



Growth and Phytostabilization Potential of Willow under Rare Earth Elements Exposure in Floating Treatment Wetlands

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Received: 19 August 2025 / Accepted: 3 November 2025 / Published online: 13 November 2025
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Abstract Phytoremediation of contaminated freshwater bodies with rare earth elements (REEs) is a promising nature-based solution, but it is rarely studied. Here, we studied how efficiently willow (*Salix schwerinii*: SS) and cultivar (Klara: KL) purify water and react to three combined doses of REEs. SS and KL were subjected to increasing combined doses of REEs, specifically lanthanum (La) and neodymium (Nd), for 8 weeks in floating treatment wetlands (FTWs). The treatments included: T0 (tap water without REEs), T1 (10 μM La + 10 μM Nd), T2 (20 μM La + 20 μM Nd), and T3 (40 μM La + 40 μM Nd). The study aimed to evaluate how La and Nd affect willow growth, including height, dry biomass, and tolerance index, as well as their uptake and translocation within the roots, stems and leaves. Results showed

that willow height increased over time, with significant biomass development and a noticeable allocation to stem biomass under REEs exposure. Height and biomass tolerance indices indicated that SS and KL exhibited high tolerance to REEs. The findings revealed the highest accumulation of La (25,252 $\mu\text{g plant}^{-1}$) and Nd (18,252 $\mu\text{g plant}^{-1}$) in the roots of SS in treatment T3. KL also showed the highest accumulation of La (16,153 $\mu\text{g plant}^{-1}$) and Nd (13,209 $\mu\text{g plant}^{-1}$) in roots, but in treatment T2. Moreover, SS and KL demonstrated increased translocation of La and Nd, particularly from the water solution to the roots, with minimal translocation to the leaves and stems. In SS, La and Nd removal efficiencies ranged from 56–95% and 40–74%, respectively. For KL, La removal varied from 22–90%, while Nd removal ranged from 21–68%. A considerable accumulation of nutrients such as P, K, Mg, and Ca in the willow tissues was also observed. Further research is needed

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s11270-025-08829-8>.

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to evaluate the long-term removal and recovery of REEs by willow and other perennial plants, with a primary focus on environmental factors and design of FTWs which may influence the uptake and translocation of REEs in plants.

Keywords Lanthanum · Neodymium · Wastewater · Phytoremediation · Biomass · Willow

1 Introduction

Worldwide, approximately 80% of wastewater is discharged into freshwater bodies without adequate treatment or management (Ortigara et al., 2018). Urban wastewater treatment plants, mining operations, industrial effluents, hospital waste, and leachates from solid waste disposal sites are the main contributors to aquatic pollution, releasing harmful contaminants through runoff or leaching processes (Mohsin et al., 2019). Rare earth elements (REEs) were discovered in 1794 by the Finnish scholar Johan Gadolin (Tao et al., 2022), are considered a critical component in modern-day technology (Ramprasad et al., 2022) and have been reported as a new form of environmental pollution (Mohsin, 2023). The presence of over 600 chemical compounds among 445 samples taken from different localities in European streams revealed that 504 substances including REEs were recorded at elevated concentrations of up to $74 \mu\text{g L}^{-1}$ (Finckh et al., 2024). The surface water in the vicinity of mining areas has been exposed to REEs up to $130\text{--}152 \mu\text{g L}^{-1}$ of water (Viana et al., 2023).

REEs are found in trace amounts in living organisms and are known to originate from chemical pollution globally (Gwenzi et al., 2018; Chen et al., 2021). These elements, typically exhibiting an iron-gray to silvery luster, possess diverse physical and chemical properties (Balaram, 2019; Erust et al., 2023). The increasing dependence on REEs in recent technologies, such as electronics, renewable energy systems, and medical devices, has led to their widespread release into aquatic environments through industrial effluents, mining activities, and improper disposal of electronic waste (Gwenzi et al., 2018; Ramzan, 2024). Although REEs are vital for the advancement of technology, their persistence and possible toxicity pose major environmental and health hazards even at low concentrations (Ben et al., 2021).

The European Union documented REEs as critical raw materials due to their supply risks (ACT CRM, 2024). These elements have a substitute index over 0.9, indicating significant challenges in substituting them (Amato et al., 2019). Globally, the Bayan Obo in China, Mountain Pass in the United States, Mount Weld in Australia, REEs deposits in Eastern Canada, and ion-adsorption deposits in several southern Chinese provinces have been documented as major REEs deposits (Wang et al., 2024a). In Northern Europe, particularly Sweden and Finland, the 70 Earth's crust holds various REEs evenly spread across 71 ancient alkaline bedrock (Mohsin et al., 2022), with total REEs concentrations generally ranging from 0.3 to 150 mg kg^{-1} (Sager & Wiche, 2024). Finland's greatest potential for REEs is associated with Devonian and Proterozoic carbonatites (such as Sokli and Korsnäs) as well as alkaline rocks (including Otanmäki, Lamujärvi, and Iivaara), alongside their finite zones and weathering products. Additionally, there is moderate potential found in kaolinitic saprolites (Tana Belt and Virtasalmi), hydrothermal ore deposits, rapakivi granites, granite pegmatite association and granites with high thorium content (Sarapää et al., 2013). Unlike conventional pollutants, REEs are not yet subject to stringent regulatory controls, and their long-term ecological and toxicological impacts remain poorly understood (Liu et al., 2021).

Lanthanum (La) and neodymium (Nd) are predominantly significant amongst REEs due to their extensive application in catalysts, magnets, and batteries, along with their growing presence in polluted water systems (Balaram, 2019). La is a soft, malleable, and silvery-white metal that fits into the light rare earth elements (LREEs) group, and it is the second most abundant rare earth element in the Earth's crust, topped only by cerium (Ce) (Aharchaou et al., 2020; Revel et al., 2025). It has an atomic number of 57 and is highly reactive, especially in the presence of water and oxygen, forming lanthanum oxide (La_2O_3) and lanthanum hydroxide ($\text{La}(\text{OH})_3$) (Jadhav et al., 2025). La has a high affinity for oxygen, making it a key component in catalysts, optical glasses, and water treatment processes (Zhi et al., 2020). The Earth's crust contains an average concentration of 30 mg kg^{-1} of La (Sharma et al., 2024). Studies have documented elevated La concentrations in dry soil, reaching up to 74 mg kg^{-1} in Cape Verde and

123 mg kg⁻¹ in Uganda (Ramos et al., 2016). On the other hand, Nd, a silvery metal with an atomic number of 60, is moderately hard and slightly malleable. It belongs to the group of LREEs (ACF Equity Research, 2023). Nd is renowned for its exceptional magnetic qualities and is crucial in manufacturing high-strength permanent magnets. These magnets are vital for wind turbines, electric vehicles, and many electronic gadgets (Heim & Vander Wal, 2023). The European Union (EU) leads the energy transition and is expected to encounter challenges in managing Nd waste from the outset (Alves Dias et al., 2020). All REEs, including Nd concentrations, in the Earth's crust have been detected within a range of 100–200 ppm (Perämäki et al., 2019). The Nd level in agricultural soils and groundwater has been detected around < 15,900–249,100 mg/kg and < 3.1 ~ 146.2 mg/L, respectively, at different worldwide sites. In addition, the concentration of Nd has been reported to be 0.76 ~ 15 ng/L in rainwater and 2.8 ng/L in seawater (Shi et al., 2021).

