% fertilizer, and 0.002% wetting agent to ensure minimal soil-related variability aside from CaCl_2 treatment. The de-icing salt employed was 74% pure CaCl_2 powder (Calcium chloride, Oriental Chemical Industries Co., Ltd., Seoul, Republic of Korea) commonly used for snow removal on roads in South Korea. Two topsoil filters, expanded clay (Hwangto-ball, YKbio, Gimpo, Korea) with a diameter of 8 mm, and granular activated carbon (8–30 mesh Carbon, Duk San Science Co., Ltd., Seoul, Republic of Korea) were utilized.

After preparation, all topsoil filter materials were dried at 105 ± 2 °C until reaching a constant weight and stored in desiccators without further treatment.

P. australis, the experimental plant, was sourced from a botanical garden in Cheonan, Chungcheongnam-do, in March 2018. Seedlings of approximately 10–12 cm in height and 2–3 cm in root length were acclimated in the greenhouse for one month. Subsequently, their aboveground sections were uniformly trimmed to 5 cm and planted in individual pots for each treatment.

2.2. Experimental Treatments

Typically, saline-sodic soils with an $EC > 4$ dS·m^{−1} have a NaCl stress threshold for plants of 80 mM or 5 g·L^{−1} [5]. Additionally, CaCl₂ concentrations have been reported to range from 1 to 10 g·L^{−1}, equivalent to salt concentrations encountered when de-icing agents directly contact snow [17]. Consequently, in the first experiment, *P. australis* was cultivated in pots with CaCl₂ solutions at concentrations of 0, 1, 2, 5, and 10 g·L^{−1}, respectively. Their actual concentrations were 0, 6.67, 13.34, 33.34, and 66.7 mM (labeled as Cont., C1, C2, C5, and C10, respectively). In the second experiment, two types of topsoil filters were each incorporated at 20% of the substrate volume, after which reeds were transplanted and subjected to high concentrations of CaCl₂ (66.7 mM or 10 g·L^{−1}). These treatments were designated as Cont. (10 g·L^{−1} CaCl₂), H (expanded clay), AC (activated carbon), P (planting reeds), H + P (expanded clay + planting reeds), and AC + P (activated carbon + planting reeds).

Phragmite australis seedlings were transplanted into 4-inch (110 mm × 90 mm) plastic pots filled with 100 g of horticulture substrate. The drainage hole at the bottom was sealed with a fiberglass mesh liner (1 mm) to prevent substrate and topsoil filter loss. Therefore, a total of 99 pots were used, consisting of a randomized complete block design with five CaCl₂ concentrations and six treatments (with or without planting and topsoil filters), each with nine replications. Plants were watered with 200 mL of tap water once every 3–4 days to prevent drying out. After preparing CaCl₂ solutions, 9 replicate pots of planted plus unplanted pots were dosed with 200 mL of de-icing salt solutions at concentrations of 0, 1, 2, 5, and 10 g·L^{−1}, respectively, every two weeks from June to August. Leachates from pots were collected 24 h later into 14 cm diameter plastic water trays placed underneath each pot [13]. Samples were gathered from each treatment and stored in a refrigerator for laboratory analysis. Leachate quality testing was carried out within a week of collection.

2.3. Soil Leachate and Plant Growth Measurement

This study analyzed leachate solutions from substrate-grown *P. australis*, focusing on pH, electric conductivity (EC), and salt exchangeable cations (K⁺, Ca²⁺, Na⁺, and Mg²⁺) [1,7]. Collected leachates were filtered through 5D filter paper (Adventec, filter paper No. 5B, Tokyo, Japan) and analyzed for electrical conductivity (ST-3100C, Ohaus Corp, Shanghai, China) and acidity (ST-3100pH, Ohaus Corp, Shanghai, China). Exchange cation contents in leachate samples were determined using inductively coupled plasma atomic emission spectrometry (ICP, Optima 5300DV, Perkin Elmer, Shelton, CT, USA). The experiment was conducted in a cold room maintained at 5 °C to prevent cation exchange in leachates.

