

Article

A Decision Matrix–Guided Framework for Screening Plant Species for Sustainable Phytoremediation of Road Salt–Contaminated Roadside Soils

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Abstract

The widespread application of road deicing salts in northern regions has led to elevated salinity in roadside soils and adjacent watersheds. Phytoremediation offers a cost-effective and sustainable approach for mitigating salt contamination, but its success depends on utilizing plant species that can both tolerate and remove salt under roadside conditions. To systematically identify high-potential candidates from the large inventory of salt-tolerant plants in North America, we developed a quantitative decision matrix incorporating criteria related to ecological safety, establishment potential on disturbed soils, aboveground biomass production, biomass use-value, and salt uptake capacity. Thirteen of the highest-ranked species were subsequently evaluated for sodium (Na^+) and chloride (Cl^-) uptake in a controlled greenhouse study under saline and non-saline conditions. The greatest total salt uptake was observed in common sunflower (*Helianthus annuus*) (35.6 mg Na^+ and $100.2 \text{ mg Cl}^- \text{ plant}^{-1}$) and pitseed goosefoot (*Chenopodium berlandieri*) (18.6 mg Na^+ and $76.0 \text{ mg Cl}^- \text{ plant}^{-1}$), while perennial species including tall fescue turfgrass (*Lolium arundinaceum*), showy goldenrod (*Solidago speciosa*), and weeping alkaligrass (*Puccinellia distans*) also demonstrated substantial uptake combined with greater long-term suitability for roadside management. Overall, this study presents a quantitative framework for phytoremediation species selection and provides experimental evidence supporting both annual and perennial species for mitigating deicing salt contamination through environmentally sustainable, low-input roadside management strategies.

Keywords: phytoremediation; sustainable remediation; road salt pollution; sodium chloride; decision matrix; roadside ecosystems



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1. Introduction

High salt loads from road deicing practices are contributing to increasing salinity in soils and freshwater systems in cold climate regions worldwide [1]. In North America, states like Minnesota (MN) apply road salt extensively each winter for traffic safety, resulting in chronic salt inputs to roadside environments and adjacent watersheds [2]. Road salt applied to roadways reaches freshwater systems via meltwater runoff and groundwater infiltration [3]. Once mobilized, salt can move through the environment via surface runoff, infiltration, subsurface flow, and groundwater pathways [4].

Chloride (Cl^-), the primary anion in most road salts, readily dissociates in melting snow and stormwater. It is difficult to precipitate and easily leaches into lakes, rivers, and

groundwater, where it can damage aquatic ecosystems [5]. In the Twin Cities Metro Area (TCMA), lake salinity has been shown to correlate with the amount of rock salt purchased by the State of MN and the percent of impervious surfaces in surrounding watersheds [6]. In 2024, the Minnesota Pollution Control Agency listed 67 water bodies impaired by chloride, up from 54 two years earlier, based on the U.S. Environmental Protection Agency chronic Cl^- limit of 230 mg L^{-1} [7]. Many more lakes in the Northeast and Midwest are predicted to exceed this threshold within the next few decades if current trends continue [8].

Salt also accumulates in soils adjacent to roadways. Monitoring of a vegetated high-way ditch in the TCMA showed that over 95% of applied Cl^- infiltrated into the soil, with less than 5% exported as surface runoff [9]. Depending on soil characteristics and precipitation patterns, Cl^- can continue leaching from roadside soils for 2.5 to 5 months after application [10]. Sodium (Na^+), a principal cation in road salt, often binds to negatively charged soil particles, contributing to elevated and persistent concentrations [11]. High Na^+ levels can reduce soil pore size, limiting root penetration, water availability, and nutrient uptake, ultimately diminishing soil stability and fertility [12]. Na^+ can also displace essential macronutrients such as calcium (Ca^{2+}), magnesium (Mg^{2+}), and potassium (K^+) from soil [13].

Elevated salinity negatively impacts plants by causing osmotic stress, which reduces water uptake and limits photosynthesis [14]. Salinity also induces the formation of reactive oxygen species (ROS) that damage cellular structures, including membranes and DNA [15]. At toxic levels, Na^+ and Cl^- cause visible injury such as leaf scorching, chlorosis, and necrosis [16]. Some plant species, however, have evolved strategies to cope with salinity, including salt exclusion, osmotic adjustment, ion compartmentalization, and salt excretion [17,18]. Salt-tolerant species are therefore important candidates for remediation efforts. Research at the University of Minnesota, for example, has focused on identifying salt-tolerant turfgrasses suitable for roadside environments [19].

Approaches to managing salt-contaminated soils include chemical amendments, organic amendments, leaching, and deep tilling, but these techniques can be disruptive, expensive, or impractical at large scales [13,20]. Phytoremediation offers a low-cost, low-impact alternative in which plants extract contaminants from soil and store them in aboveground tissues that can be harvested and removed [21,22]. This strategy improves soil health through increased carbon inputs and enhanced soil-aggregate stability, promoting better drainage and root growth [23]. Additionally, salt uptake by plants reduces leaching into groundwater, and harvested biomass may provide supplemental economic value [24–26]. Phytoremediation is often slow and limited to the rooting depth of plants [27], though it has been successfully applied to soils contaminated with metals, organic pollutants, and salts [28–31].

Several studies have examined plant species for phytoremediation of deicing salt [30,32–34]. For example, Mann et al. [34] demonstrated that native Canadian *Atriplex* species could extract on the order of $8\text{--}28 \text{ g Cl}^- \text{ m}^{-2}$ per growing season, indicating that phytoremediation can meaningfully reduce salt accumulation in roadside soils under favorable conditions. However, no comprehensive effort has been made to systematically inventory and evaluate the large number of salt-tolerant plant species available in North America. With more than 200 halophytes and numerous additional salt-tolerant non-halophytes occurring across inland and coastal regions [35], species selection remains a critical bottleneck in developing phytoremediation systems for roadside soils.

Effective species selection for roadside salt phytoremediation requires consideration of multiple criteria beyond salt tolerance alone, including ecological safety, establishment potential on disturbed soils, biomass production, and the feasibility of long-term roadside management. Multi-criteria decision matrices have previously been applied to guide plant

selection for phytoremediation, such as for heavy metal-contaminated soils, but these approaches have typically relied on literature-derived rankings and have not focused specifically on salt remediation in roadside environments [36].

