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Effects of nitrate to ammonium ratio and nitrogen level on growth of an invasive plant *Alternanthera philoxeroides* in cadmium polluted water

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Abstract

The performance of invasive plants in cadmium polluted environments has been shown to be affected by high nitrogen availability and forms, but the effect of nitrate to ammonium ratios on invasive plant performance under cadmium stress remains unclear. In a greenhouse experiment, single fragments of *Alternanthera philoxeroides* were grown in water polluted with cadmium at a concentration of 1 mg L^{-1}. The experiment involved three nitrogen levels (0.4, 2, and 10 mmol L^{-1}) and five ratios of nitrate to ammonium (1:9, 3:7, 5:5, 7:3, and 9:1) to investigate the effects of nitrogen concentration and nitrate to ammonium ratio on the growth of this invasive plant species under cadmium polluted conditions. At a nitrogen concentration of 0.4 mmol L^{-1}, the ratio of nitrate to ammonium at 1:9 significantly decreased the total biomass. In contrast, at a nitrogen concentration of 10 mmol L^{-1}, the lowest total biomass was observed when the ratio of nitrate to ammonium was 5:5. The effect on morphology both from nitrogen level and nitrate to ammonium ratio were independent from each other. Our finding suggested that when predicting and managing *Alternanthera philoxeroides* in cadmium polluted water, it is crucial to consider not only nitrogen concentration levels but also the nitrate to ammonium ratio.

KEYWORDS

Alternanthera philoxeroides, cadmium, invasive plant, nitrate to ammonium ratio, nitrogen level

1 | INTRODUCTION

Plant invasion has emerged as a significant global environmental challenge (Kuebbing et al., 2014; Li et al., 2024; Wang, Wang, et al., 2022). Invasive plants not only precipitate a substantial decline in ecosystem functions and associated services but also pose immense threats to human health and the social economy (Pyšek et al., 2012; Yang et al., 2021). Although heavy metals are naturally present in the environment, their concentrations have been escalating due to anthropogenic activities, including mining, smelting, industrial processes, and

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intensive agriculture, leading to environmental pollution (Haider et al., 2021; Hussain et al., 2021; Nagajyoti et al., 2010). Recent studies have established explicit connections between heavy metal pollution and plant invasion dynamics, providing a critical framework for predicting the future expansion patterns of invasive plants under escalating pressures of heavy metal driven environmental crises, such as soil degradation, biodiversity collapse, and food chain pollution (Li et al., 2023; Lin et al., 2024; Wang et al., 2019; Wang, Zhang, et al., 2022).

Cadmium (Cd) is one of the primary constituents contributing to heavy metal pollution, which has been frequently detected in both terrestrial and aquatic environments (Adomako et al., 2020; Haider et al., 2021; Nagajyoti et al., 2010). Although Cd is naturally present in the earth's crust, it occurs in relatively low concentrations in natural environments. However, with the increase in human activities, particularly industrialization and urbanization processes, Cd pollution has become increasingly prominent (Ashraf et al., 2019; Mahar et al., 2016; Nagajyoti et al., 2010; Wan et al., 2023). Cd is not an essential element for plants, and excessive levels of this metal adversely affect photosynthesis, transpiration rate, stomatal conductance, electrolyte penetration, resulting in the disruption of homeostasis and deficiency of essential nutrients such as iron and magnesium (Ashraf et al., 2019; Hussain et al., 2021). Ultimately, these effects inhibit plant growth and can even lead to plant death (Ashraf et al., 2019; Hussain et al., 2021). Studies have shown that invasive plants, such as *Alternanthera philoxeroides* and *Eupatorium adenophora*, are tolerant to Cd stress (e.g., Dai et al., 2020; Wang et al., 2021). This ability provides these invasive species with disproportionate opportunities to establish populations and further influence native plant communities in disturbed sites.