The growth of *Pennisetum australis* in each saline and topsoil filter substrate was assessed by measuring plant height, leaf length, leaf width, and number of leaves during its most active growth period in August. Following the growth experiment, harvested plants were washed with distilled water. Fresh weights of both shoots and roots were recorded. Dry weight was determined after drying plants in a forced-air oven (C-DE, CHANGSHIN Sci CO, Republic of Korea) at 80 °C for 72 h.

2.4. Statistical Analysis

All results underwent an analysis of variance (one-way ANOVA) utilizing the SPSS 18.0 software package (SPSS Inc., Chicago, IL, USA). Mean separations were determined by

Duncan's Multiple Range Test (DMRT) at $p \leq 0.05$. Figures were created using SigmaPlot 12.3 (Systat. Software, Inc., Cary, NC, USA).

3. Results

3.1. Soil Leachate and *P. australis* Growth Characteristics in Response to Increasing De-Icing Salt Concentrations

The acidity (pH) values of leachates from Cont., C1, C2, C5, and C10 treatments were 7.03, 6.25, 6.11, 5.90, and 5.57, respectively. As the concentration of CaCl_2 increased, pH values decreased progressively. No statistical differences in pH value were found between Cont. and C2 treatments. Meanwhile, electrical conductivity (EC) in soil leachates from Cont., C1, C2, C5, and C10 treatments were 0.63, 2.28, 2.83, 8.95, and $17.00 \text{ dS}\cdot\text{m}^{-1}$, respectively (Figure 1), showed significant increases with increasing concentration of CaCl_2 .

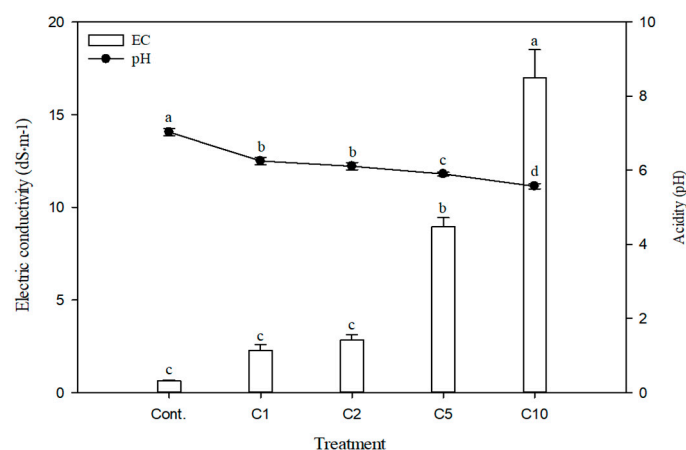


Figure 1. Average electric conductivity (EC) and acidity (pH) in the leachate of substrate-grown *P. australis* treated with increasing concentrations of CaCl_2 for 150 days in a greenhouse. Different letters indicate significant differences among treatments at $p \leq 0.05$ by Duncan's multiple range test. The vertical bar indicates the standard error ($\pm\text{SE}$) of the mean ($n = 30$). Cont.: treatment with $0 \text{ g}\cdot\text{L}^{-1}$ CaCl_2 solution, C1, C2, C5, and C10: 1, 2, 5, and $10 \text{ g}\cdot\text{L}^{-1}$ CaCl_2 solution, respectively.

Overall, increasing concentrations of CaCl_2 led to significant increases in salt-exchangeable cations (K^+ , Ca^{2+} , Na^+ , and Mg^{2+}). Levels of Ca^{2+} ions were higher than those of other ions ($p \leq 0.05$). Levels of Ca^{2+} and Na^+ in Cont., C1, and C2 treatments did not show significant differences, although they increased numerically. In contrast, the C10 treatment exhibited the highest contents of exchangeable cations, with elements of K^+ , Ca^{2+} , Na^+ , and Mg^{2+} being 3.7, 195.8, 6.4, and 595 times higher, respectively, than those in the control (Cont.). Above the C5 treatment, levels of Ca^{2+} , Na^+ , and Mg^{2+} ions remained constant in the leachate, showing no significant increases except for K^+ ions (Figure 2).