To address this gap, this study developed a comprehensive decision matrix to quantitatively evaluate salt-tolerant plant species based on criteria directly relevant to roadside salt phytoremediation. These criteria included ecological safety, establishment potential on disturbed soils, biomass yield, biomass use value, and salt uptake capacity. This matrix allowed for quantitative comparison among species and facilitated the selection of high-priority candidates for experimental testing. The highest-scoring species were then evaluated in a controlled greenhouse study to assess their salt uptake under saline irrigation conditions.

2. Materials and Methods

2.1. Decision Matrix Development

2.1.1. Species Inventory and Data Sources

Candidate species for screening were first compiled into a comprehensive Salt-Tolerant Plant Species Inventory. Halophytic species were identified using the eHALOPH Halophytes Database [37] and cross-referenced with the USDA Natural Resources Conservation Service Plants Database to determine which species were native to or commonly occurring in Minnesota [38]. To ensure local feasibility, additional moderately and highly salt-tolerant species known to establish successfully in Minnesota Department of Transportation (Mn-DOT) roadside seed mixes were included. This produced an inventory emphasizing species with documented occurrence or establishment success in disturbed roadside soils within the TCMA.

2.1.2. Decision Matrix Criteria and Scoring Framework

A quantitative decision matrix was developed to systematically screen salt-tolerant plant species for their suitability in roadside phytoremediation applications. The matrix was designed to integrate both phytoremediation performance and practical feasibility for roadside deployment. Five criteria were evaluated for each species: (1) ecological safety, (2) establishment + biomass yield, (3) salt uptake potential, (4) biomass value, and (5) life cycle. All criteria were scored on a standardized 0–10 scale and multiplied by weighting factors to reflect their relative importance. Criteria definitions, scoring ranges, and weights are shown in Table S1. The final matrix score for each species was calculated as the weighted sum of all criteria.

2.1.3. Ecological Safety, Biomass Value, and Life Cycle Scoring

The ecological safety criterion evaluated the ecological risk associated with sowing a species outside of cultivation, with emphasis on invasive or weedy potential in Minnesota and surrounding regions. Scores ranged from 0 to 10, with higher values assigned to native or non-invasive species and lower values assigned to agricultural weeds or known invasive species. Species considered noxious or globally invasive received the lowest scores. Ecological safety scores were based primarily on the USDA Plants Database and supporting literature, with condensed justifications and references provided in Table S2 [38–44].

The biomass value criterion assessed the potential utility of harvested aboveground biomass independent of yield magnitude. Scores reflected documented or plausible uses such as forage, feed, bioenergy, food, or other beneficial applications. Species with high-value, well-established uses received higher scores, while species with limited or no documented uses received lower scores. Biomass value scores and supporting justifications with references are presented in Table S2 [38,40–43,45–56].

Life cycle scoring reflected plant longevity and persistence, emphasizing suitability for long-term roadside management and early-season salt uptake during snowmelt periods. Annual species received the lowest scores, while long-lived perennial species received the highest scores. Intermediate values were assigned to biennial and moderate-lived perennial species. Life cycle classifications and scores were derived from the USDA Plants Database and are summarized in Table S2 [38].

2.1.4. Establishment + Biomass Yield Scoring

Establishment and biomass yield were combined into a single composite criterion to represent both the likelihood of successful establishment on disturbed roadside soils and the capacity to generate harvestable aboveground biomass once established. This composite score was calculated using Equation (1) below:

$$\text{Establishment} + \text{Yield} = 0.6 * (\text{Establishment score}) + 0.4 * (\text{Biomass yield score}) \quad (1)$$

The establishment score reflected germination success, seedling vigor, competitiveness, and tolerance of roadside disturbance, including variability in soil moisture and nutrient availability. Establishment scores ranged from 0 to 10 and were assigned using a standardized rubric, informed by literature descriptions of roadside occurrence, growth characteristics, and ecological amplitude (Table S3) [34,38–40,43,57–59].

The biomass yield score represented expected aboveground dry biomass production under low-input, disturbed, or stressed conditions representative of roadside environments. Literature-reported yield values were compiled for each species, prioritizing studies conducted without intensive fertilization, irrigation, or weed control when available. A single representative yield value was assigned per species using conservative assumptions, and yields were categorized into tiers corresponding to yield scores from 0 to 10. Detailed justifications, yield contexts, and scores are provided in Table S3 [46,51,60–79].

2.1.5. Salt Uptake Potential Scoring

Salt uptake potential estimated a species' capacity to remove Na^+ and Cl^- from soil via accumulation in harvestable aboveground biomass. This criterion was based on literature-reported Na^+ and Cl^- concentrations in shoot tissue, expressed as the combined $\text{Na}^+ + \text{Cl}^-$ concentration (mg g^{-1} dry mass). When species-specific data were unavailable, conservative alternative values were assigned using averages from taxonomically or functionally similar species. Studies conducted under extreme salinity that caused severe biomass suppression were excluded from direct scoring to avoid overestimating uptake potential under realistic roadside conditions.

Salt uptake scores were calculated by dividing the combined $\text{Na}^+ + \text{Cl}^-$ concentration by 20 to produce a 0–10 scale. All tissue concentration values, assumptions, references, and resulting scores are provided in Table S4 [61,64,65,72,74,76,80–88].

2.1.6. Weighting and Final Matrix Score

Each decision matrix criterion was multiplied by a weighting factor to reflect its relative importance in identifying plant species suitable for roadside salt phytoremediation. Weighting factors were assigned according to defined remediation priority preferences, emphasizing criteria most critical for sustainable roadside implementation. This approach follows established multi-criteria decision analysis frameworks used in phytoremediation, where weights are selected to align species rankings with project-specific objectives rather than relying on single attribute performance [36].