These elements are reported to enhance crop quality and yield based on the element type and its concentration (Dinh et al., 2022). According to Gjata et al. (2024), REEs have been shown to improve nutrient uptake, photosynthetic efficiency, and stress tolerance in plants while also enhancing the quality of crop yields. However, many of these studies are limited to specific growth stages or controlled laboratory conditions, raising questions about their broader applicability in real-world agricultural practices (Tao et al., 2022). Mohsin et al., (2022) demonstrated that exposure to La at 50 mg L⁻¹ significantly increased dry biomass weight, root length, and shoot diameter in willow plants (*Salix spp.*), highlighting their potential as growth stimulants. Similarly, Zhang et al. (2024) reported that REEs such as Ce, europium (Eu), La, and Nd positively influenced seed germination, root elongation, and biomass production in various plant species. Research findings suggest that La had positive effects on maize growth, exhibiting stimulatory effects at 25–50 µM (Duarte et al., 2018). However, it has also been noted that high concentrations of REEs could have inhibitory effects, particularly on secondary metabolite production in tissue-cultured plants. These findings underscore the dual role of REEs in plant physiology, where low doses may promote growth, while excessive amounts can lead to toxicity such as dysfunctional chloroplast

structure and inhibit the photosynthetic system in rice (Tao et al., 2022; Mupatsi et al., 2022; Jiang et al., 2023). The toxicity of La in plants is affected by soil characteristics, including pH, cation exchange capacity, organic matter content, and the biochemical composition of the rhizosphere. These factors can either support or disrupt the plant's physiological metabolism (von Tucher & Schmidhalter, 2005). Researchers have proven both positive and negative effects of different doses of lanthanides on plants, however, research on this issue is still limited (Kotelnikova et al., 2020). For instance, Song et al. (2021) observed that *Medicago sativa* seedlings exposed to 10–20 µM of La and Ce showed increased chlorophyll content and growth, while higher doses induced oxidative stress. Similarly, Yin et al. (2021) reported a hormetic response in citrus rootstocks, where La at 0.25–0.5 mmol L⁻¹ stimulated growth but concentrations > 1.0 mmol L⁻¹ caused toxicity and reduced root elongation. Jiao et al. (2024) noted physiological interference and stomatal irregularities in plants at La concentrations approaching 80 µM, confirming a threshold beyond which REEs become inhibitory. Kotelnikova et al. (2020) investigated La and Nd uptake at different soil concentrations (10–200 mg kg⁻¹). They observed that at low to moderate level (< 100 mg kg⁻¹), REEs had no toxic effects and even slightly stimulated biomass production, whereas the highest concentration (200 mg kg⁻¹) led to minor reductions in growth. Liu et al., (2021) observed that *Boehmeria nivea* L. (ramie) tolerated equimolar mixtures of 16 REEs up to 1.6–80 µmol L⁻¹ without growth suppression, but higher concentrations (> 160 µmol L⁻¹) significantly reduced biomass and nutrient uptake. Previously, we also observed that willow exhibited a significant increase in growth, biomass production and substantial accumulation of REEs in biomass without toxicity symptoms when exposed for four weeks to a six-REE mixture consisting of La, Y, Nd, Dy, Ce, and Tb (11.5, 11, 10.5, 10, 12 and 11.5 mg L⁻¹, respectively) and only a single-La dose (50 mg L⁻¹) under FTWs conditions (Mohsin et al., 2022).

Floating treatment wetlands (FTWs) or floating islands provide nature-based and cost-effective, and environmentally sustainable solutions for wastewater purification to reduce pollutant levels and do not require any sophisticated installations (Greger & Landberg, 2024). This plant-based technology is

being broadly applied in several countries to decontaminate wastewater in almost any wastewater treatment stage (Li et al., 2024; Zhang et al., 2024). FTWs utilize the phytoremediation process, in which plants grow with their aboveground parts exposed to the environment while their roots remain fully submerged in the water column and roots serve as a natural vegetation filter. This technology can improve pollutant reduction and significantly improve water quality (Nawrot et al., 2023).

Environmental sustainability has emerged as a paramount global concern in recent years, prompting increased attention to innovative and environmentally responsible approaches to combat environmental degradation. One such approach that has gained significant attention is phytoremediation which specifically employs trees and woody plants to remediate contaminated soil, water, and air (Budzyńska et al., 2024). Among various woody plant species, willows (*Salix* spp.) have revealed significant potential for phytoremediation due to their fast growth, high biomass production and adaptability to various environmental conditions (Yepu et al., 2025). Compared to traditional herbaceous macrophytes, trees offer long-term stability, greater pollutant interception, and resilience to urban stressors (Khan et al., 2025). Therefore, it is essential to develop methods for remediating REEs-contaminated sites and recovering these elements from secondary sources worldwide (Liu et al., 2019). Most FTWs systems are integrated with macrophytes and herbaceous plant species. Willow, a perennial plant, has been well studied for its role in terrestrial phytoremediation, particularly in soil-based systems; however, its application in FTWs remains at a nascent stage. To date, limited research has investigated willow as a potential candidate for the phytoremediation of REEs since its use has primarily focused on the removal of potentially toxic elements (Wang et al., 2024b). Nevertheless, the implications of this research are particularly pertinent to Finland and the Nordic countries, where freshwater sources are progressively exposed to industrial and mining operations (Räsänen et al., 2018). Furthermore, willow-based FTWs support urban forestry objectives by offering multifunctional green infrastructure that aids water purification and helps redevelop post-industrial or mining-impacted city areas.

This study explores the growth performance and phytoremediation potential of willow in REEs-enriched floating wetlands, assessing their ability to uptake and translocate REEs while maintaining efficient biomass production. Understanding the interaction between willow growth and REEs uptake in such an innovative system may offer new pathways for sustainable water remediation. In this context, this study aimed to examine the willow variety (*Salix schwerinii*, SS) and cultivar Klara, KL) in terms of a) growth height and biomass yield, b) phytoextraction efficiency to accumulate La and Nd in leaves, stems, and roots and their translocation efficiency in the shoot system as well as c) nutrient uptake in willow biomass for medium-terms conditions (8 weeks) under mutual doses of La and Nd. This short experiment offers critical baseline data that can guide in implementation of future long-term trials to validate the practical applicability of willow in the phytoremediation of REEs sites.

2 Materials and Methods

2.1 Experimental Setup

A willow variety (*Salix schwerinii*: SS) and cultivar (Klara: KL) were examined during May–June 2019 under REEs exposure containing La and Nd in a greenhouse at the School of Forest Sciences, University of Eastern Finland (UEF), Joensuu campus (63° 39′ N, 26° 2′ E). The control climate in the greenhouse was maintained at a day/night temperature of 24 °C/16 °C, a day/night period of 16/8 h, relative humidity of 60%, and a light intensity of 400 $\mu\text{mol m}^{-2} \text{s}^{-1}$.

2.2 Plant Materials and Treatments

A total of forty willow cuttings (Length: 20 cm and Diameter: 8 mm) of SS were collected from Siikasalmi and KL from the Eno UEF plantations. Five cuttings each of SS and KL were suspended simultaneously into four plastic tanks (Height: 18 cm; Diameter: 40 cm; Length: 70 cm) containing 3L of water.