P. australis maintained a 100% survival rate across all CaCl_2 concentration treatments, exhibiting no signs of salt toxicity or nutritional deficiencies. However, the plant height of *P. australis* varied by treatment, with measurements for Cont., C1, C2, C5, and C10 being 59.2, 65.0, 66.8, 75.4, and 71.0 cm, respectively. When the CaCl_2 concentration was increased, leaf length and width showed no statistically significant differences. The number of leaves in Cont., C1, C2, C5, and C10 was 25.8, 28.6, 36.0, 29.5, and 37.3, respectively (Table 1), showing a significant increase ($p \leq 0.01$) when the CaCl_2 concentration was increased.

Shoot fresh weight of *P. australis* showed no significant differences depending on the CaCl_2 concentration ($p \leq 0.01$) except for the control. However, significant differences were observed in the fresh weights of roots between the Cont., C1, C2, C5, and C10 treatments (fresh weights of roots: 6.70, 8.90, 11.05, 13.10, and 12.60 g, respectively). The C5 treatment displayed the highest value, although its difference from the C10 treatment was not significant. As the concentration of CaCl_2 increased, the dry weights of reeds

showed slight increases. On a dry weight basis, the largest biomass was recorded for the C10 treatment (Figure 3).

Table 1. Growth characteristics of *P. australis* treated with increasing concentrations of CaCl_2 in a greenhouse in August.

Treatment ^z	Plant Height (cm)	Leaf Length (cm)	Leaf Width (cm)	No. of Leaves
Cont.	59.2 b ^y	12.54 a	0.59 a	25.8 b
C1	65.0 ab	11.02 a	0.53 a	28.6 ab
C2	66.8 ab	11.02 a	0.57 a	36.0 ab
C5	75.4 a	11.88 a	0.57 a	29.5 ab
C10	71.0 ab	12.25 a	0.62 a	37.3 a

^z Cont.: treatment without CaCl_2 solution, C1, C2, C5, and C10: 1, 2, 5, and 10 $\text{g}\cdot\text{L}^{-1}$ CaCl_2 solution, respectively.

^y Different letters indicate significant differences among treatments by Duncan's multiple range test at $p \leq 0.05$ ($n = 9$).

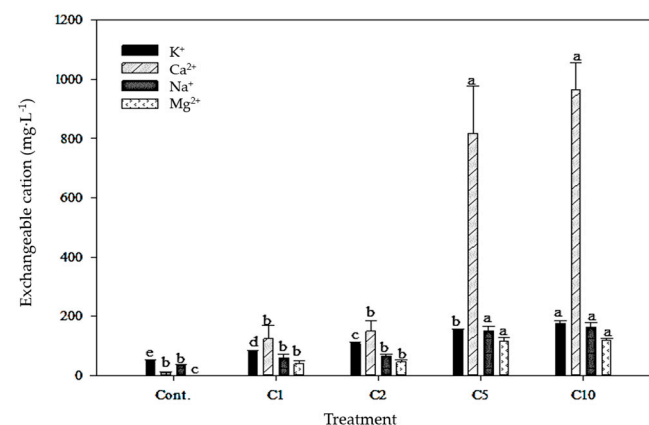


Figure 2. Average levels of exchangeable cations (K^+ , Ca^{2+} , Na^+ , and Mg^{2+}) in leachates of substrate-grown *P. australis* treated with increasing concentrations of CaCl_2 for 150 days in a greenhouse. The vertical bar indicates the standard error ($\pm$ SE) of the mean ($n = 30$). Different letters indicate significant differences among treatments at $p \leq 0.05$ by Duncan's multiple range test. Cont.: treatment with 0 $\text{g}\cdot\text{L}^{-1}$ CaCl_2 solution, C1, C2, C5, and C10: 1, 2, 5, and 10 $\text{g}\cdot\text{L}^{-1}$ CaCl_2 solution, respectively.

