

The effects of light intensity and nitrogen level on the growth and cadmium accumulation of *Rorippa sylvestris*

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Research Article

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Abstract

Aims

Phytoremediation is an environmentally friendly strategy to effectively manage cadmium (Cd^{2+})-contaminated soils. Light intensity and nitrogen level influence the growth and Cd^{2+} accumulation. This study aims to screen reasonable conditions of light intensity and nitrogen level to improve the remediation efficiency of plants on Cd-contaminated soil.

Methods

In pot experiment, *R. sylvestris* sprouting seedlings were treated with varying amounts of light (50%, 70%, and 100% relative light intensity) and nitrogen fertilizers (0, 100, and 200 $\text{mg}\cdot\text{kg}^{-1}$ N) in order to examine the growth, photosynthetic traits, and accumulation of Cd^{2+} .

Results

The findings demonstrated that combined treatments of 70% light intensity with the N1(100 $\text{mg}\cdot\text{kg}^{-1}$ N) nitrogen level, or 100% light intensity with the N2(200 $\text{mg}\cdot\text{kg}^{-1}$ N) nitrogen level, significantly enhanced the growth, photosynthetic performance, and Cd^{2+} accumulation in *R. sylvestris*. Moreover, in moderate nitrogen levels (N1), when the relative light intensity is 70% and 100%, most indicators including biomass, photosynthetic traits, shoot Cd^{2+} accumulation, bioconcentration factor (BCF), and translocation factor (TF) do not show significant differences.

Conclusion

High light intensity and nitrogen level promoted the growth of *R. sylvestris* and Cd^{2+} accumulation in organs, appropriate shading in moderate nitrogen level showed no significant difference compared to the full-light condition. The results indicated that *R. sylvestris* could be combined with woody plants in the restoration system, which not only improved the removal efficiency of cadmium, but also provided ecological and aesthetic benefits.

Introduction

Soil contamination by heavy metals is a growing environmental concern worldwide. Cadmium (Cd), recognized as one of the most hazardous heavy-metal elements, primarily originates from industrial wastewater irrigation, mining and smelting activities, and the widespread application of pesticides and fertilizers in agriculture (Souza et al., 2026; Lin et al., 2025; Fan et al., 2023). According to a 2014 nationwide survey on soil pollution, inorganic metal contaminants accounted for over 80% of soil

pollution cases, with Cd contributing to 7% of the contaminated sites (Hu et al., 2014). More recently, Jiang et al. (2023) reported that 8.03% of non-agricultural lands across 28 provinces in China exceeded the national soil risk screening value for Cd (65 mg kg⁻¹). Due to its high mobility and potential for plant uptake and accumulation, Cd can enter the food chain and pose serious health risks to humans (Zhang et al., 2016). Among heavy metal-polluted soils, Cd-contaminated soil is particularly problematic due to its extensive distribution and severe toxicity.

Phytoremediation has emerged as a promising, cost-effective, and environmentally friendly technology for soil remediation. This approach utilizes plants to extract, stabilize, or degrade contaminants, the core strategy is the identification or development of hyperaccumulator species with a capability of tolerating and accumulating high concentrations of heavy metals. To date, more than 400 hyperaccumulator plants have been identified, including *Hylotelephium spectabile*, *Rorippa globosa*, *Solanum nigrum*, and *Bidens pilosa* (Li et al., 2023). However, most reported hyperaccumulators are herbaceous species characterized by shallow root systems, slow growth rates, and low biomass, which limit their practical application in large-scale remediation. In contrast, woody plants (shrubs and trees) generally exhibit deeper roots, faster growth, and higher biomass. Although woody species may have lower metal enrichment coefficients, their greater biomass production can result in higher total metal extraction per plant, offering significant potential for the phytoremediation of heavy metal-contaminated soils (Dai et al., 2024). Furthermore, the establishment of multi-layered planting systems that combine woody plants with ornamental herbs could enhance both the aesthetic value and remediation efficiency of contaminated sites, achieving synergistic ecological and landscape benefits. The growth and metal-accumulation capacity of hyperaccumulators are strongly influenced by environmental factors such as light, water, and nutrient availability (Guo et al., 2023; Li et al., 2025). Light is a fundamental factor governing plant survival, growth, morphology, and metabolism (Valladares et al., 2008). It also modulates the synthesis and accumulation of secondary metabolites (e.g., phenolics, triterpenes, and flavonoids), which in turn can affect the translocation and detoxification of heavy metals in plants (Pandey et al., 2021; Yang et al., 2018). Light intensity further influences heavy metal uptake and transport by regulating photosynthetic and transpiration rates (Wu et al., 2015). However, responses to light vary among hyperaccumulator species. For instance, strong light has been shown to enhance pea tolerance to lead (Pb) (Romanowska et al., 2006), whereas low light intensity increased the tolerance of *Lemna minor* to zinc (Zn) and cadmium (Cd) (Artetxe et al., 2002). Similarly, moderate shading did not significantly affect Cd accumulation in *Sedum alfredii* (Jiang et al., 2010) but promoted Cd enrichment in *Solanum nigrum* (Du and Wang, 2012).

Nitrogen is another critical factor affecting plant growth, photosynthesis, and yield (Makino, 2011). It also plays a key role in modulating Cd uptake and accumulation in plants. Among essential nutrients, nitrogen is considered one of the most effective in regulating Cd dynamics (Yang et al., 2016). Nitrogen fertilization can enhance plant biomass and Cd concentration in the tissue, thereby increasing total Cd accumulation and improving plant tolerance to Cd stress (Fujimaki et al., 2010; Mitchell, 2000). Urea, the predominant nitrogen fertilizer used in China, can influence the mobility and bioavailability of heavy

metals in soil. Studies have shown that urea application promoted plant growth and Cd accumulation in species such as *Solanum nigrum* (Maqbool et al., 2020) and Italian ryegrass (Ji et al., 2020).