The chloride salts of La and Nd were added in different treatments as follows: T0 [tap water without

La and Nd], T1 [10 µM La + 10 µM Nd], T2 [20 µM La + 20 µM Nd] and T3 [40 µM La + 40 µM Nd]. These concentrations were considered based on significant availability of REEs in phosphogypsum and mining sites in Finland (MISU, 2021), as well as the background levels of REEs observed in Finnish soil (Perämäki et al., 2019). The properties of tap water provided by O-Karjalan Ympäristötutkimus Oy Joensuu (Supplementary Material I). In addition, the 3L of half strength Hoagland solution was added to all treatments to maintain nutrient stability. The Hoagland solution was contained: 1.5 M KNO₃; 2 M Ca (NO₃)₂; 1 M NH₄H₂PO₄; 0.5 M MgSO₄·7H₂O; 1 M MES and the trace elements for example, 0.5 M H₃BO₃; 0.2 M MnSO₄; 0.2 M ZnSO₄; 0.01 M CuSO₄ and 0.01 M (NH₄)₈Mo₇O₂₄ and the pH was adjusted to 5.5 with 1 M NaOH/HCL (Hoagland & Arnon, 1950). The nutrient solutions were renewed every week to prevent metal and nutrient depletion and to expose plants to constant metal concentration.

2.3 Biometric Analysis and Determination of REEs in Willow Tissues

During the experiment, height and root length were measured weekly using a scale. After the experiment, the leaves, stems, and roots of the willows were separated, cleaned and dried in an oven at 105 °C for 24 h, after which the dry weight was quantified gravimetrically. The willow samples were ground and ashed in a muffle furnace at 500 °C. The dehydrated and ashed willow samples underwent acid (HNO₃, HF, and H₃BO₃) digestion in a microwave oven at 210 °C. The detailed descriptions of the digestion method have been previously reported (Lane et al., 2020). The determination of nutrient (P, K, Ca and Mg) and La and Nd in the willow biomass was analysed in a chemical laboratory at the University of Eastern Finland using Inductively Coupled Plasma Mass Spectrometry (ICP–MS, Perkin Elmer USA) by the standard operating procedures and EPA methodology 3051 (EPA, 1996). The detection limits were 0.0039 ppb for La and 0.0047 ppb for Nd. The accumulation of REEs in willow was calculated by multiplying the concentration by the dry biomass of the respective willow tissue (Farid et al., 2020).

2.4 Tolerance Index (Ti), Translocation Factor (Tf) and Bio-concentration Factor (BF)

The tolerance index for height and dry biomass was calculated using the following Eqs. (1–2) (Yang & Ye, 2015):

$$Ti_{Biomass} = \frac{\text{Mean dry biomass in the REEs treatment}}{\text{Mean dry biomass in the control treatment}} \quad (1)$$

$$Ti_{Height} = \frac{\text{Mean height growth in the REEs treatment}}{\text{Mean height growth in the control treatment}} \quad (2)$$

The proportion of the aerial and belowground willow tissue biomass was calculated (Eq. 3) (Lebrun et al., 2021):

$$\text{Willow tissue allocation (\%)} = \frac{\text{Tissue biomass}}{\text{Total biomass}} \times 100 \quad (3)$$

According to Sajjad et al. (2025), the translocation efficiency of willow was evaluated for example, the translocation factor (TF) as the ratio of REEs concentration from roots to stem/leaves and bioconcentration factor (BF) as the ratio of REE concentration from solution to roots was calculated (Eqs. 4–6):

$$TF = \frac{\text{REEs concentration in leaves } (\mu\text{g/g})}{\text{REEs concentration in the roots } (\mu\text{g/g})} \quad (4)$$

$$TF = \frac{\text{REEs concentration in stem } (\mu\text{g/g})}{\text{REEs concentration in the roots } (\mu\text{g/g})} \quad (5)$$

$$BF = \frac{\text{REEs concentration in roots } (\mu\text{g/g})}{\text{REEs concentration in the solution } (\mu\text{g/g})} \quad (6)$$

The dynamic factor of REEs translocations (TR_{dyn}) in willow was calculated to estimate the change of intensity of the translocation after the particular treatment (Eq. 7) (Baltrėnaitė et al., 2012):

$$TR_{dyn} = \frac{TR_{i, \text{treated}}}{TR_{i, \text{control}}} = \frac{C_{i, v, \text{treated}}}{C_{i, r, \text{treated}}} \times \frac{C_{i, v, \text{control}}}{C_{i, r, \text{control}}} \quad (7)$$

where TR_{i, treated} is the translocation factor of La and Nd i in willow in the treated solution; TR_{i, control} is the translocation factor of La and Nd i in willow under the control treatment; C_{i, v, treated} is the concentration of La and Nd i in willow (leaves and

stems) in the treated solution, in $\mu\text{g g}^{-1}\text{ DW}$; $C_{i, r}$, treated is the concentration of La and Nd i in willow roots under treated solution, in $\mu\text{g g}^{-1}\text{ DW}$; $C_{i, r}$, control is the concentration of La and Nd i in willow roots under the control treatment, in $\mu\text{g g}^{-1}\text{ DW}$; and $C_{i, v}$, control is the concentration of La and Nd i in willow (leaves and stems) under the control treatment, in $\mu\text{g g}^{-1}\text{ DW}$.

The removal efficiency of rare earth elements (REEs) by willow was determined based on using the ratio of the total REEs accumulated in willow tissues (leaves, stems, and roots) to the total REEs dose applied over the 8 weeks (Eq. 8) as followed by Salam et al., (2020):

$$\text{Removal Efficiency (\%)} = \frac{\text{Total REEs in Solution} - \text{Total REEs in Willow}}{\text{Total REEs in Solution}} \times 100 \quad (8)$$

2.5 Statistical Analysis

Before conducting the analysis, Shapiro–Wilk and Levene’s test were conducted to assess the normality of data and homogeneity of variances across willows and treatments. When needed, Box-Cox transformations (Box & Cox, 1964) were applied to satisfy the assumptions of parametric testing. A repeated measures analysis of variance (ANOVA) was performed to evaluate the effects of treatment on weekly willow height growth. A two-way analysis of variance (ANOVA) was conducted to compare differences in willow dry biomass, REEs concentrations and accumulations between willow and treatments, followed by Tukey’s HSD test at $p < 0.05$. All statistical analyses were carried out using SPSS v29.0.2.0 (IBM Corp., Armonk, NY, USA), and the results are reported as (Means $\pm$ SE). Although nutrient concentrations in leaves, stems and roots were quantified, but statistical analyses were not performed due to a lack of replication. These data are presented descriptively to elucidate potential trends and to guide future research.

3 Results

3.1 Assessment of Willow Height Growth under Lanthanum and Neodymium Exposure

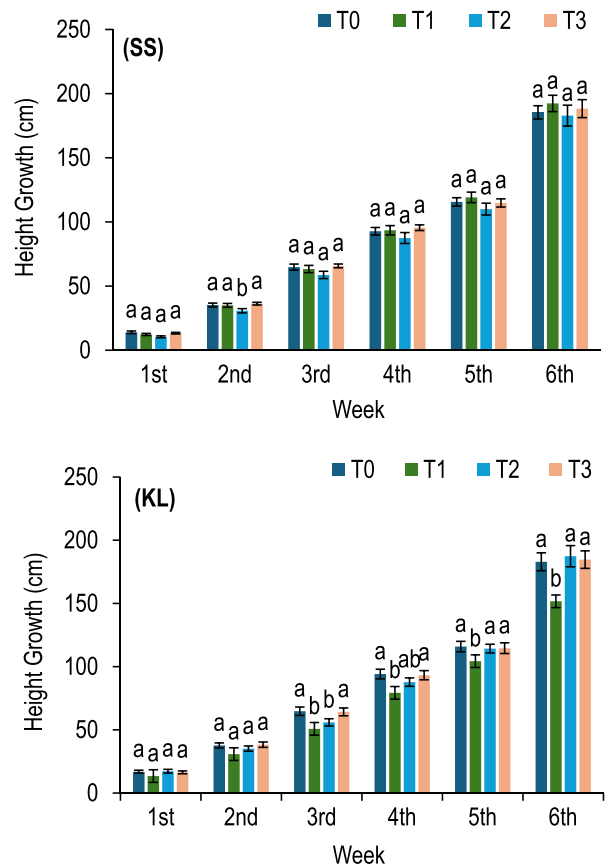
Salix schwerinii showed an exponential increase in weekly height growth in low-dose treatment T1 as