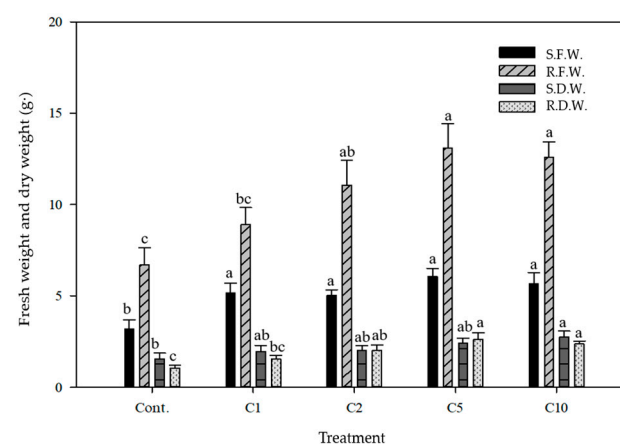


Figure 3. Average fresh weight and dry weight of *P. australis* treated with increasing concentrations of CaCl_2 for 150 days in a greenhouse. Different letters indicate significant differences among treatments at $p \leq 0.05$ by Duncan's multiple range test. The vertical bar indicates the standard error ($\pm$ SE) of the mean ($n = 9$). S.F.W.: shoot fresh weight; R.F.W.: root fresh weight; S.D.W.: shoot dry weight; R.D.W.: root dry weight. Cont.: treatment with 0 $\text{g}\cdot\text{L}^{-1}$ CaCl_2 solution, C1, C2, C5, and C10: 1, 2, 5, and 10 $\text{g}\cdot\text{L}^{-1}$ CaCl_2 solution, respectively.

3.2. Synergistic Effect of Planting *P. australis* and Adding Topsoil Filters at High Concentration of De-Icing Salts on Salinity Reduction

Topsoil filters planted with reeds reduced all evaluated EC levels in soil leachates compared to the control, with the exception of the treatment planting only *P. australis* (P). The greatest decrease in the leachate EC value was observed in the group treated with activated carbon + *P. australis* planting (AC + P). In terms of leachate pH, no significant difference was observed between non-planted controls (Cont.) and treatments using activated carbon (AC) or activated carbon + *P. australis* planting (AC + P). Conversely, there was a significant reduction ($p \leq 0.05$) in the order of expanded clay (H) > expanded clay + *P. australis* planting (H + P) > *P. australis* planting (P) (Figure 4) was observed.