Light and nitrogen are not only vital for plant growth but also interact to shape plant physiological responses and heavy metal accumulation. The interactive effects of light and nitrogen can improve both light-use efficiency and nitrogen uptake, thereby promoting plant growth (Simionato et al., 2015). *Rorippa sylvestris*, a perennial herb in the Brassicaceae family, possesses a well-developed root system, strong suckering ability, and attractive bright yellow flowers, giving it high ornamental value. It has been identified as a Cd hyperaccumulator, showing no significant growth inhibition in soil containing 50 mg kg⁻¹ Cd and achieving an aboveground enrichment coefficient of 2.59 (Qu et al., 2022).

In this study, clonal seedlings of *R. sylvestris* were grown in Cd-contaminated soil under controlled conditions to: (1) evaluate its adaptability to different light intensities; (2) investigate the effects of light intensity on growth and Cd accumulation; and (3) assess its phytoremediation potential under varying light and nitrogen regimes. The findings aim to explore the feasibility of integrating *R. sylvestris* with woody plants in remediation systems to enhance Cd removal efficiency while simultaneously providing ecological and aesthetic benefits.

Materials and Methods

Plant Culture, Cd Exposure, Shading, and Nitrogen Treatments

The experiment was conducted at the Tianzhu Mountain Experimental Base of Shenyang Agricultural University (41°51' N, 123°34' E), a region characterized by a temperate continental monsoon climate with an average annual temperature of 8°C and annual precipitation ranging from 600 to 800 mm. In early May 2023, sprouting seedlings of *R. sylvestris* were initially cultivated in plastic seedling trays containing nutrient soil for 15 days. Thereafter, uniformly sized seedlings (approximately 5.0 cm in height) were selected and transplanted into pots (14.5 cm in diameter, 17 cm in height) for the main experiment. The soil was artificially contaminated with cadmium (Cd) at a concentration of 50 mg kg⁻¹. This was achieved by thoroughly mixing the soil with an aqueous cadmium chloride solution one month prior to planting to ensure homogeneity. The basic physicochemical properties of the soil were as follows: pH, 7.14 ± 0.18; organic matter, 0.69 ± 0.01 g kg⁻¹; total phosphorus, 0.25 ± 0.00 g kg⁻¹; total potassium, 9.97 ± 0.24 g kg⁻¹; alkali-hydrolyzable nitrogen, 8.97 ± 0.06 mg kg⁻¹; available phosphorus, 58.32 ± 1.12 mg kg⁻¹; available potassium, 54.56 ± 1.03 mg kg⁻¹; and total Cd, 0.12 ± 0.00 mg kg⁻¹. Following a 15-day acclimatization period after transplanting, light and nitrogen treatments were initiated. Three light intensity levels were established using shading nets to achieve 50%, 70%, and 100% (full) natural sunlight. Nitrogen was applied at three levels: N0 (0 mg kg⁻¹ N), N1 (100 mg kg⁻¹ N), and N2 (200 mg kg⁻¹ N). All pots were manually watered and weeded as needed. Growth conditions were kept consistent across all treatments except for the manipulated light and nitrogen variables. Each treatment combination was replicated six times. The entire experiment was conducted under a rain shelter to

prevent the leaching of Cd from the pots by rainfall. Measurements of all parameters were taken after one month of treatment application.

Measurement of Plant Growth

Plant height was measured using a ruler. At harvest, plants were carefully removed from the pots, and roots were gently rinsed with running water to remove adhering soil. After blotting excess moisture with absorbent paper, plant samples were first oven-dried at 105°C for 30 minutes and then at 70°C for 48 hours to obtain a constant dry weight. Root morphological parameters, including total root length, mean root diameter, total root surface area, and total root volume, were analyzed using a root scanner and the WinRHIZO analysis software. Six biological replicates were used for all growth measurements.

Determination of Gas-exchange Parameters

Leaf gas-exchange parameters were measured on a sunny, windless morning around 10:00 A.M. using a portable photosynthesis system (LI-6800, LI-COR, Lincoln, NE, USA). The measurements were performed under controlled conditions: atmospheric CO₂ concentration of 400 μmol mol⁻¹, leaf and air temperature of 25°C, relative air humidity of 50–70%, and a photosynthetically active radiation (PAR) level of 1000 ± 12 μmol m⁻² s⁻¹. For each treatment, three plants were selected, and one healthy, sun-exposed leaf at a similar developmental position was measured per plant. The parameters recorded were net photosynthetic rate (P_n), transpiration rate (T_r), intercellular CO₂ concentration (C_i), and stomatal conductance (G_s). Three technical replicates were performed per treatment. Instantaneous water-use efficiency (WUE) was calculated as P_n/T_r (Yu et al., 2025; Qu et al., 2022).

Determination of Chlorophyll Content

Fresh leaf tissue (0.1 g) was placed in a test tube containing 10 mL of an ethanol-acetone mixture (1:1, v/v) and stored in darkness for 48 hours until complete decolorization. The absorbance of the extract was then measured using a visible spectrophotometer, and chlorophyll content was calculated according to standard methods (Xu et al., 2024). Three replicates were analyzed per treatment.

Determination of Cd Content in Tissues

At harvest, plants were separated into roots, stems, and leaves. After thorough washing, the tissues were oven-dried and weighed. Subsequently, approximately 300 mg of dry, powdered plant material was digested using a concentrated acid mixture of HNO₃/HClO₄ (3:1, v/v). The Cd concentration in the digest was determined by inductively coupled plasma atomic emission spectroscopy (ICP-AES). The certified reference material (GBW#08,513) was supplied by the National Institute of Standards and Technology for quality control. The recovery of the Cd assay was 96%. There were three repetitions.

Data Analysis

The translocation factor (TF) represents the ability of Cd to be transported from underground parts to aboveground parts. The bioconcentration factor (BCF) refers to the capability of Cd accumulation in plant tissues. The phytoextraction coefficient (PEC) denotes the ability to transfer Cd from Cd-polluted soils to plants. (Mattina et al. 2003).