In fact, heavy metals can interact with other environmental factors, such as nutrients and light, to further affect plant growth (Adomako & Yu, 2023; Li et al., 2023; Wang, Zhang, et al., 2022; Yang et al., 2019; Zhang, Chen, Cui, et al., 2023). The effect of nutrient enrichment on plant invasions has been extensively tested in various researches (Li et al., 2024; Qin et al., 2018). Because nitrogen (N) is an essential macronutrient for plant growth and development, many invasive plants, such as *Paspalum notatum*, *Sphagneticola trilobata*, and *A. philoxeroides*, tend to absorb and utilize N more efficiently than native plants, especially under high N levels, which aids their invasion success (Fallovo et al., 2009; Ge et al., 2008; Li et al., 2024; Luo et al., 2019; Qin et al., 2018). Moreover, N can enhance Cd tolerance of invasive plant species by maintaining biochemical and physiological characteristics during phytoextraction of Cd (Adomako & Yu, 2023; Lin, Alpert, et al., 2012; Lin, Zhu, et al., 2012; Nazar et al., 2012). However, excessive nitrogen levels will become toxic to plants and exacerbate the adverse effects of environmental stressors on them (Li et al., 2023; Si et al., 2020). Furthermore, previous studies have shown that the performance of plants under Cd stress is not only affected by N concentration but also related to N form and the interaction between N concentration and N form (Hassan et al., 2005; Li et al., 2023; Nadeem et al., 2010). Different N concentrations and forms can influence the N-metabolic pathways in plants, affecting the synthesis of N-containing compounds such as amino acids and proteins (Bigg & Daniel, 1978; Hassan et al., 2005; Li et al., 2023; Paulissen et al., 2004). Under Cd stress, plants must adjust their metabolic processes to mitigate heavy metal-induced damage (Lin, Alpert, et al., 2012; Lin, Zhu, et al., 2012; Song et al., 2025; Zhao et al., 2021). By regulating N-metabolic pathways, different N concentrations and forms may alter the levels of related metabolites, thereby modulating the plants' responses to Cd stress (Yang et al., 2019; Zhang et al., 2022; Zhu et al., 2018).

Ammonium (NH_4^+-N) and nitrate (NO_3^--N) are the two primary inorganic forms of N available to plants (Majerowicz & Kerbauy, 2002; Qian et al., 2020; Wei et al., 2024). Different plant species exhibit varying preferences for NH_4^+-N and NO_3^--N (Borgognone et al., 2013; Ge et al., 2008; Song et al., 2015). For instance, an increase in NH_4^+-N relative to NO_3^--N could better promote the growth of *Flaveria bidentis* (Huangfu et al., 2016), while *Ipomoea cairica* exhibits higher plant height, total biomass, and specific leaf area under NO_3^--N compared to NH_4^+-N treatment (Chen & Chen, 2019). In a recent study conducted by Li et al. (2023), it was found that the invasive plant species *A. philoxeroides* exhibited superior growth when supplied with NO_3^--N compared to NH_4^+-N or glycine under Cd stress. The natural equilibrium of the NO_3^--N to NH_4^+-N ratio can be disrupted by variations in the rates of nitrification, denitrification, and plant uptake (Hůnová et al., 2017; Song et al., 2015; Wang et al., 2023). This disruption has been exacerbated by anthropogenic activities, such as the intensified use of synthetic N fertilizers in agriculture, combustion of fossil fuels, and improper waste management practices, which have significantly increased N emissions into natural ecosystems (Liu & Xian, 2018; Sabina et al., 2025; Song et al., 2015; Wang et al., 2023). Therefore, the adaptability of invasive plants to varying ratios of NO_3^--N to NH_4^+-N is pivotal in determining their invasiveness. However, there is a dearth of studies investigating this aspect.

In this study, we investigated the effect of N level and NO_3^--N to NH_4^+-N ratio on the growth of

A. philoxeroides, a widely spread invasive plant, in the presence of Cd. We conducted a greenhouse hydroponic experiment, cultivating single fragments of *A. philoxeroides* in containers with a Cd concentration of 1 mg L^{-1}. The containers were filled with solutions containing five different ratios of NO_3^--N to NH_4^+-N and three levels of N concentration, respectively. Specifically, we tested the following hypotheses: (1) the response of *A. philoxeroides* under Cd stress will vary depending on the ratio of NO_3^--N to NH_4^+-N; (2) the responses of *A. philoxeroides* to the ratio of NO_3^--N and NH_4^+-N will be affected by N level.