compared to the 1st week, for example, 2nd (191%), 3rd (425%), 4th (683%), 5th (891%) and 6th (1500%). In medium-dose treatment T2, the growth increase in different weeks was observed as 2nd (210%), 3rd (490%), 4th (770%), 5th (1000%) and 6th (1730%) compared to the 1st week. In the case of high-dose treatment T3, the weekly growth increased as 2nd (137%), 3rd (300%), 4th (500%), 5th (618%) and 6th (1075%) compared to the 1st week. However, the different treatments do not affect the height growth of SS. After every week, there was a consistent increase in stem height in each treatment except treatment T3 (Fig. 1 SS). There was no significant effect of treatments ($p = 0.568$) on SS height growth, but weekly

trend shows that growth was expressively improved among treatments. There was no significant effect of treatments ($p = 0.568$) on SS height growth, but the weekly trend shows that growth was significantly improved among the treatments.

The KL growth was tremendously increased from the 1st to the 6th week in all treatments. There was a noticeable increase in the 1st week growth in low-dose treatment T1 when compared with different weeks, for example, 2nd (138%), 3rd (292%), 4th (507%), 5th (700%) and 6th (1069%). For medium-dose treatment T2, the weekly growth increment in different weeks was observed as 2nd (105%), 3rd (229%), 4th (417%), 5th (570%) and 6th (1000%) when compared with week 1st. A similar increase in weekly growth was also noted in high-dose treatment T3 when compared with week 1st, for example, in the week 2nd (137%), 3rd (300%), 4th (481%), 5th (618%) and 6th (1056%). However, in the 6th week, the highest growth (192 cm) and (187 cm) was noticed for SS and KL, respectively in low dose treatment T1 and medium-dose treatment T2 (Fig. 1). Results demonstrated that both willows produced efficient height growth under REEs exposure without any significant decline compared to the control treatment T0. After every week, there was a consistent increase in stem height in each treatment except treatment T1 (Fig. 1 KL). There was a significant treatments effect ($p < 0.05$) observed on KL weekly height growth which indicates that growth was significantly increased over time.

Fig. 1 Weekly growth height of *Salix schwerinii* (SS) and Klara (KL) grown under control (T0) and La and Nd treatments (T1–T3). Similar small letters indicate non-significant differences between willows at $p > 0.005$ (Mean $\pm$ SE, $n = 3$)



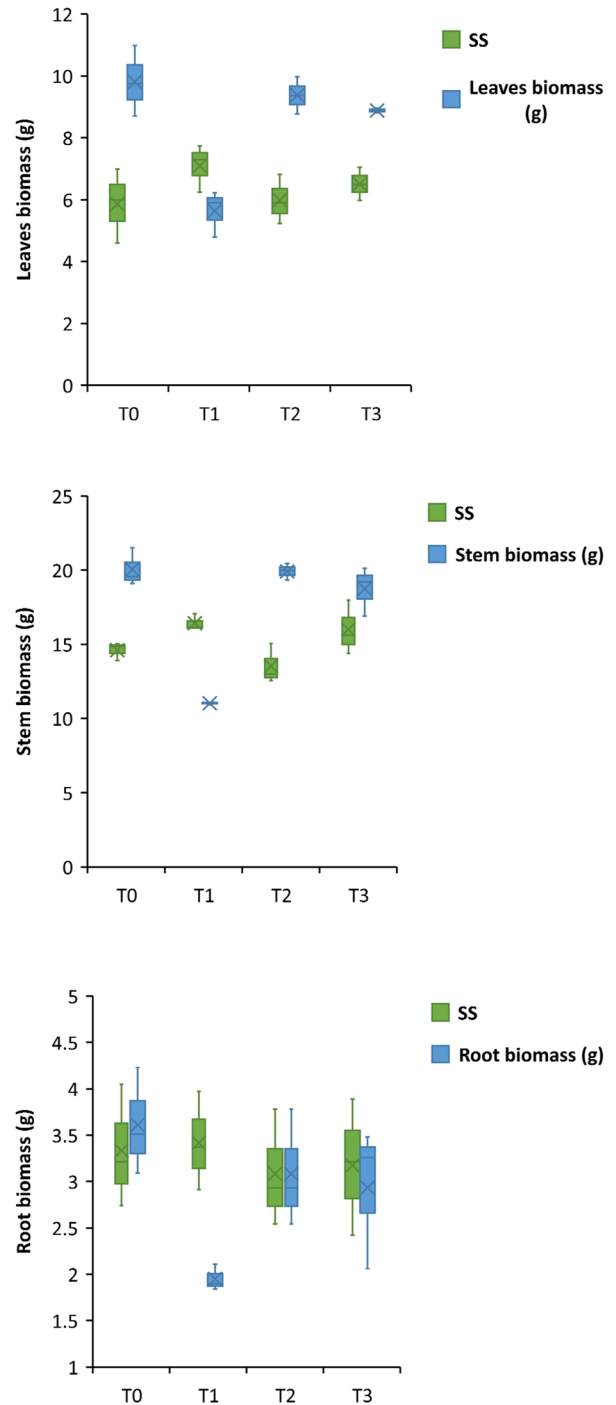
3.2 Assessment of Willow Dry Biomass, Biomass Allocation and Tolerance Index under Lanthanum and Neodymium Exposure

Results show that willows produced the highest stem dry biomass, followed by leaves and roots under control and REEs treatments (Fig. 2). There were a statistically significant effect of treatment ($p < 0.05$) and a significant interaction between treatment and willow (SS and KL) on the leaves dry biomass. Results show that KL produced relatively higher leave dry biomass than SS in different treatments, for example, T0 (67%), T2 (56%) and T3 (36%), excluding T1 where SS produced around 25% more biomass compared to KL. Similarly, KL produced the comparatively higher stem dry biomass in T0 (37%), T2 (47%), T3 (17%) and low biomass in T1 (32%) as compared with SS. There were a statistically significant effect of treatment ($p < 0.05$) and a significant interaction between treatment and willow (SS and KL) on the stem dry biomass. In contrast, there was no statistically

significant effect of treatment ($p = 0.216$) and a no significant interaction ($p = 0.106$) between treatment and willow (SS and KL) on the stem dry biomass. SS produced more root dry biomass in REEs treatment T1 (49%), T2 (4%) and T3 (8%), and a slight reduction was observed in T0 (7%) when compared with KL.

The biomass allocation estimation for SS and KL, where the highest allocation was observed for shoot biomass (leaves and stem) in the range 90–91% for SS and 92–94% for KL and the root biomass allocation was estimated around 9–10% for SS and 6–8% for KL (Supplementary materials II). This biomass allocation indicates that both willow species are predominantly invested in shoot biomass development rather than root growth. Additionally, the presence of REEs shown to favor increased allocation to shoots over roots, indicating that REEs exposure may stimulate aboveground growth more than belowground biomass production.