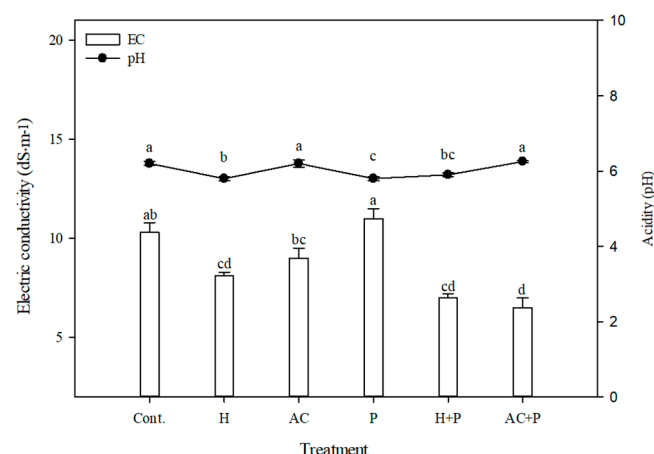


Figure 4. Average EC and pH in leachates of substrate-grown *P. australis* added with topsoil filters (expanded clay and activated carbon) and treated with CaCl_2 at a concentration treatment of $10 \text{ g} \cdot \text{L}^{-1}$ for 150 days in a greenhouse. Different letters indicate significant differences between treatments at $p \leq 0.05$ by Duncan's multiple range test. The vertical bar indicates the standard error ($\pm \text{SE}$) of the mean ($n = 36$). Cont.: treatment with $10 \text{ g} \cdot \text{L}^{-1}$ CaCl_2 solution; H: expanded clay; AC: activated carbon; P: *P. australis* planted alone; H + P: expanded clay + *P. australis* planted; AC + P: activated carbon + *P. australis* planted.

Comparisons of exchangeable cations in leachates of the six treatments showed significant differences. Specifically, the Ca^{2+} concentration was the highest in the control treatment, reaching $1164.8 \text{ mg} \cdot \text{L}^{-1}$. Concentrations of K^+ , Na^+ , and Mg^{2+} were the lowest in the group having activated carbon treatment with *P. australis* planted (AC + P). They were measured at 344.2 , 218.4 , and $119.8 \text{ mg} \cdot \text{L}^{-1}$, respectively. Exchangeable ion levels in the substrate leachate showed significant decreases when *P. australis* was planted compared to those when using a topsoil filter alone. Moreover, activated carbon treatments notably reduced leachate concentrations of K^+ , Ca^{2+} , Na^+ , and Mg^{2+} , likely due to an elevated pH (Figures 4 and 5).

The plant height of *P. australis* was numerically the highest in the treatment with only reeds planted, although it was not significantly different from that in the treatment with topsoil filters. The leaf length and number of leaves of *P. australis* in treatments exclusively using reeds were significantly higher than those in treatments with topsoil filters. The leaf width of *P. australis* was the greatest in the H + P (expanded clay + *P. australis* planted) treatments. Overall, the growth characteristics of reeds under high-concentration de-icing salt ($10 \text{ g} \cdot \text{L}^{-1}$) showed longer plant heights and leaf lengths with more leaves in treatment where plants were grown alone— $\text{P} > \text{H} + \text{P} > \text{AC} + \text{P}$ —compared to those with the addition of topsoil filters (Table 2). This suggests that reeds can grow and expand vertically under hypersaline conditions.

Relative biomass partitioning between aboveground and belowground parts of *P. australis* was influenced by differences in topsoil filters. However, the shoot fresh weight (S.F.W.) and dry weight (S.D.W.) of *P. australis* were unaffected by the topsoil filter treat-

ment. Meanwhile, root fresh and dry weights were higher in P (*P. australis* planted alone) treatments than in those with topsoil filters, H + P or AC + P (Figure 6).

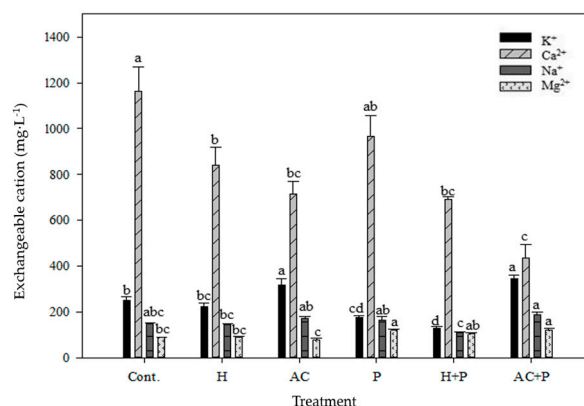


Figure 5. Average levels of exchangeable cations (K^+ , Ca^{2+} , Na^+ , and Mg^{2+}) in the leachate of substrate-grown *P. australis* with topsoil filters (expanded clay and activated carbon) and treated with a $CaCl_2$ at a concentration of $10\text{ g}\cdot\text{L}^{-1}$ for 150 days in a greenhouse. Different letters indicate significant differences among treatments at $p \leq 0.05$ by Duncan's multiple range test. The vertical bar indicates the standard error ($\pm$ SE) of the mean ($n = 36$). Cont.: treatment with $10\text{ g}\cdot\text{L}^{-1}$ $CaCl_2$ solution; H: expanded clay; AC: activated carbon; P: *P. australis* planted alone; H + P: expanded clay + *P. australis* planted; AC + P: activated carbon + *P. australis* planted.