2 | MATERIALS AND METHODS

2.1 | Plant species

Alternanthera philoxeroides s (Mart.) Griseb., or alligator weed, is a perennial herbaceous clonal plant (Julien et al., 1995; Julien & Bourne, 1988). This species is native to the temperate regions of South America and was introduced to China as a fodder crop in the 1930s (Julien et al., 1995; Pan et al., 2007). *A. philoxeroides* can be usually found in both aquatic and wet terrestrial habitats (Xu & Wu, 2018; Xu & Zhou, 2016). It exhibits clonal growth and can rapidly spread through stem nodes, which are capable of producing roots and two opposite leaves, serving as potential ramets (Dong et al., 2015; Zhou et al., 2017). Currently, it has emerged as one of the worst invasive weeds in China, particularly in the southern regions (Pan et al., 2007). The plant materials used in this study were collected from the campus of Handan University (36°34′ N, 114°29′ E), which located in Handan, Hebei Province, China. The university is situated in a region characterized by cinnamon soils and a warm temperate continental monsoon climate.

2.2 | Experimental design

This study employed a completely randomized experimental design with two factors: N concentrations and N form ratios. The N concentrations were set at three levels, specifically 0.4, 2, and 10 mmol L^{-1}, representing the total N concentration, which included all forms of N. The N form ratio was defined as the ratio of NO_3^--N (supplied by Ca $(NO_3)_2{\cdot}4H_2O$) to NH_4^+-N (supplied by $(NH_4)_2SO_4$), and was set at five levels, specifically 1:9, 3:7, 5:5, 7:3, and 9:1. Each treatment was replicated six times resulting in a total of 90 experimental units. Cd polluted water was simulated using a solution containing Cd provided by $3CdSO_4{\cdot}8H_2O$ at a concentration of 1 mg L^{-1}. Additionally, each treatment received KH_2PO_4 at a concentration of 1 mmol L^{-1} to supply the essential elements phosphorus and potassium for plant growth. The N and Cd concentrations we used in this study followed established procedures and the levels that constitute pollution in the Environmental Quality Standards for Surface Water in China (http://english.mee.gov.cn/SOE/soechina1997/water/standard.htm; Adomako et al., 2020; Li et al., 2023; Wang, Zhang, et al., 2022; Zhang et al., 2020).

On July 15, 2023, 130 fragments were cut from the same stock plant. Each fragment consisted one node, two opposite leaves, and a nascent bud emerging from the axil of each leaf. Subsequently, these fragments were subjected to hydroponic cultivation in plastic containers filled with tap water in the aforementioned greenhouse. On July 21, 90 plants with uniform size (including one node containing roots, two leaf axillary branches, and an apex) were selected from the previously cultured plant materials. Each container, with a volume of 1000 mL (10 cm diameter at the bottom, 15 cm diameter at the top, and 9 cm height), was filled with 800 mL of a Cd solution containing the N required for each treatment, as described earlier. The fragments were fixed onto floating plates such that their oldest node and roots passed through holes of the float plate, remaining submerged below the water surface, while allowing other nodes and apex to remain above the water surface for upward growth.

The experiment was conducted over a four-week period in the same greenhouse where the plant material was cultivated. All containers were randomly placed on a shelf in the greenhouse. The containers were spaced at least 10 cm apart to ensure that the plants in different containers did not come into contact, thereby avoiding potential interference with the experimental results. During the experiment, the average air temperature and relative humidity inside the greenhouse were 24.3°C and 53.9%, respectively. To compensate for evaporation and absorption losses, tap water was added accordingly. On August 12, new solutions as described in the experimental design above, were introduced to replace those used in each treatment.

2.3 | Measurements and data analysis

At harvest, we measured the length of the main stem and counted the number of nodes of *A. philoxeroides* in each container. Subsequently, plants were separated into shoot

(include leaves and stems) and root parts. These parts were then dried at 70°C until a constant weight was achieved, and then weighed. Additionally, we calculated the shoot mass ratio (shoot dry mass/total dry mass) and root mass ratio (root dry mass / total dry mass).