Fig. 2 Boxplot of Leaves, stemss and roots dry biomass of *Salix schw-erinii* (SS) and Klara (KL) produced under control (T0) and La and Nd treatments (T1–T3)



The height tolerance index (Ti) for species SS was 1 in all treatments, while cultivar KL displayed Ti between 0.84 and 1. In low-dose and medium-dose treatments (T1 and T2), both willows showed

a significant difference with SS performing better relative to treatment T1 and KL in treatment T2. In high-dose treatment (T3), no significant difference was observed between SS and KL. Regarding

Table 1 The tolerance index (Ti) for height and dry biomass was calculated in La and Nd treatments (T1–T3). Different small alphabetical letters indicate a significant difference between willows at $p < 0.05$ ($n = 5$)

Treatment	Willow	Ti (Height)	Ti (dry biomass)
T1	SS	1 ^a	1.14 ^a
	KL	0.84 ^b	0.55 ^b
T2	SS	0.93 ^a	0.95 ^a
	KL	1 ^b	0.96 ^a
T3	SS	1 ^a	1.08 ^a
	KL	1 ^a	0.91 ^b

the biomass tolerance index, the Ti values varied 0.95–1.14 and 0.5–0.96 and 0.55–0.96 for SS and KL, respectively. Both willows showed a non-significant difference in treatment T2 while a significant difference was observed in treatments T1 and T3 (Table 1).

3.3 Lanthanum and Neodymium Concentration in *Salix schwerinii* and *Klara*

3.3.1 La and Nd concentration in SS and KL leaves

In leaves, the concentration of La was in the range from 1.79–12.94 for SS and 0.78–11.58 $\mu\text{g/g}$ DW for KL, and the Nd concentrations in SS leaves varied between 1.39–11.47 $\mu\text{g/g}$ DW and 0.98–8.21 $\mu\text{g/g}$ DW were noticed for KL. Noticeably, La and Nd leaves concentration were higher in SS than KL in the medium dose (20 μM) treatment T2. When compared to the control T0, La concentration in SS leaves was significantly increased in the different treatments: T1 (432%), T2 (622%), and T3 (279%). The concentration of La in KL leaves also substantially increased in T1 (1384%), T2 (664%) and T3 (397%) treatments as compared to the control T0. La concentrations in leaves were significantly affected by treatments and their interaction with willows ($p < 0.05$; Table 3). Similarly, Nd concentration in SS leaves surged significantly in the various treatments: T1 (500%), T2 (725%), and T3 (369%). The concentration of Nd in KL leaves also increased in treatments T1

(737%), T2 (504%), and T3 (265%) compared to the control T0. The interaction between willows indicated a significant effect for La and Nd accumulation in leaves across all treatments, except for low dose (10 μM) T1, where both willows showed a non-significant trend for Nd concentration (Table 3). Concludingly, the results show that SS accumulated more La and Nd in the leaves than KL in treatment T2. Nd concentrations in leaves showed a significant difference among treatments ($p < 0.05$), while the interaction between willows and treatments was not significant ($p = 0.251$; Table 3), indicating that both willows responded similarly across treatments.

3.3.2 La and Nd Concentrations in SS and KL Stems

La concentration in stems varied between 0.15–3.15 for SS and 0.16–2.16 $\mu\text{g g}^{-1}$ DW for KL, and the Nd concentrations in SS and KL stems were 0.28–2.44 and 0.18–1.60 $\mu\text{g g}^{-1}$ DW, respectively. Importantly, La and Nd leaves concentrations were higher in SS than KL in the medium dose treatment T2 (20 μM). La concentration in SS stems was relatively increased in the different treatments as compared to the control treatment T0, for example, T1 (826%), T2 (2000%), and T3 (1046%). The concentration of La in KL stems was also increased in treatments T1 (681%), T2 (1156%), and T3 (1250%) compared to T0. Similarly, there was an increased notice for Nd concentration in SS stems in the various treatments: T1 (435%), T2 (771%), and T3 (457%). La concentrations in stems showed a significant difference among treatments ($p < 0.05$), while the interaction between willows and treatments was not significant ($p = 0.643$; Table 3), represents that both willows responded correspondingly across treatments. Nd stem concentrations in KL considerably increased in T1 (355%), T2 (772%), and T3 (788%) when compared with the control T0. Results demonstrated that SS and KL significantly accumulated La and Nd in stems solely in medium-dose (20 μM) treatment T2. Concludingly, the results show that SS accumulated more La and Nd in the stems than KL in treatment T2. Nd concentrations in stems were significantly affected by treatments ($p < 0.05$), while no significant interaction between treatments and willows was observed ($p = 0.263$; Table 3).

Table 2 Lanthanum (La) and Neodymium (Nd) concentrations [$\mu\text{g g}^{-1}$ DW] in *Salix schwerinii* (SS) and Klara (KL) leaves, stem and roots under control (T0) and La and Nd treatments (T1–T3) for 8 weeks in FTWs. Different small alphabetical letters indicate a significant difference between willows at $p < 0.05$ (Mean $\pm$ SE, $n = 5$)

Tissues	Treatment	Willow	La ($\mu\text{g g}^{-1}$ DW)	Nd ($\mu\text{g g}^{-1}$ DW)
Leaves	T0	SS	1.79 ± 0.14^a	1.39 ± 0.12^a
		KL	0.78 ± 0.13^b	0.98 ± 0.04^b
	T1	SS	9.54 ± 0.78^a	8.35 ± 1.19^a
		KL	11.58 ± 1.13^b	8.21 ± 0.22^a
	T2	SS	12.94 ± 1.06^a	11.47 ± 0.92^a
		KL	5.96 ± 0.83^b	5.92 ± 0.86^b
	T3	SS	6.79 ± 0.80^a	6.53 ± 1.21^a
		KL	3.88 ± 0.30^b	3.58 ± 0.48^b
Stem	T0	SS	0.15 ± 0.02^a	0.28 ± 0.07^a
		KL	0.16 ± 0.01^a	0.18 ± 0.03^a
	T1	SS	1.39 ± 0.20^a	1.05 ± 0.07^a
		KL	1.25 ± 0.39^a	0.82 ± 0.20^a
	T2	SS	3.15 ± 0.41^a	2.44 ± 0.27^a
		KL	2.01 ± 0.50^b	1.57 ± 0.35^b
	T3	SS	1.72 ± 0.12^a	1.56 ± 0.20^a
		KL	2.16 ± 0.49^a	1.60 ± 0.30^a
Roots	T0	SS	7.8 ± 0.96^a	11.08 ± 1.35^a
		KL	9.61 ± 1.12^a	8.61 ± 0.73^b
	T1	SS	3091 ± 163^a	2448 ± 77.80^a
		KL	5234 ± 80.29^b	3410 ± 41.92^b
	T2	SS	4207 ± 268^a	3335 ± 81.98^a
		KL	5470 ± 235^b	4493 ± 209^b
	T3	SS	8045 ± 292^a	5626 ± 580^a
		KL	3363 ± 50.47^b	3333 ± 111^b

*Bold digits represent the highest values

3.3.3 La and Nd Concentrations in SS and KL Roots

Salix schwerinii has exhibited La and Nd concentrations in roots in the range 7.8–8045 and 11.08–5626 $\mu\text{g g}^{-1}$ DW, respectively. Klara displayed La and Nd root concentrations respectively in the range 9.61–5470 and 8.61–4493 $\mu\text{g g}^{-1}$ DW (Table 2). La and Nd root concentrations were observed to be greatest in SS compared to KL in the high dose (40 μM) treatment T3. There was a remarkable increase in the La concentration in SS and KL roots across different treatments. Compared to the control T0, La concentration in SS increased by 396-fold in T1, 539-fold in T2 and 103-fold in T3. For KL, La concentration increased by 545-fold in T1, 569-fold in T2 and 350-fold in T3. La concentrations in roots showed a significant difference among treatments, as well as a significant interaction between treatments and willow ($p < 0.05$; Table 3). Correspondingly, Nd concentration was also massively increased in SS and KL roots across all treatments. When compared with the control T0, Nd concentration in SS increased by 220-fold in T1, 301-fold in T2 and 508-fold in T3. A similar increasing pattern of Nd concentration in roots was noticed for KL across different treatments compared to the control T0, for example, 396-fold (T1), 522-fold (T2), 387-fold (T3). Concludingly, the results show that SS accumulated more La and Nd in the roots than KL in treatment T3. Results show that Nd concentrations in roots were significantly affected by treatments ($p < 0.05$), while no significant interaction between treatments and willows was observed ($p = 0.117$; Table 3).