Weighting factors were selected to balance remediation effectiveness with ecological safety and practical feasibility for roadside management. Salt uptake potential was assigned

a high weight (2.5) due to its direct relevance to the primary objective of the study: removal of Na^+ and Cl^- from contaminated soils. Establishment potential, including biomass yield, received the highest overall weight (3) because successful remediation requires both reliable establishment on disturbed roadside soils and sufficient biomass production to enable meaningful salt removal. Ecological safety was weighted at two to ensure that species with high invasive or weedy potential were appropriately penalized, reflecting the ecological risks associated with roadside seeding. Life cycle was assigned a moderate weight (1.5) to emphasize the importance of long-term persistence and early-season salt uptake, particularly during spring snowmelt, while avoiding over-penalization of high-performing annual species. Biomass use-value received a lower weight (1) to acknowledge potential secondary benefits of harvested biomass without allowing economic considerations to dominate remediation performance. While weights were selected to reflect roadside remediation priorities relevant to this study, the framework is adaptable and weights can be adjusted for different regions or management objectives while maintaining a consistent evaluation structure.

Final matrix scores were calculated as the sum of all weighted criterion scores. Higher total scores indicate species that best balance salt uptake potential, establishment feasibility, ecological safety, and practical utility for roadside phytoremediation applications.

2.2. Greenhouse Screening Experiment

A subset of highly ranked species was subsequently evaluated in controlled greenhouse experiments, allowing matrix-based rankings to be compared with experimentally measured Na^+ and Cl^- uptake.

2.2.1. Experimental Design

Seeds of each species were germinated in trays containing germination mix potting soil (Sun Gro Horticulture, Agawam, MA, USA). Due to interspecies differences in germination timing and early growth rates, seedlings were maintained in germination trays for variable durations prior to transplanting, ranging from approximately 9 to 30 days. Seedlings were replanted once they reached a comparable early vegetative stage suitable for pot establishment into individual 10.16 cm (4-inch) diameter pots containing approximately 75 g of general mix potting soil (Sun Gro Horticulture). Pots were placed on collection trays to capture drainage and minimize salt loss.

Following two–three weeks of establishment, each pot received 100 mL of quarter-strength Hoagland solution amended with either the control (tap water) or saline (50 mM NaCl) treatments. Treatments were applied weekly for four weeks, for a total of 400 mL solution and 1.17 g NaCl added per pot in the saline treatment. After the first salt addition, all plants were grown for six weeks before harvest and stored at 4 °C until analysis.

Greenhouse conditions were controlled using an automated climate control system. Plants were grown under natural sunlight supplemented with HPS lighting to maintain a 14 h photoperiod, with relative humidity maintained between 30 and 80% and daylight temperatures between 23.3 and 24.4 °C. During the 10 h dark period, relative humidity was maintained between 75 and 80% and temperatures between 21.7 and 23.3 °C.

2.2.2. Plant Tissue Analysis

Aboveground biomass was separated from roots, and roots were washed to remove soil. All plant material was oven-dried at 105 °C for 12–24 h, and dry mass was recorded. Shoots were finely ground prior to ion analysis.

Only aboveground tissues were analyzed because these tissues are removed during harvest and contribute directly to phytoremediation. Na^+ and Cl^- analyses followed the nitric-acid digestion method of Muchate et al. [31]. A 100 mg sample of dried tissue was digested in 30 mL of 0.5% nitric acid at 100 °C for 30 min, filtered, and refrigerated

at 4 °C. Na⁺ and Cl[−] concentrations were quantified using a Dionex™ Aquion™ ion chromatography system equipped with ICS-1100 and ICS-2100 modules (Thermo Fisher Scientific, Waltham, MA, USA).

2.2.3. Statistical Analysis

Data are presented as means ± standard deviation. Treatment effects were evaluated using two-way analysis of variance (ANOVA) followed by Tukey's post hoc test, with statistical significance defined as $p < 0.05$. Two independent greenhouse experiments were conducted using identical plant species, soil, salinity treatments, and experimental protocols, each including five replicates per treatment group. Data from both experiments were combined for analysis to increase replication, incorporating variability across experimental runs.

3. Results

3.1. Decision Matrix–Based Species Screening

The plant species selected for the greenhouse experiment were those with some of the greatest matrix scores (Table 1), representing the highest potential to effectively and cost-efficiently remove salt from contaminated roadside soils in the TCMA. The information below in Table 1 provides the rationale and background supporting the matrix values for thirteen of the highest-ranked species that were subsequently evaluated in a greenhouse study. Additional information and reasoning for each score is found in Supplementary Tables S1–S4.

Table 1. Multi-criteria decision matrix results for species selection.

Scientific Name	Common Name	Ecological Safety (×2)	Establishment + Yield (×3)	Salt Uptake (×2.5)	Biomass Value (×1)	Life Cycle (×1.5)	Total Matrix Score
<i>Elymus trachycaulus</i>	Slender wheatgrass	10	8.6	1.7	8	7.5	69.3
<i>Solidago canadensis</i>	Canada goldenrod	9	8.8	2.2	4	10	68.9
<i>Pascopyrum smithii</i>	Western wheatgrass	10	7.4	1.7	7	10	68.5
<i>Bouteloua dactyloides</i>	Buffalo grass	10	7.7	1.7	6	10	68.4
<i>Medicago sativa</i>	Alfalfa	8	7.7	2.1	9	10	68.3
<i>Solidago speciosa</i>	Showy goldenrod	10	7.4	2.2	4	10	66.7
<i>Panicum virgatum</i>	Switchgrass	9	7.7	0.7	7	10	64.8
<i>Spartina pectinata</i>	Prairie cordgrass	10	7.4	1.4	4	10	64.7
<i>Andropogon gerardii</i>	Big bluestem	10	6	1.7	7	10	64.3
<i>Chenopodium berlandieri</i>	Pitseed goosefoot	10	6.6	6.9	5	1	63.6
<i>Helianthus annuus</i>	Common sunflower	10	8.6	2.2	9	1	61.8
<i>Distichlis spicata</i>	Saltgrass	9	6.5	1.4	5.5	10	61.6
<i>Lolium arundinaceum</i>	Tall fescue turfgrass	8	8.1	2.0	5	7.5	61.6
<i>Festuca rubra</i>	Creeping red fescue	9	6.6	1.7	4	10	61.1
<i>Suaeda calceoliformis</i>	Horned seablite	10	4.1	9.3	1	2.5	60.3
<i>Rhus glabra</i>	Smooth sumac	8.5	8.2	0.6	2	10	60.2
<i>Bouteloua curtipendula</i>	Side oats grama	10	5.5	1.7	8	7.5	60.0
<i>Phragmites australis</i>	Common reed	5	8.3	0.9	7	10	59.2
<i>Schoenoplectus tabernaemontani</i>	Softstem bulrush	10	5	1.7	4	10	58.1
<i>Atriplex prostrata</i>	Triangle orache	10	6.2	5.0	4	1	56.6
<i>Hordeum vulgare</i>	Barley	8	7.7	2.5	9	1	55.8
<i>Salicornia europaea</i>	Common glasswort	10	3	7.5	5.5	1	54.8
<i>Hordeum jubatum</i>	Foxtail barley	7	6.9	3.6	3	5	54.2
<i>Beta vulgaris</i>	Sugar beet	10	1.4	6.7	9	2.5	53.7
<i>Spergularia marina</i>	Salt sandsburry	10	3.3	7.3	1	2.5	52.8
<i>Puccinellia nuttalliana</i>	Nuttall's alkaligrass	10	3.9	1.7	4	7.5	51.3
<i>Chenopodium album</i>	Lambsquarters	3	6.6	6.9	4	1	48.6
<i>Typha latifolia</i>	Broadleaf cattail	1	7.9	1.8	6	7.5	47.5
<i>Puccinellia distans</i>	Weeping alkaligrass	7	3.1	1.7	5	7.5	43.9
<i>Portulaca oleracea</i>	Common purslane	0	7.2	4.1	4	1	37.3