We employed a two-way analysis of variance (ANOVA, Type III method) to examine the effects of N level, NO_3^--N to NH_4^+-N ratio, and their interaction on the total mass, leaf mass, stem mass, root mass, node number, main stem length, leaf mass ratio, stem mass ratio, and root mass ratio of *A. philoxeroides*. Subsequently, we used Duncan's post hoc test to compare the means of each variable. Prior to the analysis, the data were checked for normality and homoscedasticity and transformed as necessary to enhance homoscedasticity. Figures show untransformed data. All statistical analyses were performed using SPSS 22.0 (IBM, Inc., Armonk, NY, USA).

3 | RESULTS

3.1 | Effects of nitrogen level and nitrate to ammonium ratio on biomass

The N level and NO_3^--N to NH_4^+-N ratio significantly affected root mass of *A. philoxeroides* as main factors, but had no effect on total mass and shoot mass (Table 1). Over all, root mass was reduced when the NO_3^--N to NH_4^+-N ratio was 1:9 and 5:5 (Figure 1c). Furthermore, root mass was lower at an N level of 10 mmol L^{-1} compared to 0.4 and 2 mmol L^{-1} (Figure 1c). The interaction between N level and NO_3^--N to NH_4^+-N ratio significantly affected total mass, shoot mass, and root mass. Specifically, at an N level of 0.4 mmol L^{-1}, the lowest values for total mass, shoot mass, and root mass were observed when the NO_3^--N to NH_4^+-N ratio was 1:9 (Figure 1). At an N level of 2 mmol L^{-1}, the NO_3^--N to NH_4^+-N ratio did not exhibit an obvious effect on total mass, shoot mass, or root mass (Figure 1). However, at an N level of 10 mmol L^{-1}, the growth of *A. philoxeroides* reached its lowest point when the ratio of NO_3^--N to NH_4^+-N was 5:5 (Figure 1).

3.2 | Effects of nitrogen level and nitrate to ammonium ratio on morphology

The N level mainly influenced main stem length, shoot mass ratio, and root mass ratio of *A. philoxeroides*, but had no effect on the number of nodes (Table 2). Overall, an increase in the N level led to a decrease in both the main stem length and the root mass ratio, but an increase in shoot mass ratio (Figure 2b, Figure 3). The NO_3^--N to NH_4^+-N ratio mainly affected the shoot mass ratio and the root mass ratio, but did not affect the number of nodes and the main stem length (Table 2). The highest shoot mass ratio was observed when the NO_3^--N to NH_4^+-N ratio was 5:5, and the lowest root mass ratio was observed under the same conditions (Figure 3). There was no interaction effect between N level and NO_3^--N to NH_4^+-N ratio on any measured parameters, including the number of nodes, main stem length, shoot mass ratio, and root mass ratio.

4 | DISCUSSION

4.1 | Response of biomass to nitrogen level and nitrate to ammonium ratio

The main aim of this study was to elucidate the effects of N level and N form ratios on the growth of *A. philoxeroides* under Cd stress, based on well-verified inhibitory effects of Cd induced phytotoxicity (Li et al., 2023; Wang, Zhang, et al., 2022). We observed no significant effects of N concentration levels (Table 1), as a main factor, on the total mass (as a measure of overall growth) of *A. philoxeroides*. Even at a high N concentration of 10 mmol L^{-1}, there was no growth inhibition, which contrasts with the established toxicity thresholds under single N form conditions (e.g., 8 mmol L^{-1} reported by Li et al., 2023). The possible reason lies in the fact that plants activate distinct absorption and assimilation pathways when taking up N in a single form versus a mixture of multiple forms (Choi et al., 2023; Sun et al., 2023). Moreover, a single N source may lead to the production of more toxic intermediate products during

TABLE 1 Effects of nitrogen level and the ratio of nitrate to ammonium on total mass, shoot mass, and root mass of *Alternanthera philoxeroides* in cadmium polluted water.