Table 3 Translocation factor (TF), bioconcentration factor (BF) and dynamic factor of translocation (TR_{dyn}) by *Salix schwerinii* (SS) and Klara (KL) under lanthanum (La) and neodymium (Nd) treatments for 8 weeks

	Treatment	Leaves (TF)	Stems (TF)	Roots (BF)	TR_{dyn}
SS (La)	T1	0	0	2.23	0.0134
	T2	0	0	1.51	0.0133
	T3	0	0	1.45	0.0037
	T1	0	0	3.70	0.00018
	T2	0	0	1.97	0.00009
	T3	0	0	0.61	0.00009
	T1	0	0	1.7	0.0273
	T2	0	0	1.16	0.0273
	T3	0	0	0.98	0.0093
KL (La)	T1	0	0	2.37	0.00027
	T2	0	0	1.56	0.00015
	T3	0	0	0.58	0.00012

*Bold digits represent the highest values

3.4 Lanthanum and Neodymium Translocations in *Salix Schwerinii* and Klara

Results demonstrated that a low translocation of La and Nd to willow leaves and stems were noted, as the TF values of SS and KL were less than 1. In contrast, translocations of La and Nd from rhizosphere water to willow roots were observed. The BF values of La in SS and KL varied from 1.45 to 2.23 and 0.61 to 3.70, respectively. For Nd, BF values in willow ranged between 0.98 to 1.70 for SS, and 0.58 to 2.37 for KL. In addition, the greatest TR_{dyn} of La and Nd exhibited by SS in treatment T1 which demonstrates its active role in REEs uptake compared to KL (Table 3).

3.5 Phosphorus, Potassium, Calcium and Magnesium Concentration in *Salix Schwerinii* and Klara Biomass

Although the primary focus of this study was the uptake and translocation of REEs in willow tissues, we also performed a preliminary assessment of macromicronutrient (P, K, Ca and Mg) concentrations in leaves, stems, and roots from each treatment (Fig. 3).

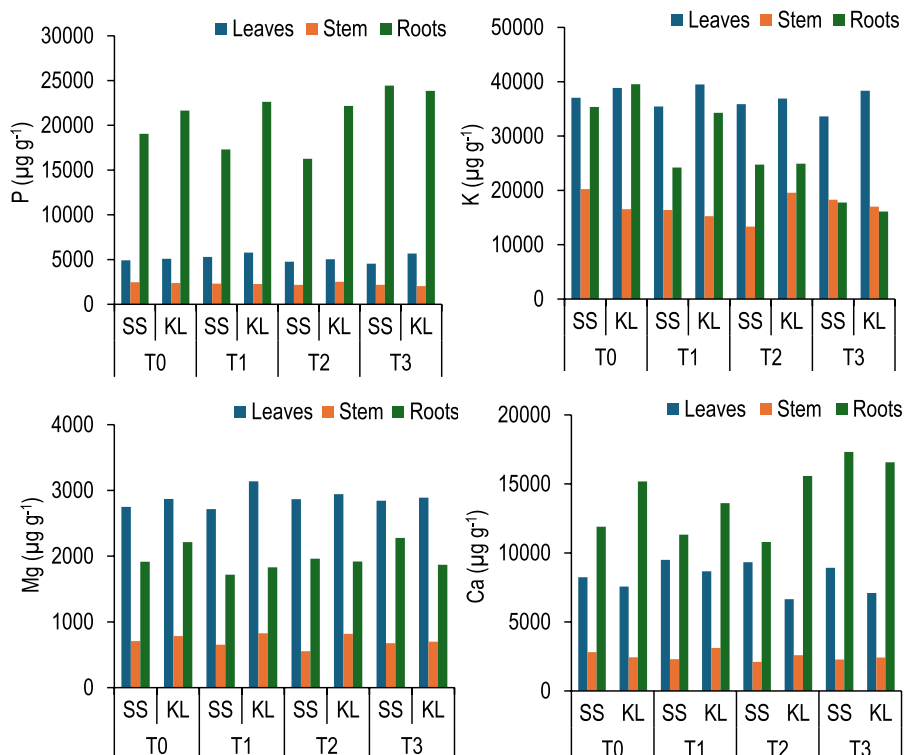
The results show a significant P uptake in SS with the highest concentrations in the roots followed by stems and leaves in all treatments. In KL, the highest P was found in the roots, followed by stems and leaves in all treatments, excluding low-dose (10 μM) treatment T1. The uptake of P was not significantly altered by REEs exposure, suggesting that willow could maintain nutrient balance while remediating REEs. However, due to the absence of replicates, the data is presented descriptively without statistical inference. The observed differences between treatments for nutrient concentration in leaves, stem and roots may suggest potential trends but require further replicated trials for confirmation.

4 Discussion

4.1 Impact of Lanthanum and Neodymium on Willows Growth Parameters

No visual signs of stress, such as chlorosis or necrosis, were observed in willow under REE exposure during the growth period. We observed an increasing trend in weekly growth and efficient dry biomass

Fig. 3 Nutrient concentrations in leaves, stems, and roots of willow grown under different REEs treatments. Values represent single composite samples for each treatment. Data is presented for exploratory purposes only



weight produced by SS and KL under control and REE-treated water. These findings support the statement of Velasco-Arroyo et al. (2024) that plants used for phytoremediation purposes grow rapidly, produce high biomass, and possess an extensive root system. The selection of plant species for phytoremediation must consider the capability of the plant to withstand or biodegrade elevated concentrations of pollutants, accumulate elements of significance, exhibit rapid growth, produce substantial quantities of biomass, and maintain resistance to diseases, pests, and challenging environmental conditions (Mocek-Plóćiniak et al., 2023). Plant biomass is one of the factors determining the suitability of a given plant species for phytoremediation (Gmur et al., 2025). It has been found that the usage of REEs in agricultural crops greatly increased their productivity by 5–15% in rice and 12–24% in maize. (de Oliveira et al., 2024). However, using REEs in high concentrations has a retarding effect on the growth of plants (Agathokleus et al., 2019). It has been demonstrated that adding fertilizer in a dose of less than 10 kg/ha containing REEs increased the yield of the tested plant (Tommasi et al., 2023). In the study, willow has shown a productive response in terms of growth height and dry biomass under REEs exposure compared to the control. However, a consistent increase in willow height was observed across all treatments weekly, except for treatment T3 in SS and T1 in KL, where growth was reduced. This reduction may be attributed to factors such as limited nutrient received by willow, pH fluctuations, or temperature variations during the experiment. Regarding plant biomass allocation (supplementary materials II), both willows were able to produce more shoot biomass under REEs exposure which support the statement of Poorter and Nagel (2000), who reported that plants occasionally distribute more biomass to shoots under favorable conditions to improve photosynthetic efficiency. The higher shoot allocation in KL compared to SS might be due to species and cultivar-specific strategies or environmental factors.