Species are listed in order of highest total matrix scores first. Slender wheatgrass (*Elymus trachycaulus*) is a native short-lived perennial cool-season grass. Due to its fast growth and quick establishment, it is commonly used as a filler in seed mixtures and for the reclamation of saline roadsides and other disturbed areas [89]. It has moderate salt tolerance (10 to 20 dS m⁻¹) and is a palatable and nutritious forage with high crude protein content [38].

Canada goldenrod (*Solidago canadensis*) is an herbaceous, long-lifespan perennial native to MN. It is an aggressive, rhizomatous species that commonly colonizes disturbed sites like roadsides [38,90]. It is used for revegetation and erosion control and has good to fair palatability for livestock [38]. Canada goldenrod has been utilized for phytoextraction of zinc (Zn)-contaminated soils and shows a mild growth decrease under saline conditions [91,92].

Western wheatgrass (*Pascopyrum smithii*) is a native, long-lifespan perennial cool-season grass. It is an excellent erosion control plant widely used for revegetation of saline and alkaline areas [38]. It is considered to have high forage quality and equivalent salt tolerance to inland saltgrass (*Distichlis spicata*) [41,93].

Buffalograss (*Bouteloua dactyloides*) is a native, low-growing, long-lived perennial warm-season grass utilized for grazing and erosion control [38]. No studies were found testing its phytoremediation ability, although its moderate salt tolerance makes it a strong candidate [94].

Alfalfa (*Medicago sativa*) is a long-lived perennial legume crop widely used as hay. While not native, it is commonly found along roadsides in MN [38]. Alfalfa has shown potential for salt phytoremediation, with cultivation reducing soil salinity and one study showing a reduction of 1.8 dS m⁻¹ in moderately saline soil [85,95].

Showy goldenrod (*S. speciosa*) is a clumping perennial wildflower native to MN that is included in MnDOT's native seed mixes and is listed as having medium salt tolerance [38,96]. It is less aggressive than *S. canadensis* and is suitable for roadsides and restoration projects. No studies were found on its specific phytoremediation ability, but it was included due to its local establishment success and lower invasive potential compared to Canada goldenrod [38].

Switchgrass (*Panicum virgatum*) is a native, fast-growing, long-lived perennial warm-season grass used for soil stabilization and forage [38,97]. It is moderately salt-tolerant but tends to avoid high Na⁺ and Cl⁻ accumulation in shoots [86]. However, its high biomass production makes it a practical candidate for phytoremediation [97,98].

Big bluestem (*Andropogon gerardii*) is a long lifespan perennial warm-season grass native to MN. While it has relatively weak seedling vigor, it is one of the most palatable warm-season grasses and is favored for livestock and erosion control [38]. It has medium salt tolerance, and one study showed it had the highest germination rates under increasing salt levels compared to prairie cordgrass and switchgrass [99]. No studies were found investigating its phytoremediation capabilities, so its potential score was based on other grass species in the matrix.

Pitseed goosefoot (*Chenopodium berlandieri*) is an herbaceous annual plant native to MN and commonly found on disturbed soils, including roadsides [57]. While its phytoremediation capability has not been tested, it is closely related to *C. album*, which is capable of high salt extraction (around 40 g Na⁺ + Cl⁻ m⁻²) [64]. Furthermore, its leaves are high in protein and can be mechanically harvested for animal feed [48].

Weeping alkaligrass (*Puccinellia distans*) is a non-native perennial cool-season grass selected as a substitute for the native salt accumulator *Distichlis spicata* when seeds were unavailable [73,93]. It is a known halophyte and is favorable for stabilizing saline rangelands [87]. Studies measured Na⁺ and Cl⁻ accumulation in shoots under high-salt con-

ditions, and it is known to show no visual damage on highway roadsides with high salt application rates [87,100].

Tall fescue (*Lolium arundinaceum*) is a non-native, long-lived perennial cool-season grass widely used for forage and erosion control [38]. It is more salt-tolerant than many other turfgrasses [101,102]. Although not widely investigated for salt remediation, it has shown promise in extracting lead due to high biomass yield [103]. A study using 50 mM NaCl irrigation reported shoot Na^+ and Cl^- content of approximately 5.0 and 35 mg g^{-1} dry mass, respectively [81].

Common sunflower (*Helianthus annuus*) is an annual species native to Minnesota, often found in disturbed soils [38]. When grown on saline soil, it has been observed to contain an average of 2.96% Na^+ in the stem and 2.49% Cl^- in the leaves by dry mass, theoretically capable of removing 18 g of Na^+ plus Cl^- per meter squared [83,104]. It is also a major oilseed crop, and the meal byproduct has high nutritional value for animal feed, increasing its harvested biomass value [50,105].

Creeping red fescue (*Festuca rubra*) is a long-lived perennial cool-season grass with moderate salt tolerance [38]. While the species complex is not native and can become weedy, various varieties within the complex, such as the one tested (Strong creeping red fescue), have been used extensively on roadsides and for heavy metal remediation [106–108]. Based on a study of closely related fescue varieties, a balance of salt tolerance (resulting in higher biomass) and salt uptake was prioritized for selection [82].