Variable	Nitrogen level (N)		Nitrate to ammonium ratio (R)		N × R	
	$F_{2,75}$	*p*	$F_{4,75}$	*P*	$F_{8,75}$	*p*
Total mass	0.610	0.546	1.910	0.118	**2.918**	**0.007**
Shoot mass	0.403	0.670	1.749	0.148	**2.923**	**0.007**
Root mass	**7.444**	**0.001**	**3.343**	**0.014**	2.711	**0.011**

Note: All data of biomass were transformed to the nature log. Values of F and *p*, and degree of freedom (subscript for "F") are given. Values of F and *p* are in bold when $p < 0.05$.

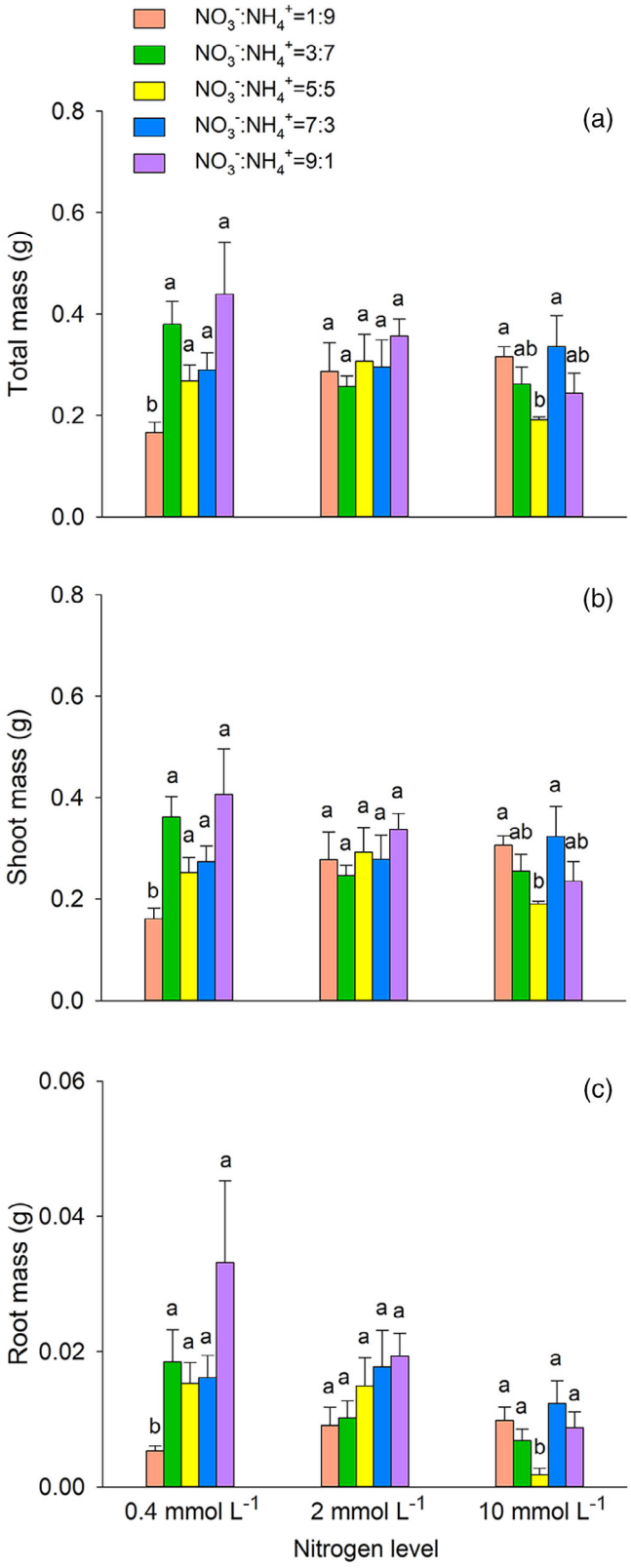


FIGURE 1 Effects of nitrogen level and the ratio of nitrate to ammonium on total mass (a), shoot mass (b), and root mass (c) of *Alternanthera philoxeroides* in cadmium polluted water. Bars and vertical lines are means and SE. Different small letters above bars indicate significant differences among the five ratios of nitrate to ammonium within each of the three nitrogen levels.

absorption and metabolism (Britto & Kronzucker, 2002). In contrast, under conditions with multiple N forms, plants may optimize N resource utilization more efficiently, thereby reducing toxicity accumulation (Choi et al., 2023; Melino et al., 2022; Sun et al., 2023).