$TF = \text{Cd content in shoots (mg kg}^{-1}\text{)} / \text{Cd content in roots (mg kg}^{-1}\text{)}$

$BCF = \text{Cd content in plant tissues (mg kg}^{-1}\text{)} / \text{Cd content in medium (mg kg}^{-1}\text{)}$

$PEC = \text{Cd content in plant (mg kg}^{-1}\text{)} / \text{Cd content in medium (mg kg}^{-1}\text{)}$

All figures were prepared using Microsoft Office Excel 2019. Statistical analysis was performed using SPSS 27.0. A two-way analysis of variance (ANOVA) was conducted to evaluate the effects of light, nitrogen, and their interaction. Where significant differences were found, means were compared using Duncan's multiple range test at a significance level of $p < 0.05$.

Results

Effect of Light Intensity and Nitrogen Level on Plant Height of *R. sylvestris*

The plant height of *R. sylvestris* was significantly influenced by both light intensity and nitrogen level (Fig. 1). At a given light intensity, plant height generally increased with increasing nitrogen application. Conversely, under a fixed nitrogen level, plant height exhibited a trend of initial increase followed by decrease as light intensity increased. No significant difference in plant height was observed between the 70% and 100% light intensity treatments under the N1 nitrogen condition. The maximum plant height was achieved under the combination of N2 nitrogen level and 70% light intensity.

Different lowercase letters indicated significant differences ($p < 0.05$) among nitrogen treatments within the same light level. Different uppercase letters indicated significant differences ($p < 0.05$) among light treatments within the same nitrogen level.

Effect of Light Intensity and Nitrogen Level on Biomass of *R. sylvestris*

The biomass responses of *R. sylvestris* to light and nitrogen treatments were shown in Fig. 2. Under shaded conditions (50% and 70% light intensity), both shoot biomass and total plant biomass initially increased and then decreased with increasing nitrogen levels, with the highest values observed under 70% light intensity at the N2 nitrogen level. In contrast, under full sunlight (100% light intensity), shoot and total plant biomass increased progressively with nitrogen application and reached their maxima at the N2 level. No significant difference in biomass was found between the 70% and 100% light intensity treatments under the N1 nitrogen level ($p > 0.05$).

Different lowercase letters indicated significant differences ($p < 0.05$) among nitrogen treatments within the same light level. Different uppercase letters indicated significant differences ($p < 0.05$) among light

treatments within the same nitrogen level.

Effect of Light Intensity and Nitrogen Level on Root Morphological Traits of *R. sylvestris*

As shown in Fig. 3, all measured root morphological traits—including root length, root diameter, root surface area, and root volume—exhibited a similar response pattern under 50% and 70% light intensities, showing an initial increase followed by a decline as nitrogen levels increased. The highest values for these traits under shaded conditions were generally observed at 70% light intensity combined with the N1 nitrogen level. In contrast, under full sunlight (100% light intensity), all root traits increased progressively with rising nitrogen levels, reaching their maximum at the N2 nitrogen level. In the N1 nitrogen treatment, root length was significantly greater under 70% light intensity than that under 100% light intensity, whereas root surface area did not differ significantly between the two light intensities ($p > 0.05$).

A: root diameters; B: root surface areas; C: root diameters; D: of *R. sylvestris*.

Note

Different lowercase letters indicated significant differences ($p < 0.05$) among nitrogen treatments within the same light level. Different uppercase letters indicated significant differences ($p < 0.05$) among light treatments within the same nitrogen level.

Effect of Light Intensity and Nitrogen Level on Gas-exchange Parameters and Chlorophyll Content of *R. sylvestris*

As shown in Fig. 4, under a given nitrogen level, the net photosynthetic rate (P_n), transpiration rate (T_r), and stomatal conductance (G_s) of *R. sylvestris* increased with increasing light intensity, whereas intercellular CO₂ concentration (C_i), water use efficiency (WUE), and chlorophyll content exhibited the opposite trend. Under 50% or 70% light intensity, P_n , T_r , G_s , WUE, and chlorophyll content generally showed an initial increase followed by a decrease with rising nitrogen levels. In contrast, under full sunlight (100% light intensity), these parameters increased progressively with nitrogen application, while C_i decreased correspondingly.

Different lowercase letters indicated significant differences ($p < 0.05$) among nitrogen treatments within the same light level. Different uppercase letters indicated significant differences ($p < 0.05$) among light treatments within the same nitrogen level.

Effect of Light Intensity and Nitrogen Level on Cadmium Accumulation in Tissues of *R. sylvestris*

As shown in Fig. 5A, the cadmium (Cd) accumulation in shoots of *R. sylvestris* exhibited an initial increase followed by a decrease with increasing nitrogen levels under 50% and 70% light intensity. The maximum shoot Cd accumulation (148.17mg kg⁻¹) was observed under 70% light intensity combined with the N1 nitrogen level. Under full sunlight (100% light intensity), shoot Cd accumulation increased

progressively with nitrogen addition, reaching 152.07 mg kg⁻¹ at N1 nitrogen level and peaking at 161.53 mg kg⁻¹ under the N2 treatment.

The bioconcentration factor (BCF), translocation factor (TF), and phytoextraction coefficient (PEC) showed trends similar to those of shoot Cd accumulation (Fig. 6B–D). Under the N1 nitrogen level, the BCF values were 2.96 and 3.09 at 70% and 100% light intensity, respectively, with no significant difference between them ($p > 0.05$). Similarly, TF values were 1.71(70% light) and 1.7(100% light), and PEC values were 2.51 (70% light) and 2.65 (100% light), none of which differed significantly between the two light intensities ($p > 0.05$).

Different lowercase letters indicated significant differences ($p < 0.05$) among nitrogen treatments within the same light level. Different uppercase letters indicated significant differences ($p < 0.05$) among light treatments within the same nitrogen level.