Taken together, the decision matrix identified a subset of species that balance ecological safety, establishment potential, biomass production, and salt uptake capacity under roadside conditions. While most high-ranking species advanced successfully to experimental screening, prairie cordgrass (*Spartina pectinata*) did not establish reliably under greenhouse conditions and was therefore excluded from quantitative analyses. The remaining species represent a range of functional types, life histories, and predicted phytoremediation strategies, providing a robust basis for controlled evaluation of salt uptake and growth responses under saline conditions.

3.2. Plant Growth Responses to Salinity

Aboveground shoot and belowground root dry biomass varied by species and salinity treatment (Table 2). Across species, shoot biomass under the saline treatment was generally comparable to the control, apart from big bluestem, which showed lower shoot biomass under salinity.

Table 2. Aboveground (shoot) and belowground (root) oven-dry biomass of plant species grown under control and saline conditions.

Species	Shoots (Control) (g)	Shoots (Saline) (g)	Roots (Control) (g)	Roots (Saline) (g)
Common sunflower	1.53 ± 0.49 ^{ab}	1.28 ± 0.43 ^{bcde}	0.38 ± 0.14 ^f	0.23 ± 0.16 ^f
Pitseed goosefoot	1.39 ± 0.26 ^{abcd}	1.33 ± 0.28 ^{bcde}	0.51 ± 0.07 ^{ef}	0.49 ± 0.07 ^{ef}
Big bluestem	1.45 ± 0.56 ^{abcd}	1.03 ± 0.23 ^{cde}	1.05 ± 0.45 ^{bc}	0.53 ± 0.09 ^e
Buffalograss	0.97 ± 0.55 ^{cde}	0.89 ± 0.24 ^{ef}	0.55 ± 0.15 ^{ef}	0.46 ± 0.09 ^{ef}
Creeping red fescue	1.55 ± 0.37 ^{ab}	1.54 ± 0.51 ^{ab}	1.58 ± 0.27 ^a	1.05 ± 0.20 ^{bc}
Slender wheatgrass	1.25 ± 0.18 ^{abcd}	1.40 ± 0.42 ^{abcd}	1.11 ± 0.13 ^b	1.14 ± 0.21 ^{ab}
Switchgrass	1.06 ± 0.38 ^{bcde}	0.94 ± 0.23 ^{def}	0.67 ± 0.13 ^{def}	0.52 ± 0.15 ^e
Weeping alkaligrass	1.49 ± 0.35 ^{abc}	1.45 ± 0.44 ^{abc}	0.85 ± 0.06 ^{bcde}	0.65 ± 0.14 ^{de}
Western wheatgrass	1.01 ± 0.26 ^{bcde}	1.13 ± 0.24 ^{bcde}	0.93 ± 0.16 ^{bcd}	1.02 ± 0.34 ^{bc}
Tall fescue	1.72 ± 0.154 ^a	1.86 ± 0.25 ^a	1.54 ± 0.20 ^a	1.34 ± 0.16 ^a

Table 2. *Cont.*

Species	Shoots (Control) (g)	Shoots (Saline) (g)	Roots (Control) (g)	Roots (Saline) (g)
Alfalfa	0.86 ± 0.16 ^{de}	1.01 ± 0.18 ^{cdef}	1.00 ± 0.24 ^{bcd}	1.11 ± 0.26 ^{abc}
Canada goldenrod	0.64 ± 0.41 ^e	0.53 ± 0.21 ^f	0.71 ± 0.32 ^{cdef}	0.59 ± 0.23 ^{de}
Showy goldenrod	1.00 ± 0.30 ^{bcde}	1.03 ± 0.31 ^{cde}	1.07 ± 0.33 ^b	0.83 ± 0.19 ^{cd}

Notes: Species are grouped by plant category (annuals, perennial grasses, and perennial forbs) and listed in alphabetical order by common name within each group. Values are means ± standard deviations. Within each salt treatment and plant part, species sharing the same letter are not significantly different (Tukey's HSD test, $p < 0.05$).

Tall fescue turfgrass and strong creeping red fescue produced the greatest root biomass under both treatments, whereas common sunflower, buffalograss, and pitseed goosefoot consistently had the lowest root biomass. Root-to-shoot ratios (Table 3) were lower for the annual species common sunflower and pitseed goosefoot compared to perennial species, although values for many perennials remained below 1.0 under both treatments.

Table 3. Root-to-shoot biomass ratios of plant species under control and saline conditions.

Species	Root/Shoot (Control)	Root/Shoot (Saline)
Common sunflower	0.25	0.19
Pitseed goosefoot	0.38	0.38
Big bluestem	0.72	0.54
Buffalograss	0.69	0.56
Creeping red fescue	1.07	0.73
Slender wheatgrass	0.90	0.84
Switchgrass	0.72	0.60
Tall fescue	0.91	0.73
Weeping alkaligrass	0.61	0.50
Western wheatgrass	0.88	0.89
Alfalfa	1.18	1.11
Canada goldenrod	1.28	1.18
Showy goldenrod	1.09	0.90

3.3. Sodium and Chloride Concentrations in Aboveground Tissues

Shoot Na^+ and Cl^- concentrations increased significantly under salinity for nearly all species compared to the control (Table 4). In the control treatment, Na^+ concentrations were consistently low across species, while greater interspecies variation was observed for Cl^- , with tall fescue and pitseed goosefoot exhibiting higher shoot Cl^- concentrations than most other species.

Table 4. Na^+ and Cl^- concentrations (mg g^{-1} dry mass) in aboveground biomass of plant species grown under control and saline conditions.