Table 2. Effects of adding topsoil filters (expanded clay or activated carbon) and $CaCl_2$ at a concentration of $10\text{ g}\cdot\text{L}^{-1}$ in August in a greenhouse on growth characteristics of *P. australis*.

Treatment	Plant Height (cm)	Leaf Length (cm)	Leaf Width (cm)	No. of Leaves
P ^z	71.0 a ^y	12.02 a	0.6 ab	37.3 a
H + P	67.7 a	9.37 b	0.5 b	29.3 ab
AC + P	59.5 a	8.25 b	0.7 a	24.7 b

^z P: *P. autaralis* planted alone; H + P: expanded clay + *P. australis* planted; AC + P: activated carbon + *P. autralis* plnted. ^y Different letters indicate significant differences among treatments by Duncan's multiple range test at $p \leq 0.05$ ($n = 9$).

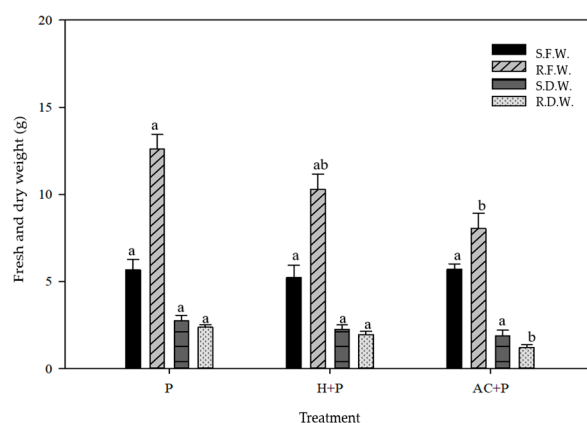


Figure 6. Average fresh weight and dry weight of *P. australis* added with topsoil filters (expanded clay and activated carbon) and $CaCl_2$ at a concentration treatment of $10\text{ g}\cdot\text{L}^{-1}$ for 150 days in a greenhouse. Different letters indicate significant differences among treatments at $p \leq 0.05$ by Duncan's multiple range test. The vertical bar indicates the standard error ($\pm$ SE) of the mean ($n = 9$). S.F.W.: shoot fresh weight; R.F.W.: root fresh weight; S.D.W.: shoot dry weight; R.D.W.: root dry weight; P: *P. australis* planted alone; H + P: expanded clay + *P. australis* planted; AC + P: activated carbon + *P. australis* planted.

4. Discussion

The pH of soil leachate was found to be between 6.5 and 7.5, gradually decreasing with an increased concentration of CaCl_2 . Therefore, a higher concentration of CaCl_2 is associated with a lower pH level in the soil leachate because concentrations of acidic ions are increased due to the substitution of hydrogen ions (H^+), acidic cations in the leachate, by alkaline ions [18]. Cations in the soil related to alkalinity include potassium, calcium, magnesium, and sodium. When a large amount of these cations is selectively absorbed by plants, hydrogen ions (H^+) are relatively easily released into the soil, accelerating soil acidification [19]. On the other hand, higher concentrations of de-icing salts seem to gradually increase electrical conductivity as concentrations of inorganic elements in soil leachates increase [20]. Electrical conductivity indicates the strength of electrolyte ions in soils [21]. Typically, soils are considered saline when the conductivity of saturation extracts exceeds $4 \text{ dS}\cdot\text{m}^{-1}$. In a hypersaline environment, salinity levels can reach or exceed that of seawater ($>35\text{--}40 \text{ g}\cdot\text{L}^{-1} \text{ NaCl}$) [22]. Based on these criteria, Cont., C1, and C2 treatments can be classified as saline soils, while C5 and C10 treatments can qualify as hypersaline soils in terms of electrical conductivity.