As demonstrated in previous studies (Chen & Chen, 2019; Li et al., 2023; Wei et al., 2024), plants can utilize N in various forms and proportions, with NO_3^--N and NH_4^+-N being two main inorganic forms (Majerowicz & Kerbauy, 2002; Qian et al., 2020; Wei et al., 2024). In this experiment, we specifically investigated the interaction between the NO_3^--N to NH_4^+-N ratio and N concentration level. Interestingly, the total biomass of plants, was not significantly affected by the NO_3^--N to NH_4^+-N ratio as a main factor. However, a significant interaction effect between the NO_3^--N to NH_4^+-N ratio and N level was observed. At a low N level of 0.4 mmol L^{-1}, where NH_4^+-N significantly dominated over NO_3^--N (NO_3^--N to NH_4^+-N ratio at 1:9), *A. philoxeroides* exhibited lower total biomass compared to other ratios. It is possible that under low N concentration conditions, this species preferentially absorb NO_3^--N. This inference is indirectly supported by the findings of Li et al. (2023), which reported that *A. philoxeroides* exhibits enhanced growth when supplied with NO_3^--N as the single N source. When the NO_3^--N content is insufficient to meet the plant's preference for nitrate nitrogen, it may negatively impact plant growth. Conversely, at a high N concentration level of 10 mmol L^{-1}, the total biomass was lower when the NO_3^--N to NH_4^+-N ratio was 5:5 compared to ratios of 1:9 and 7:3. Our experiment demonstrated that in the presence of both N forms, increasing the proportion of NO_3^--N at low N levels can promote plant growth, while a high proportion of either NO_3^--N or NH_4^+-N can benefit plant growth under high N levels. This may be attributed to the fact that, under conditions of abundant N supply and equal proportions of NO_3^--N and NH_4^+-N, the metabolic pathways for both N forms in plants could be concurrently activated (Li et al., 2023; Wang, Zhang, et al., 2022; Zayed et al., 2023). In such a case, plants tend to prioritize energy allocation toward N metabolism, thereby disrupting the C/N balance and further diminishing carbohydrate synthesis efficiency, which ultimately suppresses plant growth (Li et al., 2025; Zayed et al., 2023). Additionally, the plant's growth stage and the duration of the experiment might also play a role in these performance responses of plants.

These results suggested that the effects of N on *A. philoxeroides* in Cd polluted water were multifaceted and may involve complex interactions between N form, concentration, and the plant's physiological responses to Cd stress. Further research is needed to fully elucidate

TABLE 2 Effects of nitrogen level and the ratio of nitrate to ammonium on number of nodes, main stem length, shoot mass ratio, and root mass ratio of *Alternanthera philoxeroides* in cadmium polluted water.

Variable	Nitrogen level (N)		Nitrate to ammonium ratio (R)		N × R	
	$F_{2,75}$	*p*	$F_{4,75}$	*p*	$F_{8,75}$	*p*
Number of nodes	0.001	0.999	0.462	0.764	1.616	0.134
Main stem length[a]	**6.925**	**0.002**	1.517	0.206	1.284	0.265
Shoot mass ratio	**9.891**	**<0.001**	**3.163**	**0.019**	1.016	0.432
Root mass ratio[b]	**10.284**	**<0.001**	**2.940**	**0.026**	1.516	0.166

Note: Values of F and *p*, and degree of freedom (subscript for "F") are given. Values of F and *p* are in bold when $p < 0.05$.
[a]Data were transformed to the nature log.
[b]Data were transformed to the square root.