Species	Na^+ (Control) (mg g^{-1} DM)	Na^+ (Saline) (mg g^{-1} DM)	Cl^- (Control) (mg g^{-1} DM)	Cl^- (Saline) (mg g^{-1} DM)
Common sunflower	2.49 ± 1.37 ^a	27.28 ± 4.23 ^a	13.14 ± 4.10 ^{bcde}	73.66 ± 21.57 ^a
Pitseed goosefoot	1.32 ± 1.07 ^{ab}	14.48 ± 3.66 ^{bc}	18.39 ± 6.23 ^{ab}	58.02 ± 5.64 ^{ab}
Big bluestem	0.93 ± 0.65 ^{ab}	4.43 ± 1.11 ^{de}	13.46 ± 2.15 ^{bcde}	31.92 ± 5.49 ^{cde}
Buffalograss	1.38 ± 1.03 ^{ab}	7.05 ± 4.87 ^{cde}	7.58 ± 2.58 ^e	20.74 ± 13.66 ^{def}

Table 4. *Cont.*

Species	Na ⁺ (Control) (mg g ⁻¹ DM)	Na ⁺ (Saline) (mg g ⁻¹ DM)	Cl ⁻ (Control) (mg g ⁻¹ DM)	Cl ⁻ (Saline) (mg g ⁻¹ DM)
Creeping red fescue	1.32 ± 2.35 ^{ab}	2.38 ± 1.26 ^e	10.97 ± 4.14 ^{cde}	14.95 ± 6.23 ^f
Slender wheatgrass	0.60 ± 0.24 ^b	3.40 ± 2.16 ^{de}	12.30 ± 7.23 ^{bcde}	18.53 ± 8.36 ^{ef}
Switchgrass	0.77 ± 0.27 ^b	5.80 ± 5.16 ^{de}	9.52 ± 3.26 ^{de}	22.68 ± 11.14 ^{def}
Tall fescue	2.14 ± 1.28 ^{ab}	6.45 ± 1.26 ^{de}	23.34 ± 1.94 ^a	33.28 ± 3.74 ^{cde}
Weeping alkaligrass	1.32 ± 0.68 ^{ab}	6.31 ± 3.19 ^{de}	16.62 ± 6.87 ^{bc}	26.66 ± 10.41 ^{def}
Western wheatgrass	0.57 ± 0.23 ^b	3.21 ± 0.72 ^{de}	15.23 ± 5.86 ^{bcd}	23.24 ± 8.49 ^{def}
Alfalfa	1.77 ± 0.59 ^{ab}	10.60 ± 3.77 ^{bcd}	11.11 ± 1.49 ^{cde}	24.90 ± 6.93 ^{def}
Canada goldenrod	1.78 ± 1.55 ^{ab}	14.88 ± 13.93 ^b	8.99 ± 1.75 ^{de}	35.25 ± 16.41 ^{cd}
Showy goldenrod	0.63 ± 0.31 ^b	8.47 ± 2.20 ^{bcde}	14.21 ± 3.22 ^{bcd}	44.85 ± 9.25 ^{bc}

Notes: Values are means ± standard deviations. Within each salt treatment and ion (Na⁺ or Cl⁻), species sharing the same letter are not significantly different (Tukey's HSD test, $p < 0.05$).

Under the saline treatment, common sunflower accumulated the highest concentrations of both Na⁺ and Cl⁻. Pitseed goosefoot and Canada goldenrod exhibited the next highest Na⁺ concentrations, while pitseed goosefoot and showy goldenrod showed relatively high Cl⁻ accumulation under salinity. Grasses generally accumulated lower shoot Na⁺ and Cl⁻ concentrations than non-grass species, although substantial variation existed within this group. Under salinity, tall fescue and big bluestem exhibited significantly higher shoot Cl⁻ concentrations than creeping red fescue, which accumulated the lowest concentrations among the grasses.

Across all species and treatments, Cl⁻ accumulation exceeded Na⁺ accumulation on a molar basis (Table 5). Cl⁻/Na⁺ ratios were consistently greater than 1.0, with particularly high ratios observed under control conditions. Under the saline treatment, ratios declined but remained above 1.0 for all species.

Table 5. Molar Cl⁻/Na⁺ ratios of aboveground biomass under control and saline conditions.

Species	Cl ⁻ /Na ⁺ (Control)	Cl ⁻ /Na ⁺ (Saline)
Common sunflower	3.79	1.73
Pitseed goosefoot	10.73	2.72
Big bluestem	14.76	4.85
Buffalograss	4.23	2.07
Creeping red fescue	11.21	4.49
Slender wheatgrass	12.78	3.98
Switchgrass	8.82	4.40
Tall fescue	8.98	3.41
Weeping alkaligrass	10.04	3.02
Western wheatgrass	18.84	4.81
Alfalfa	4.69	1.58
Canada goldenrod	7.33	2.82
Showy goldenrod	17.12	3.51

3.4. Total Na⁺ and Cl[−] Uptake

Figure 1 summarizes total aboveground Na⁺ and Cl[−] uptake for each species under control and saline conditions. Under the control treatment, total Na⁺ uptake was uniformly low across species, consistent with the low shoot Na⁺ concentrations observed in the biomass. Total Na⁺ uptake remained comparatively low for most species under salinity, with the primary exceptions being common sunflower and pitseed goosefoot.