Correlation Analysis of Cadmium Accumulation with Growth and Photosynthetic Parameters in *R. sylvestris*

As shown in Fig. 6, cadmium (Cd) accumulation in *R. sylvestris* showed a highly significant positive correlation with plant height, biomass, root morphological traits (including root length, root diameter, root surface area, and root volume), and net photosynthetic rate (P_n). Conversely, it exhibited a highly significant negative correlation with intercellular CO₂ concentration (C_i) and water use efficiency (WUE). No significant correlation was observed between Cd accumulation and chlorophyll content.

‘**’ represented an extremely significant correlation at $p < 0.01$ level; ‘*’ represented a significant correlation at $p < 0.05$ level

Discussion

Light and nitrogen are two critical environmental factors governing plant growth and development. In this experiment, under the same nitrogen level, appropriate shading promoted plant height growth. At the moderate nitrogen level (N1), there was no significant difference in biomass between the 70% and 100% light intensities, and root length was significantly greater at 70% than at 100% relative light intensity. In contrast, root surface area showed no significant difference between the two light intensities ($p > 0.05$), suggesting that moderate shading (70% relative light intensity) did not substantially inhibit the growth of *R. sylvestris*.

Optimal light and nutrient conditions are essential for efficient phytoremediation, as these factors regulate plant growth and physiological traits, thereby influencing metal uptake and accumulation (Zhang et al., 2023). Plant biomass and the bioavailability of Cd in soil are key determinants of phytoremediation efficiency (Song et al., 2025). Biomass accumulation is largely driven by photosynthesis, in which nitrogen plays a vital role (Chen et al., 2016; Lang et al., 2018). Generally, greater biomass correlates with enhanced Cd accumulation capacity due to increased root surface area

for metal uptake (Zhang et al., 2024) and more efficient vascular transport systems for metal translocation to shoots (Zhang et al., 2025). In addition, excessive nitrogen fertilization can cause soil acidification, which impairs root development and nutrient uptake, thereby limiting plant biomass accumulation (Farhan et al., 2024). Conversely, appropriate nitrogen application can enhance the photosynthetic capacity and dry matter translocation in wheat leaves, helping to mitigate the yield losses caused by insufficient light. However, Zhang et al. note that under moderate or heavy shade, this compensatory effect of nitrogen is diminished, necessitating a reduction in application rates.

Photosynthetic parameters—including net photosynthetic rate (P_n), transpiration rate (T_r), stomatal conductance (G_s), and intercellular CO_2 concentration (C_i)—are key indicators of photosynthetic efficiency. Light intensity directly influences these parameters. In this study, P_n , T_r , and G_s increased with increasing light intensity, whereas C_i decreased. These parameters are strongly influenced by light intensity. In this study, P_n , G_s , and T_r increased with rising light intensity, while C_i decreased. The elevated C_i observed under low light suggested impaired CO_2 assimilation in chloroplasts, indicating that non-stomatal limitations predominantly constrain photosynthesis under shaded conditions (Lang et al., 2018). Adequate light can enhance photosynthetic activity and improve plant tolerance to Cd^{2+} , potentially increasing Cd^{2+} accumulation (Adomako et al., 2023). Transpiration is another important driver of Cd^{2+} uptake and transport, as it influences the mass flow of water and solutes within the plant (Sheoran et al., 2016). Studies have shown that genotypes with higher transpiration rates tend to accumulate more Cd^{2+} in aboveground tissues (Guo et al., 2023). Although elevated transpiration can facilitate root-to-shoot Cd^{2+} translocation, it may also heighten plant sensitivity to Cd^{2+} toxicity (Liu et al., 2016). For example, under nitrogen fertilization, higher transpiration rates were correlated with increased Cd^{2+} accumulation in durum wheat (Özkutlu, 2024). Similarly, a high-Cd-accumulating eggplant cultivar exhibited greater transpiration and Cd^{2+} uptake than a low-accumulating cultivar under Cd^{2+} stress (Shen et al., 2023).

Chlorophyll content in *R. sylvestris* increased with decreasing light intensity, likely due to reduced photo-oxidative damage of pigments and structural adjustments in chloroplasts, such as enlarged grana and enhanced thylakoid stacking (Atanasova et al., 2003; Guan et al., 2024). Nitrogen fertilization also significantly affects photosynthetic performance. Moderate nitrogen application promotes the synthesis and activity of photosynthetic enzymes, thereby increasing photosynthetic rate (Noor et al., 2023) and enhancing chlorophyll content, which improves light capture and conversion efficiency (Sun et al., 2023; Chen et al., 2021). In this experiment, the N1 level significantly boosted P_n , T_r , G_s , chlorophyll content, and water-use efficiency under 50% and 70% light intensities, whereas the N2 level produced similar enhancements under 100% light intensity. These results align with findings that optimal nitrogen application can improve photosynthetic efficiency and promote Cd^{2+} uptake in crops such as wheat (Yang et al., 2020), underscoring the importance of balanced light and nitrogen inputs for maximizing plant performance and Cd accumulation.

Nitrogen fertilization enhances Cd^{2+} bioavailability in soil by lowering soil pH. This acidification promotes Cd desorption from soil minerals and organic matter, elevating its concentration in the soil solution and thus facilitating plant uptake. Additionally, nitrogen fertilizer can stimulate Cd accumulation in plants by boosting plant growth and altering the chemical forms of heavy metals in the soil (Xu et al., 2021). For example, enhanced biomass under nitrogen supply may improve a plant's capacity to enrich Cd.

In this study, N1 treatment significantly increased Cd accumulation and enrichment in *R. sylvestris* under 50% and 70% light intensities, while N2 treatment markedly reduced these parameters under the same light conditions. In contrast, under 100% light intensity, N2 treatment promoted Cd accumulation and enrichment in *R. sylvestris*. This suggests that excessive nitrogen application can modify soil physicochemical properties—such as pH, organic matter content, electrical conductivity, and cation exchange capacity—which may in turn alter Cd availability (De Vargas et al., 2019; Wang et al., 2022) and ultimately diminish plant capacity for Cd accumulation and enrichment.