4.2 Lanthanum and Neodymium Accumulation Assessment by *Salix schwerinii* and *Klara*

The findings demonstrate that both willows SS (La: 25,252 $\mu\text{g plant}^{-1}$; Nd: 18,453 $\mu\text{g plant}^{-1}$) and KL (La: 16,153 $\mu\text{g plant}^{-1}$ & Nd: 13,209 $\mu\text{g plant}^{-1}$) can accumulate a significant amount of La and Nd in the roots

rather than the stem and leaves. Overall, SS has shown more accumulation than KL in terms of La and Nd accumulation in leaves, stem, and roots under low- to high-dose treatments. There was a significant effect of treatments ($p < 0.05$) observed for La and Nd accumulation in SS and KL leaves, stem and roots. However, a significant interaction between treatment and willows was observed ($p < 0.05$) solely for La accumulation in roots, while all other interactions showed a non-significant effect ($p > 0.05$) (Table 4). In addition, the removal of REEs by willows varied across treatments. In SS, La and Nd removal efficiencies ranged from 56–95% and 40–74%, respectively. For the KL, La removal ranged from 22–90%, while Nd removal ranged from 21–68%. Removal efficiency of both willows decreased by increasing REEs doses might be due to toxicity stress that limited REEs (Table 4).

Gmur et al. (2025) documented the significant REEs deposits in roots of different plant species, which is in line with our findings. The uptake of metals by roots is influenced by plant species and numerous environmental parameters such as temperature, type of chemicals, pH, redox potential and nutrient availability (Okoroafor et al., 2022). It has been demonstrated that plant roots possess the capacity to accumulate REEs due to their resemblance in ionic radii to calcium. In this context, REEs are capable of substituting calcium molecules in numerous physiological processes that are primarily responsible for plant growth and development (Carpenter et al., (2015).

Phytolacca americana has been observed to efficiently translocate heavy rare earth elements (HREEs) to its shoots under both hydroponic conditions and in natural REE-mining areas (Yuan et al., 2018). In non-accumulating species, various angiosperms such as *Triticum aestivum*, *Glycine max*, and *Oryza sativa* have been reported to have a higher root-to-shoot transfer of HREEs compared to LREEs (Liang, 2006). This fractionation mechanism may be due to the production of specific compounds with distinct REE-chelating properties or REEs peptides. For example, The REE-accumulating fern, *Dicranopteris dichotoma*, produces a specific LREE-binding peptides that may be involved in the detoxification and homeostasis of LREEs, suggesting that the LREE-binding peptide is less toxic to cellular plant metabolism than free metal ions. However, it is plausible that the fractionation of REEs may have significant variability even among varieties of the same species, or

Table 4 Lanthanum (La) and Neodymium (Nd) accumulations [$\mu\text{g plant}^{-1}$] in *Salix schwerinii* (SS) and Klara (KL) leaves, stem and roots, and removal (%) efficiency under control (T0) and La and Nd treatments (T1–T3) for 8 weeks. Different small alphabetical letters indicate a significant difference between willows at $p < 0.05$ (Mean $\pm$ SE, $n = 5$)

Tissues	Treatment	Willow	La [$\mu\text{g plant}^{-1}$]	Nd [$\mu\text{g plant}^{-1}$]	Removal La (%)	Removal Nd (%)
Leaves	T0	SS	10.68 $\pm$ 1.65 ^a	7.97 $\pm$ 0.45 ^a		
		KL	7.56 $\pm$ 1.29 ^b	9.57 $\pm$ 0.63 ^b		
	T1	SS	67.18 $\pm$ 5.09 ^a	59.66 $\pm$ 9.37 ^a		
		KL	64.92 $\pm$ 6.98 ^a	46.44 $\pm$ 3.78 ^b		
	T2	SS	76.68 $\pm$ 5.49 ^a	68.86 $\pm$ 7.48 ^a		
		KL	55.17 $\pm$ 6.26 ^b	55.18 $\pm$ 7.79 ^a		
	T3	SS	43.57 $\pm$ 3.78 ^a	41.59 $\pm$ 6.33 ^a		
		KL	34.41 $\pm$ 2.67 ^b	31.81 $\pm$ 4.33 ^a		
Stem	T0	SS	2.19 $\pm$ 0.34 ^a	4.03 $\pm$ 1.01 ^a		
		KL	3.13 $\pm$ 0.41 ^a	3.84 $\pm$ 0.65 ^a		
	T1	SW	22.89 $\pm$ 3.29 ^a	17.24 $\pm$ 1.26 ^a		
		KL	13.78 $\pm$ 4.29 ^b	9.15 $\pm$ 2.25 ^b		
	T2	SS	41.94 $\pm$ 4.14 ^a	32.78 $\pm$ 3.10 ^a		
		KL	40.34 $\pm$ 10.13 ^a	31.38 $\pm$ 7.17 ^a		
	T3	SS	27.32 $\pm$ 1.43 ^a	25.18 $\pm$ 3.50 ^a		
		KL	41.67 $\pm$ 10.58 ^b	30.68 $\pm$ 6.75 ^a		
Roots	T0	SS	24.94 $\pm$ 1.30 ^a	37.44 $\pm$ 6.17 ^a		
		KL	34.34 $\pm$ 3.17 ^b	30.61 $\pm$ 1.65 ^a		
	T1	SS	10,458 $\pm$ 390 ^a	8423 $\pm$ 885 ^a		
		KL	9942 $\pm$ 1210 ^a	7781 $\pm$ 773 ^a		
	T2	SS	12,733 $\pm$ 392 ^a	10,391 $\pm$ 1213 ^a		
		KL	16,153 $\pm$ 1207 ^b	13,209 $\pm$ 685 ^b		
	T3	SS	25,252 $\pm$ 1970 ^a	18,453 $\pm$ 3727 ^a		
		KL	9866 $\pm$ 1217 ^b	9759 $\pm$ 1199 ^b		
Total	T1	SS	10,548	8499	95	74
		KL	10,020	7836	90	68
	T2	SS	12,851	10,492	58	45
		KL	16,248	13,295	73	57
	T3	SS	25,322	18,519	56	40
		KL	9942	9821	22	21

*Bold digits represent the highest values

crop cultivars, although this aspect has not yet been addressed by dedicated fundamental research (Martina et al., 2025).

4.3 Lanthanum and Neodymium Translocations in Willow Biomass

The translocation factor (TF) and bioconcentration factor (BF) exhibit metal(loid) distribution between shoots and roots and rhizosphere to roots, in turn, the potential use of a plant for phytoextraction (TF > 1) or phytostabilization (BF < 1) strategies (Sharma et al., 2022). The transport of REEs from roots to shoots in plants is influenced by the efficiency of transport

systems and the mobility of REEs within the plant. This process is regulated by cell wall absorption, phosphate deposition, and intracellular complexation with carboxylates (Wiche & Pourret, 2023). Plants with a combination of $\text{BCF} < 1$ and $\text{TF} < 1$, $\text{BCF} < 1$ and $\text{TF} > 1$, $\text{BCF} > 1$, and $\text{TF} < 1$ show phytostabilisation potential and are excluders because they possess mechanisms that maintain low uptake of soil-metal contents and small shoot-metal contents. In contrast, plants with $\text{BCF} > 1$ and $\text{TF} > 1$ are good accumulators and are suitable for phytoextraction (Gajić et al., 2020). In the study, $\text{BCF} > 1$ represents the potential of willow for phytoremediation of REE-contaminated water. In this study, the results of the lowest

translocation of REEs to aerial parts are in agreement with Yuan (2017) for *Phytolacca americana* and, Grosjean et al. (2019) for *Phytolacca clavigera* and *Phytolacca icosandra* who observed $TF < 1$ in a hydroponic study.