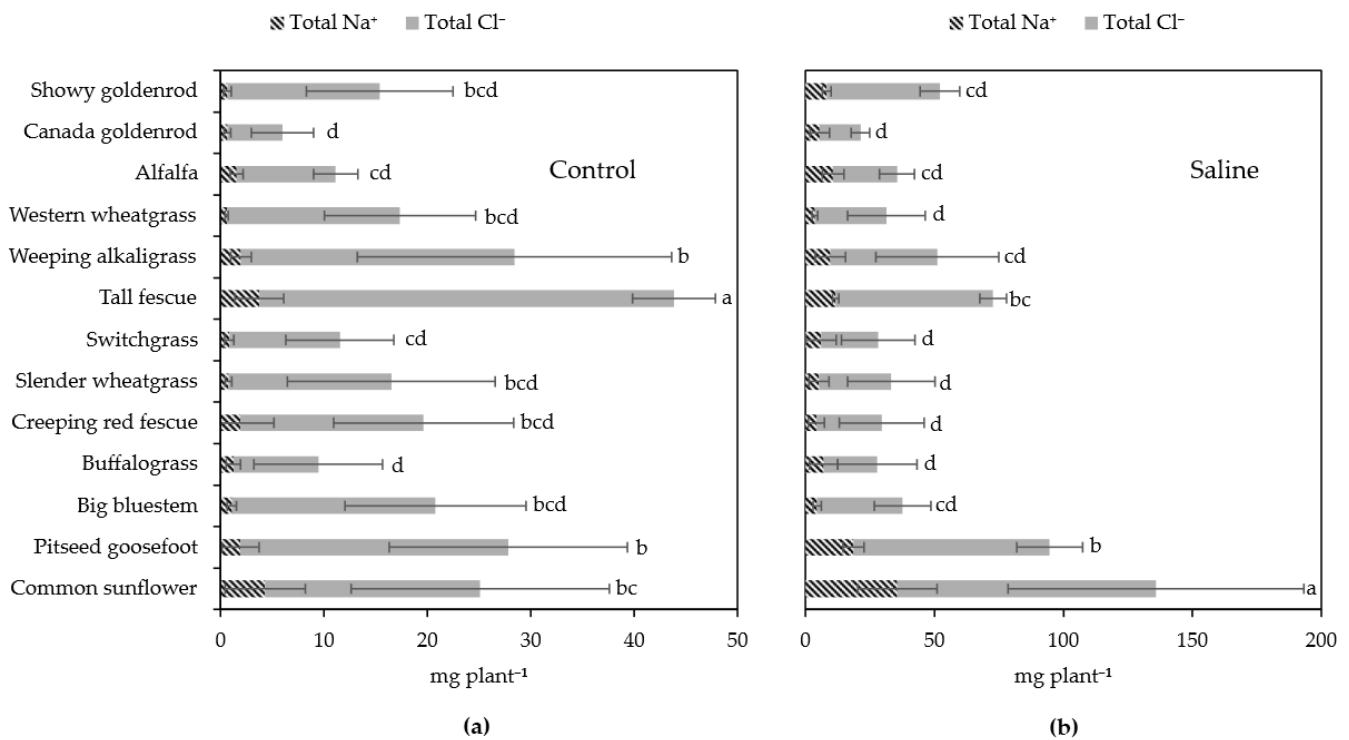


Figure 1. Total Na⁺ and Cl[−] uptake in aboveground biomass of plant species grown under control (a) and saline (b) conditions. Within each salt treatment, total salt uptake (Na⁺ plus Cl[−]) of species sharing the same letter is not significantly different. Error bars represent ± one standard deviation.

In the control treatment, tall fescue exhibited the greatest total salt uptake, followed by weeping alkaligrass, pitseed goosefoot, and common sunflower. Under the saline treatment, common sunflower and pitseed goosefoot showed the highest total uptake, reflecting their high shoot ion concentrations and considerable biomass production. Among perennial species, tall fescue maintained relatively high total uptake under salinity, followed by showy goldenrod and weeping alkaligrass.

4. Discussion

4.1. Growth Responses and Salt Tolerance Mechanisms

Under the saline treatment, only one species, big bluestem, exhibited a statistically significant reduction in shoot biomass relative to the control, whereas significant reductions in belowground biomass were observed in six species. The limited reduction in shoot biomass across most species suggests moderate salt tolerance and indicates that these species likely employ effective physiological strategies to mitigate salt stress, including ion exclusion, osmotic adjustment, and intracellular compartmentalization [12]. Because roots are directly exposed to elevated soil salinity, early growth inhibition may reflect osmotic stress and ion effects that constrain root elongation and biomass allocation even when shoot growth is maintained.

The annual species, common sunflower and pitseed goosefoot, exhibited lower root biomass and root/shoot ratios than perennial species, consistent with fast-growth strategies and shorter life cycles. Root/shoot ratios of annual crops are typically <0.3 , whereas perennial crops often exceed 1 [109]. Although perennial species in this study showed higher root/shoot ratios than annuals, most values remained below one, likely reflecting root growth constraints imposed by pot size.

4.2. Salt Accumulation Patterns in Aboveground Biomass

Species differed substantially in shoot Na^+ and Cl^- concentrations. Annual species, particularly common sunflower and pitseed goosefoot, accumulated high concentrations of both ions, whereas grasses generally accumulated less, consistent with reports that many salt-tolerant grasses limit salt translocation to shoots as a primary tolerance mechanism [110]. However, notable differences were observed among grass species. Tall fescue, weeping alkaligrass, and big bluestem exhibited relatively higher shoot Cl^- concentrations than other grasses, consistent with reported values for tall fescue ($\sim 35 \text{ mg Cl}^- \text{ g}^{-1}$) and Nuttall's alkaligrass ($\sim 32 \text{ mg Cl}^- \text{ g}^{-1}$), which rank among the highest Cl^- concentrations reported for grass species included in the decision matrix (Table S4) [74,81].

This study is the first to report shoot Na^+ and Cl^- concentrations for goldenrod species under saline conditions. Showy goldenrod accumulated comparatively high chloride (44.9 mg g^{-1}) and modest Na^+ (8.5 mg g^{-1}), placing it among the higher-performing perennial species evaluated. Alfalfa exhibited higher Na^+ concentrations (10.6 mg g^{-1}) and somewhat lower Cl^- concentrations (24.9 mg g^{-1}) than previously reported for moderately saline field soils ($\sim 1.5\text{--}2.3 \text{ mg Na}^+ \text{ g}^{-1}$ and $\sim 40\text{--}65 \text{ mg Cl}^- \text{ g}^{-1}$) [85].

Shoot Na^+ concentrations in common sunflower ($27.3 \text{ mg Na}^+ \text{ g}^{-1}$) observed in this screening were consistent with values reported in the literature, which commonly range from approximately $15\text{--}45 \text{ mg Na}^+ \text{ g}^{-1}$ [83,104,111]. Cl^- concentrations ($73.7 \text{ mg Cl}^- \text{ g}^{-1}$) were toward the upper end of reported values, which typically span $\sim 17\text{--}50 \text{ mg Cl}^- \text{ g}^{-1}$ [83,111,112]. Substantial variability in both Na^+ and Cl^- accumulation has been documented across studies, reflecting differences in salinity treatment, experimental design, plant tissue analyzed, growth duration, and cultivar. Notably, some studies report relatively low Na^+ accumulation even under saline conditions, indicating that Na^+ concentrations in sunflower shoots can vary widely [112,113]. Pitseed goosefoot accumulated lower shoot salt concentrations ($14.5 \text{ mg Na}^+ \text{ g}^{-1}$; $58 \text{ mg Cl}^- \text{ g}^{-1}$) than its close relative *Chenopodium album*, which has been reported to accumulate up to $33.6 \text{ mg Na}^+ \text{ g}^{-1}$ and $105 \text{ mg Cl}^- \text{ g}^{-1}$ under field conditions with moderate to high soil salinity [64]. Compared to species previously evaluated for roadside salt phytoremediation, shoot salt concentrations observed for common sunflower and pitseed goosefoot were similar to those reported by Mann et al. [34] for *Atriplex* species, which accumulated $41\text{--}64 \text{ mg Cl}^- \text{ g}^{-1}$ under highly saline conditions.