In the present study, *R. amphibibia* decreased the accumulation with decreasing light intensity at the same nitrogen level, and the Cd enrichment capacity decreased, probably because the changes in light intensity affected physiological activities. Low light intensity leads to a decrease in the synthesis content of antioxidant secondary metabolites such as terpenoids, phenolics, and alkaloid compounds in plants, which affects the metabolism of substances and energy, and ultimately may affect the uptake of heavy metals (Yang et al., 2018). However, the accumulation and enrichment capacity of Cd^{2+} were non-significant under 70% and 100% light intensities, and N0 and N1 nitrogen level ($p > 0.05$), which suggests that proper shading does not significantly affect the uptake of Cd^{2+} and accumulation in *R. sylvestris*.

Conclusions

Under low-light conditions, plants can mitigate the adverse effects of insufficient light on growth and heavy metal uptake with the assistance of nitrogen fertilizer. However, excessive nitrogen application may counteract these benefits. The optimal amount of nitrogen fertilizer varies depending on plant species and the prevailing light conditions. Therefore, achieving a suitable balance between light intensity and nitrogen supply is crucial for promoting healthy plant growth and development. In this study, combined treatments of 70% light intensity with the N1 nitrogen level, or 100% light intensity with the N2 nitrogen level, significantly enhanced the growth, photosynthetic performance, and Cd^{2+} accumulation in *R. sylvestris*. Moreover, under the light–nitrogen combinations of 70% light–N1 and 100% light–N1, most parameters—including shoot biomass, photosynthetic traits, shoot Cd^{2+} accumulation, bioconcentration factor (BCF), and translocation factor (TF)—showed no significant differences. These results suggest that appropriate shading did not diminish the ability of *R. sylvestris* to grow and accumulate Cd^{2+} . Therefore, adopting a composite planting system combining *R. sylvestris* with trees in Cd^{2+} -contaminated soils could enhance the ecological remediation efficiency of soils and provide additional avenues for the ecological application of *R. sylvestris* in landscape phytoremediation.

Declarations

Competing interest

The authors declare no conflicts of interest.

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Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Figures

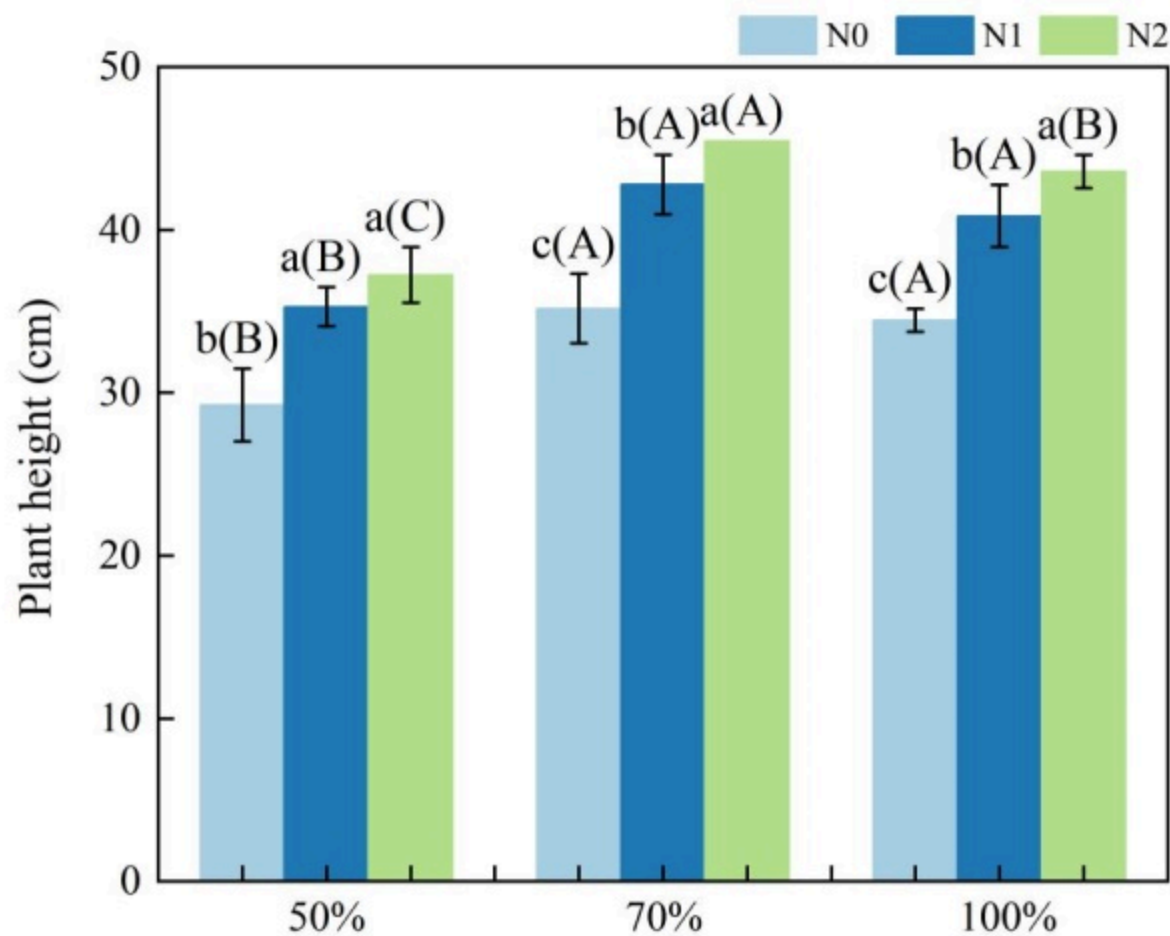


Figure 1
Effects of light intensity and nitrogen level on plant height of *R. sylvestris*

Different lowercase letters indicated significant differences ($p < 0.05$) among nitrogen treatments within the same light level. Different uppercase letters indicated significant differences ($p < 0.05$) among light treatments within the same nitrogen level.