Sodium and chloride concentrations exceeding $0.3 \text{ g}\cdot\text{L}^{-1}$ typically have a detrimental effect on vegetation [3]. Studies have shown that under severe salt stress, an ion imbalance characterized by an increased accumulation of K^+ ions within the plant and a reduced influx of Ca^{2+} and Na^+ ions into the soil can occur [7,23]. Plant growth response is an effective indicator of salt tolerance, and it has been observed that an increase in salinity inhibits plant growth [24]. However, salt-tolerant plants can preserve their normal physiological functions by excreting salts (such as K^+ , Ca^{2+} , Na^+ , Mg^{2+} , and Cl^-) or transferring salts into salt pouches within their bodies [25]. *P. australis* is known to tolerate a wide range of salinity levels, exhibiting significant variations locally and regionally due to climate and substrate content [26]. According to Hartzendorf and Rolletschek (2001), low survival rates of reeds are primarily observed in low-salt treatments, with the optimal salt conditions for culturing this species being around 5‰ salinity [27]. Shoots of *P. australis* treated with NaCl for 28 days in a hydroponic system displayed the most severe wilting and chlorosis at the lowest NaCl concentration of $30 \text{ g}\cdot\text{L}^{-1}$ [22]. Therefore, in this experiment, salinity did not affect the growth characteristics of *P. australis* under favorable nutritional conditions. When grown in water with a NaCl concentration of approximately $200 \text{ mmol}\cdot\text{L}^{-1}$, *P. australis* has been reported to accumulate significant amounts of Na^+ and Cl^- [11]. Consequently, these properties of *P. australis* appear to contribute to favorable growth outcomes, even under the highest concentration of $10 \text{ g}\cdot\text{L}^{-1} \text{ CaCl}_2$ treatment.

P. australis grows rapidly and produces large quantities of biomass quickly. Consequently, it is one of the most utilized plants in constructed wetlands [11]. In all de-icing salt treatments, the reeds produced more shoots and responded better to increasing levels of CaCl_2 compared to the control, with a significant increase in reed root growth, exceeding the growth of shoots. These responses are governed by a de-icing salt cation exclusion mechanism in its roots, suggesting that changes in plant metabolism are crucial during various growth stages. Furthermore, *P. australis* is a Cl^- accumulator species, with juvenile plants capable of accumulating chloride in their aerial parts up to a critical threshold value of approximately $25 \text{ mg}\cdot\text{g}^{-1} \text{ DW}$ [4]. For sodium chloride, both ionic tissue content and biomass are key factors in Na^+ accumulation, while Cl^- accumulation is predominantly influenced by biomass production [11]. This indicates that plant selection for de-icing salt cation accumulation should prioritize both biomass production and ion accumulation, particularly prioritizing biomass when selecting for Cl^- removal.

In the context of desalination, topsoil filters such as activated carbon and expanded clay can enhance a substrate's adsorption capacity by increasing the surface area available for binding, the presence of surface functional groups, changes in pH, and an increase in cation exchange capacity through surface charge. Both specific and non-specific adsorption significantly depend on soil pH, with a higher pH providing more negatively charged sites due to reduced H^+ competition. Activated carbon can enhance the soil's

buffering capacity, thereby helping stabilize pH and prevent the desorption of de-icing salt ions [28]. Additionally, clay minerals can enhance physical qualities and augment pH buffering capacity in a substrate based on bark and peat [15]. Our results demonstrate that incorporating activated carbon into substrates can raise the pH compared to the control, potentially reducing competition with H^+ , thereby increasing the adsorption of de-icing salt ions onto colloidal surfaces and decreasing EC.