Across most species evaluated, Cl^- accumulation exceeded Na^+ accumulation on a molar basis, particularly under control conditions, consistent with reported patterns in many non-halophytic and moderately salt-tolerant species, which are generally more effective at excluding Na^+ than Cl^- [114]. Under saline treatment, Cl^-/Na^+ ratios declined but remained >1 for all species, suggesting increased Na^+ influx relative to Cl^- under higher salinity. Although several halophytic species, including *Suaeda calceoliformis*, *Salicornia europaea*, and *Spergularia marina*, exhibit high salt accumulation capacity, they received lower overall rankings in the decision matrix due to limitations in life cycle, establishment potential, or biomass value. This highlights the importance of integrating physiological performance with practical feasibility in roadside phytoremediation applications.

4.3. Total Salt Uptake and Implications for Phytoremediation

Phytoremediation potential depends not only on tissue salt concentrations but also on total aboveground biomass production, which together determine the overall amount of salt that can be removed from soil. In this screening, common sunflower and pitseed goosefoot exhibited the highest total Na^+ and Cl^- uptake among the species tested, reflecting their combination of high shoot biomass and elevated tissue ion concentrations. Despite this strong performance, removal of the total salt added in the saline treatment would require multiple harvest cycles, underscoring that phytoremediation of highly salt-contaminated soils is inherently a gradual process rather than a single-season solution.

Although annual species removed the greatest amount of salt in the greenhouse study, perennials are ultimately more practical for roadside applications because they persist year to year, remove salt early in spring when concentrations are highest, and lower reseeding and management needs [115]. Among the perennials tested, tall fescue, showy goldenrod, and weeping alkaligrass demonstrated the greatest salt uptake potential under greenhouse conditions.

Salt uptake results from the greenhouse experiment were largely consistent with predictions from the decision matrix (Table S4). Some discrepancies between predicted and observed performance are expected, as matrix values were derived from literature spanning a wide range of experimental conditions such as salinity levels, soil types, and management regimes. Nevertheless, the general consistency between matrix scores and greenhouse performance indicates that the decision matrix is an effective screening tool for narrowing a large inventory of salt-tolerant species into a manageable list of high-potential phytoremediation candidates, and that it can be further refined with experimental data.

From a practical standpoint, annual species such as common sunflower may provide high seasonal salt removal and offer opportunities for beneficial biomass use, including oilseed production or forage. However, perennial species likely remain better suited for long-term roadside management. For example, a perennial species like alfalfa, rated one of the highest in the matrix, may also be a promising species for both longer-term salt extraction and use as a nutritious animal feed once harvested.

Similarly, grass species such as western wheatgrass and slender wheatgrass may be particularly advantageous due to their reliable establishment and biomass production, even if their tissue salt concentrations are lower than those of annuals or halophytes. Although Canada goldenrod exhibited relatively low salt uptake in the greenhouse study, its high establishment and biomass yield score indicates that it may perform more effectively under field conditions. Taken together, these results suggest that multi-species plantings incorporating complementary functional traits may provide the most robust and resilient phytoremediation strategy for roadside environments.

This study integrated matrix-based rankings with controlled greenhouse measurements of sodium and chloride uptake, allowing predicted performance to be examined alongside physiological responses under standardized conditions. This combined approach demonstrates how a decision-matrix framework can be used not only to synthesize existing knowledge but also to inform experimental screening and refine candidate selection prior to field deployment. The framework provides a transparent and adaptable tool that can be adjusted for region-specific objectives and further validated through field-based studies.

4.4. Greenhouse Study Limitations and Future Research

The greenhouse study was designed as a controlled screening experiment and therefore has several limitations that should be considered when interpreting the results. Growth in small pots likely constrained root development and influenced root-to-shoot ratios and uptake dynamics, particularly for perennial species with extensive root systems. In

addition, greenhouse conditions do not capture the full range of environmental stresses characteristic of roadside settings, including drought, competition, temperature extremes, and physical disturbances characteristic of roadside activities.

Despite these limitations, the results provide a strong foundation for subsequent field-scale research. Future studies should evaluate multi-year performance of perennial species, test mixed-species plantings, assess establishment success on roadside soils, determine optimal harvest timing to maximize salt removal, and further explore the economic potential of harvested biomass. Overall, this study demonstrates that both annual and perennial species can contribute meaningfully to phytoremediation of salt-impacted roadside soils and presents a systematic, quantitative framework for selecting species that balance physiological performance with practical feasibility.

5. Conclusions

This research integrated a quantitative decision matrix with greenhouse experiments to identify promising species for phytoremediation of roadside soils impacted by deicing salt. The decision matrix successfully narrowed a large inventory of salt-tolerant species to those with strong feasibility for roadside establishment and expected phytoremediation performance. Greenhouse trials confirmed that annual species such as common sunflower and pitseed goosefoot achieved the greatest total salt uptake, while perennial species including tall fescue, showy goldenrod, and weeping alkaligrass demonstrated strong uptake combined with greater long-term practicality for roadside management. Together, these findings highlight that both annual and perennial species have roles in salt remediation systems, with perennials providing persistent early-season uptake and reduced management requirements, and annuals contributing high seasonal extraction. This study provides a framework for species selection and supports the development of field-scale phytoremediation strategies, including multi-species mixes that enhance establishment, resilience, and sustained salt removal under variable roadside conditions.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/su18041986/s1>, Table S1: Decision matrix criteria definitions, scoring ranges, and weights, Table S2: Ecological safety, biomass value, and life cycle scores, Table S3: Establishment and biomass yield scoring, Table S4: Shoot Na^+ and Cl^- concentrations and salt uptake scores.

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Abbreviations

Na	Sodium
Cl	Chloride
MN	Minnesota
Ca	Calcium
Mg	Magnesium
K	Potassium
ROS	Reactive oxygen species
ANOVA	analysis of variance
Zn	Zinc

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