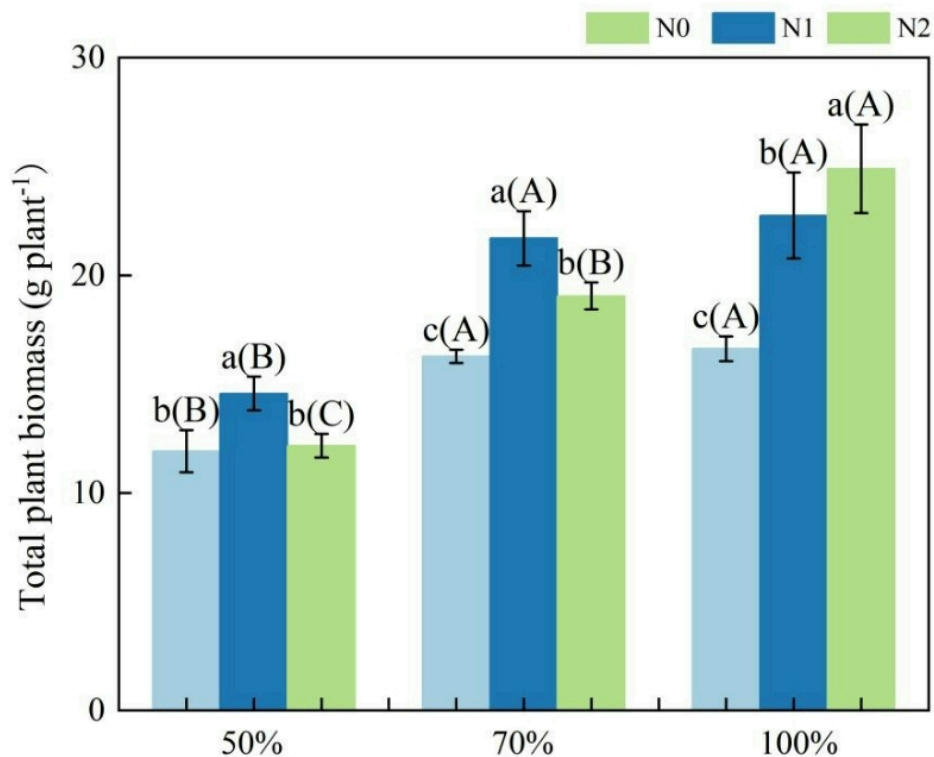


Figure 2

Effect of light intensity and nitrogen level on biomass of *R. sylvestris*.

Different lowercase letters indicated significant differences ($p < 0.05$) among nitrogen treatments within the same light level. Different uppercase letters indicated significant differences ($p < 0.05$) among light treatments within the same nitrogen level.

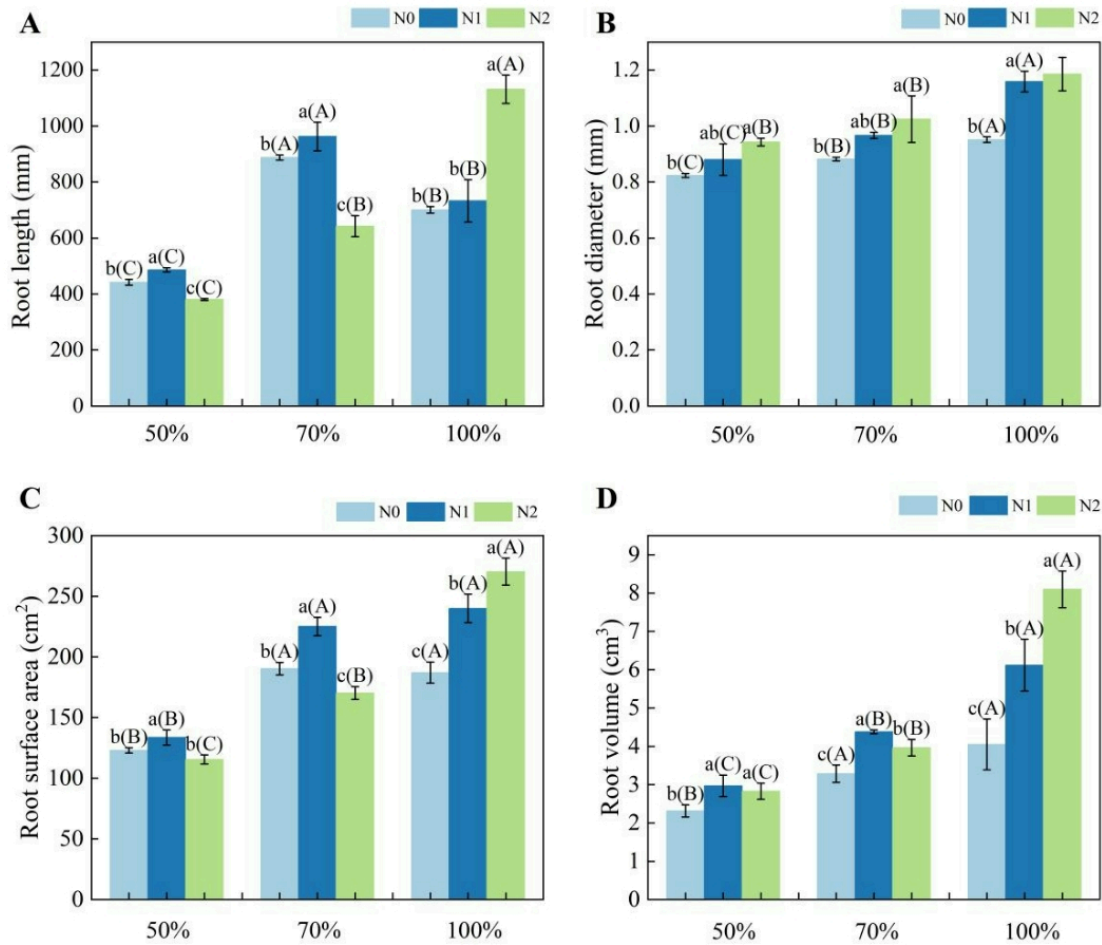


Figure 3

Effect of light intensity and nitrogen level on the root diameters

A: root diameters; B: root surface areas; C: root diameters; D: of *R. sylvestris*.