Willows can be considered “underground accumulators,” which supports earlier findings (Milić et al., 2021; Nawaz et al., 2020). Velasco-Arroyo et al. (2024) stated that the increased accumulation of REEs in roots may be due to the large intercellular air spaces characterizing their cortex parenchyma. Researchers reported that the Casparian strip blocks REEs uptake in the roots and limits their translocation to the plant shoot, confirming the efficient filtering capacity of the endodermis (Martina et al., 2025). REEs deposits were observed exclusively in the cell walls and on the outer surface of the plasma membrane of epidermal, cortical, and endodermal cells, extending up to the Casparian strip. However, they were completely absent from the stele (Barberon, 2017; Martina et al., 2025). However, REEs are predominantly deposited in the roots, however, they can also be translocated to the shoots efficiently, reliant on the plant types and environmental conditions (Huang et al., 2023). In this context, the results suggest that willow species are suitable for phytostabilisation strategies. Future research direction should focus on the recovery of REEs from plant biomass ashes rather than from traditional ores, as extraction of REEs from ores are more challenging to solubilize and process (Viana et al., 2023).

We assume that the low translocation of REEs to willow aerial parts and their high retention in roots indicates their suitability for urban development, such as in urban and industrial wastewater streams, particularly for phytoremediation applications. Willow’s potential to stabilise REEs within its root system reduces the risk of these elements entering the food chain, making it a safe option for urban forestry initiatives. Willow can serve as an effective buffer plant in industrial zones, mining areas, rain gardens, and wastewater treatment systems, helping to lower REE concentrations in urban environments. When used in FTWs, willow provides efficient metal phytostabilisation with the added benefit of easier biomass harvesting compared to soil-based applications. The use of FTWs for REEs remediation with willow has not yet been widely studied. Our findings provide pioneering evidence of willow’s suitability for REEs uptake

under FTWs conditions. Our findings align with previous reports that REEs predominantly accumulate in roots due to their strong affinity for binding with root cell wall components and organic acids in the rhizosphere (Mohsin et al., 2022). The limited mobility of La and Nd within the plant shoots indicates an intrinsic barrier to xylem which possibly serves as a protective strategy to reduce toxicity to photosynthetic tissues (He et al., 2024). However, the contrastive patterns of nutrient distribution and strong retention of REEs underscore a complex physiological response that involves modulation of membrane transport, potential detoxification strategies and chemical complexation. These findings provide insight into how plants regulate nutrient balance when exposed to REEs and advocate possibilities for phytoremediation or safe crop cultivation on REE-enriched wastewater.

4.4 Nutrient Concentrations in Willow

The concentration of P in willow tissues remained consistent across various rare REEs treatments, indicating that REEs did not interfere with the willow capacity to absorb essential nutrients. This finding highlights the potential of willow for phytostabilisation in REEs-contaminated environments, where maintaining nutrient uptake is critical for sustainable growth and remediation effectiveness. In the study, the increased P and Ca accumulation in roots at higher REEs treatment (40 μM La + 40 μM Nd) could suggest a nutrient compensation mechanism. These studies indicate that P and Ca availability and root exudation processes can affect REEs uptake and distribution in plants (Wiche & Pourret, 2023). Moreover, the co-localization of greater P and Ca contents with REEs accumulation in roots signifies a chemical interaction, possibly due to the formation of insoluble LaPO_4 , NdPO_4 , and $\text{Ca}_3(\text{PO}_4)_2$ precipitates. These formations limit the bioavailability and translocation of these nutrients to plant aerial parts (Liu et al., 2013). Additionally, ammonium from $\text{NH}_4\text{H}_2\text{PO}_4$ may acidify the rhizosphere which influences P solubility and REEs binding (Shen et al., 2011). These processes could justify significant uptake of P and Ca in roots under REEs treatments.

Furthermore, the high concentrations of Mg and K in willow leaves demonstrate that their transportation systems have remained undisturbed under REEs exposure. Mg plays a crucial role in chlorophyll

synthesis, while K is essential for stomatal regulation and enzyme activation. These elements exhibit remarkable mobility within plant tissues and are likely prioritised during stress (Marschner, 2012). The absence of significant accumulation interactions between REEs and both Mg and K further supports the mechanism of selective ion homeostasis, where essential macronutrients are preserved through tightly regulated transport mechanisms. This selective uptake may be attributed to variations in ionic radius and charge between REEs and essential nutrients, thereby mitigating competition at specific membrane transporters (Wiche et al., 2017). Additionally, contemporary studies indicate that plants can regulate specific transporters or employ compartmentalisation strategies to prevent nutrient displacement during metal stress (Bhat et al., 2025).

5 Conclusions

This study demonstrates that willows are highly versatile for use in FTWs. Their ability to produce significant biomass, regenerate through coppicing, and be easily harvested makes them ideal bioenergy crops. Additionally, their phytostabilisation potential in aquatic environments increases their usefulness for long-term pollutant immobilization. These combined traits position willow as a promising and effective option for sustainable FTWs applications, particularly in regions focused on both remediation and bioenergy generation. This study concludes that both willows have not been exposed to stress, for example, chlorosis, leaf fall and necrosis under REEs doses. Willows showed an exponential increased in weekly height growth in all REEs treatments (T1-T3) including control treatment (T0) whereas a slight reduction was noted for SS in the medium dose REEs treatment (20 μ M La+20 μ M Nd) and KL in low dose REEs treatment (10 μ M La+10 μ M Nd) across all treatments. Willows showed the greatest La and Nd accumulation in roots, followed by leaves and stems. The translocation factor of willow was observed to be below 1, while bioconcentration factors exceeding 1 indicate significant phytostabilization potential. Willows tend to accumulate P and Ca primarily in their roots, while K and Mg are concentrated in their leaves which indicates their potential behaviour in nutrient uptake and may play a key role in FTWs systems.

These results support that willow is a promising candidate for wastewater purification, particularly for the remediation of REEs and regulation of nutrient balance. Further research is required to investigate the complex interaction between REEs and plant physiological mechanisms as well as identification of genes that potentially regulate or participate in REEs uptake and tolerance within plant cells. Additionally, potential recovery of REEs from contaminated biomass should be explored to reduce environmental risk and facilitate resource reuse.

Author Contributions **Muhammad Mohsin:** Writing – original draft, Formal analysis, Investigation, Data curation. **Muhammad Ramzan:** Writing – original draft, Formal analysis. **Edita Baltrėnaitė-Gedienė:** Formal analysis, Writing – review & editing. **Nicole Nawrot:** Writing – review & editing. **Erik Kaipainen:** Investigation, Data curation. **Fahad Rasheed:** Writing – review & editing. **Zikria Zafar:** Writing – review & editing. **Ewa Wojciechowska:** Writing – review & editing. **Ari Pappinen:** Conceptualization, Supervision, Project administration, Methodology. **Suvi Kuittinen:** Writing – review & editing, Supervision.

Funding Open access funding provided by University of Eastern Finland (including Kuopio University Hospital). The study has been funded by the Karelia CBC program, the European Union, the Russian Federation, and the Republic of Finland. The project is entitled “Reaching Congenial Region through the Valorization of Municipal and Industrial Wastewaters and Sludge” (Project No: KA4020). The authors would like to thank Maa ja vesiteknikan tuki ry (MVTT) Finland for supporting this research.

Data Availability The data will be made available on reasonable request.

Declarations

Ethics Approval and Consent to Participate Not applicable

Consent for Publication All authors have agreed to publish this data.

Competing interests The authors declare that they have no conflict of interest.

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