Activated carbon boasts a high surface area, a low bulk density, a high porosity, and a substantial carbon content, enabling effective absorption of soil contaminants. Notably, activated carbon exhibits greater recalcitrance, thus serving as an effective sorbent of contaminants in the soil over extended periods [28]. Granular activated carbon has demonstrated reliable removal of pesticides and herbicides from water [15]. Houben et al. (2013) have observed significant reductions of Ca concentrations in $CaCl_2$ extracts with rising levels of activated carbon, 0–10% [29]. Meanwhile, clay mineral content is known to affect CEC concentrations in soil, with varying absorption capabilities based on its structure and specific surface area [22]. *P. australis* possesses high CEC concentrations in its roots [30], indicating that its synergistic interaction with topsoil filters could facilitate the desalinization and restoration of de-icing salt-contaminated soil by combining salt removal and sequestration.

These results mirrored trends observed in the first experiment, where increased concentrations of de-icing salts corresponded to higher plant height and more leaves on reeds compared to the control. Employing activated carbon as a topsoil filter in street tree pits can enhance soil's ability to retain urban runoff contaminants found in urban runoff. This increased retention may reduce peak concentrations of soluble trace metals and de-icing salts in the soil solution, consequently diminishing quantities absorbed by tree roots or leached into the groundwater [28]. However, prior studies have shown that excessive use of activated carbon can adversely affect plant health primarily by adsorbing essential nutrients and elevating soil pH [31]. Lehmann et al. (2003) have also discovered that soils amended with charcoal could negatively impact the growth of cowpeas (*Vigna unguiculate*) by increasing the soil's C/N ratio and inhibiting nitrogen absorption by the plant [32]. Therefore, expanded clay and activated carbon may reduce the growth of *P. australis*, although they are effective for remediating the de-icing of salt-contaminated soil.

These results are consistent with previous studies demonstrating that moderate concentrations of $CaCl_2$ can stimulate the growth of *P. australis* and that it is less sensitive to higher concentrations of $CaCl_2$. Some authors have found that the fresh weights of roots and both fresh and dry weights of shoots of *S. fruticosa* are increased under salinity conditions ranging from 200 to 400 mM [7]. Above all, *P. australis* species, being halophytes, were found to have a relatively low biomass reduction, even when they were treated with high concentrations of $CaCl_2$. Thus, *P. australis* can act as vegetation cover, even in the presence of high concentrations of de-icing salts in soil.

5. Conclusions

This study evaluated the effects of two different topsoil filters (expanded clay and activated carbon) as immobilizers in supporting the phytodesalinization of *Phragmites australis* contaminated by de-icing salts. The salt tolerance of *P. australis* was shown to exceed 66.7 mM ($10\text{ g}\cdot\text{L}^{-1}$) $CaCl_2$, although high-concentration treatments revealed differences between topsoil filters. It is believed that further improvements can be made by selecting halophytic species that can tolerate extremely high salinity levels, thus being suitable for phytomanagement in hypersaline areas. De-icing salt removal exhibited more positive effects in treatments with added topsoil filters than in those planted with *P. australis* alone. Specifically, activated carbon was proven to be a beneficial topsoil filter for roadside soils vulnerable to de-icing salt contamination, although over-application could negatively affect the growth of *P. australis*. These findings provide valuable insights for remediating soils contaminated with de-icing salts, especially in intermittently submerged roadside environments. Based on the results of this study, both topsoil filters contributed to the removal

of high concentrations of de-icing salts, although the underlying mechanisms remain not completely clear and warrant further investigation. Additionally, factors affecting growth can vary with climate. Thus, field application may influence the salt tolerance of *P. australis*, particularly under hypersaline conditions.

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