Note: Different lowercase letters indicated significant differences ($p < 0.05$) among nitrogen treatments within the same light level. Different uppercase letters indicated significant differences ($p < 0.05$) among light treatments within the same nitrogen level.

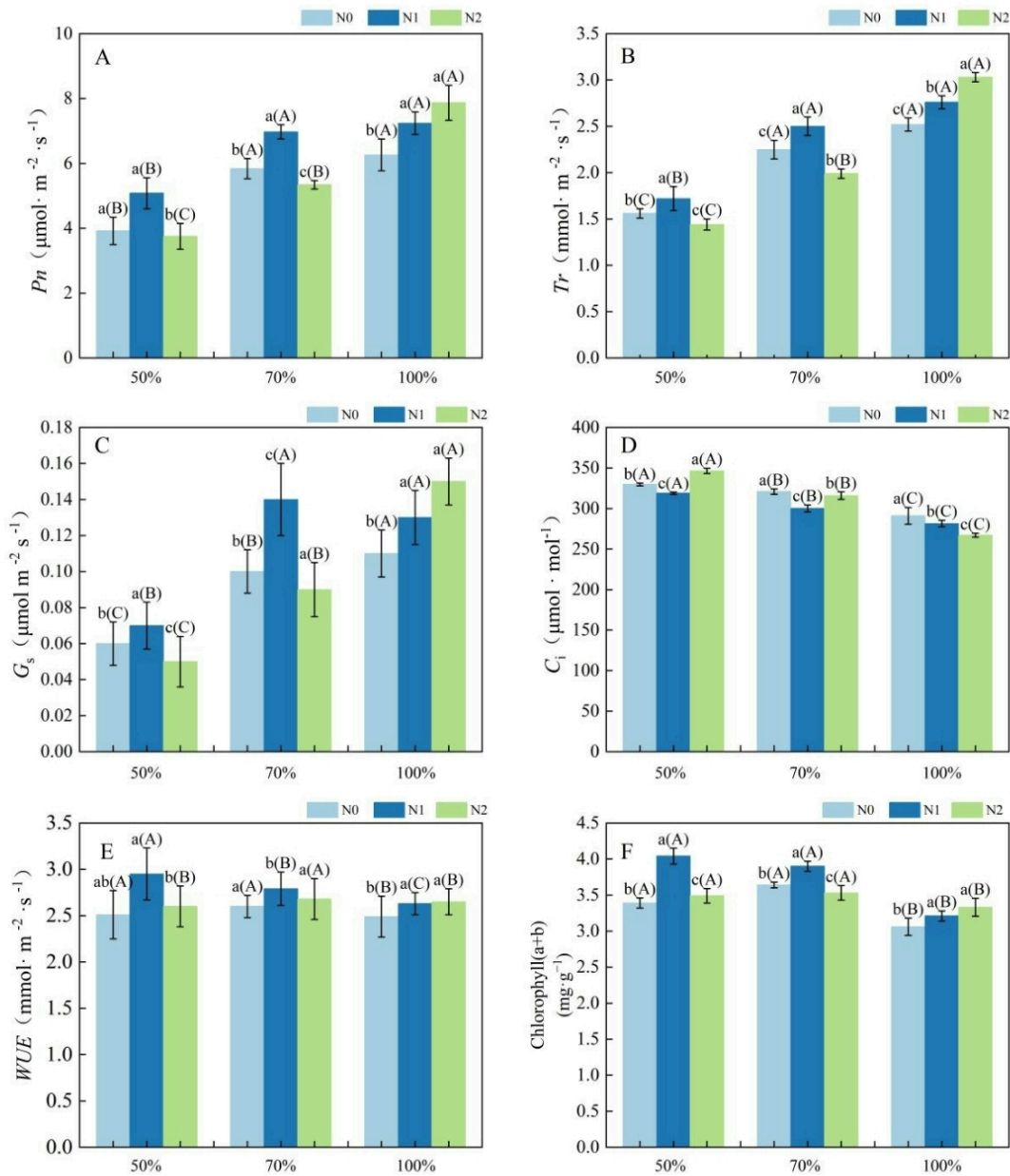


Figure 4

Effect of light intensity and nitrogen level on gas-exchange parameters and chlorophyll content of *R. sylvestris*

Different lowercase letters indicated significant differences ($p < 0.05$) among nitrogen treatments within the same light level. Different uppercase letters indicated significant differences ($p < 0.05$) among light

treatments within the same nitrogen level.

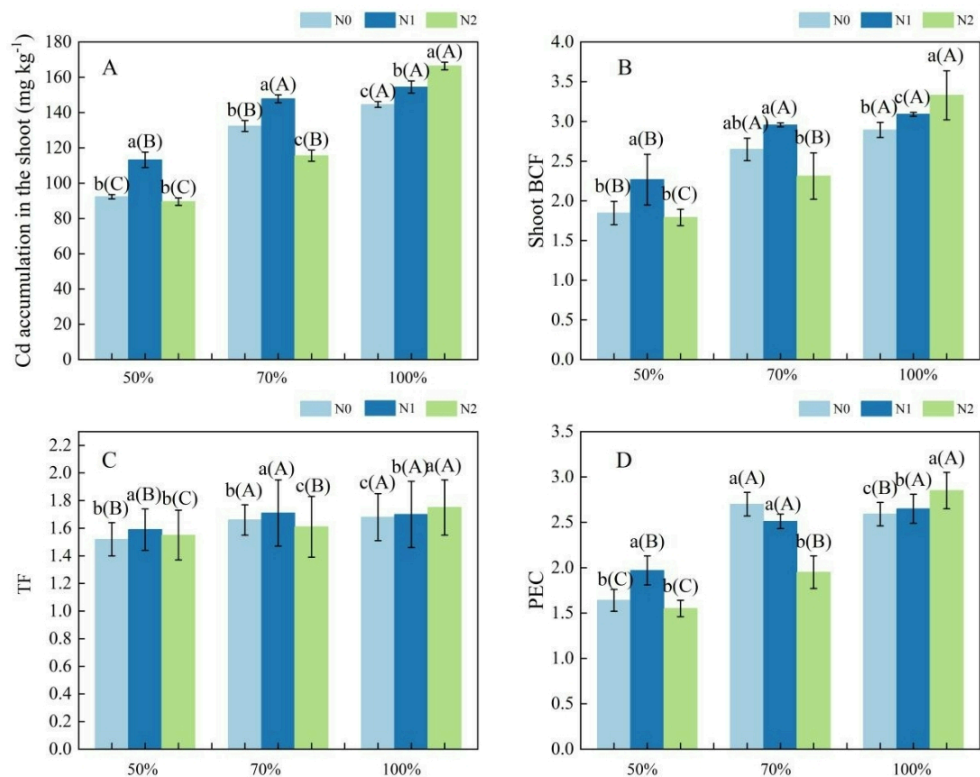


Figure 5

Effects of different light intensities and nitrogen levels on Cd²⁺ accumulation in tissues of *R. sylvestris*. A: Cd accumulation in the shoot; B: BCF; C: TF; D: PEC.

Different lowercase letters indicated significant differences ($p < 0.05$) among nitrogen treatments within the same light level. Different uppercase letters indicated significant differences ($p < 0.05$) among light treatments within the same nitrogen level.

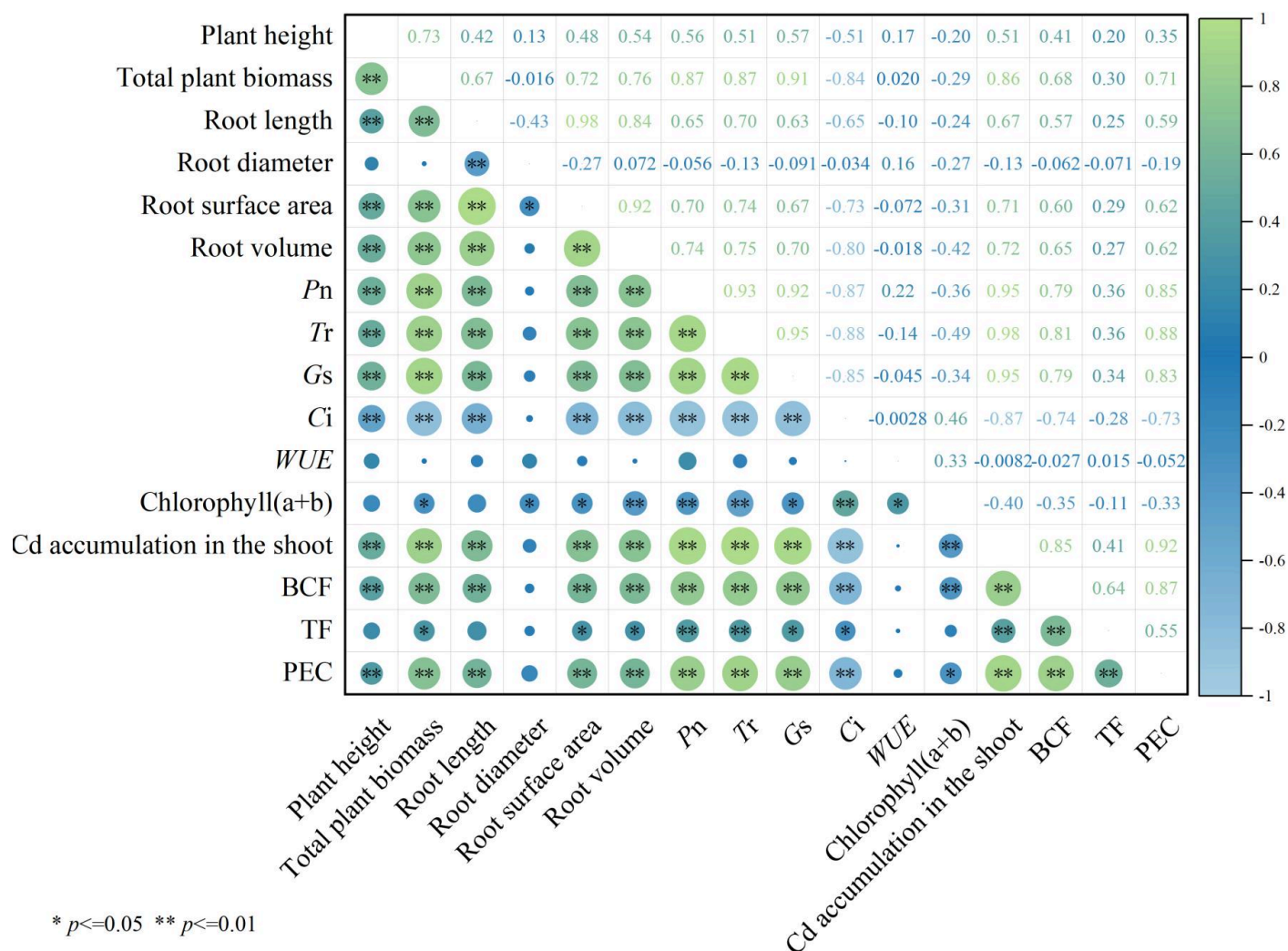


Figure 6

Correlation analysis of cadmium accumulation with growth and photosynthetic parameters in *R. sylvestris*

‘**’ represented an extremely significant correlation at $p < 0.01$ level ‘*’ represented a significant correlation at $p < 0.05$ level