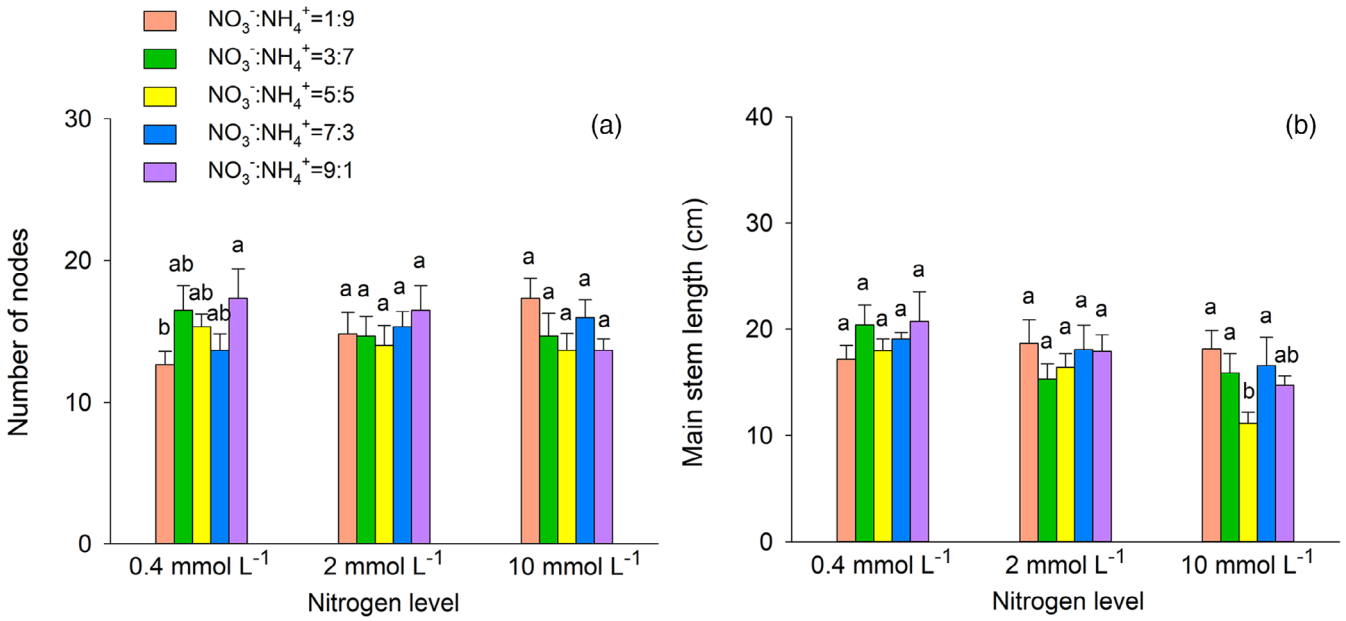


FIGURE 2 Effects of nitrogen level and the ratio of nitrate to ammonium on node number (a) and main stem length (b) of *Alternanthera philoxeroides* in cadmium polluted water. Bars and vertical lines are means and SE. Different small letters above bars indicate significant differences among the five ratios of nitrate to ammonium within each of the three nitrogen levels.

the exact mechanisms underlying these interactions and to develop effective strategies for managing N nutrition in Cd polluted environments.

4.2 | Response of morphology to nitrogen level and nitrate to ammonium ratio

For clonal plants, the capacity for vegetative propagation is closely associated with the number of nodes, as each node possesses the potential to develop into an individual offspring (Lin, Alpert, et al., 2012; Lin, Zhu, et al., 2012; Wang et al., 2021). In this experiment, although the two-way analysis of variance did not reveal significant main or interactive effects of N level and NO_3^--N to NH_4^+-N ratio on node numbers, post-hoc comparisons indicated that under low N concentration (0.4 mmol L^{-1}), a higher proportion of NO_3^--N (9:1 ratio) significantly reduced node numbers in *A. philoxeroides*. This suggests that N form may modulate vegetative propagation under low N concentration conditions, potentially through effects on resource allocation or hormonal signaling (Li et al., 2023; Wang, Zhang, et al., 2022). The length of the main stem decreased as the N concentration increased, despite no reduction in node number. This reduction in stem length likely represents a trade-off between vertical exploration and horizontal spread under high N availability; shorter stems may prioritize local resource exploitation over exploratory growth (Li et al., 2023; Wang, Zhang, et al., 2022; Zhang, Chen, Lyu, et al., 2023). The stem of clonal plants connects ramets and serves as the

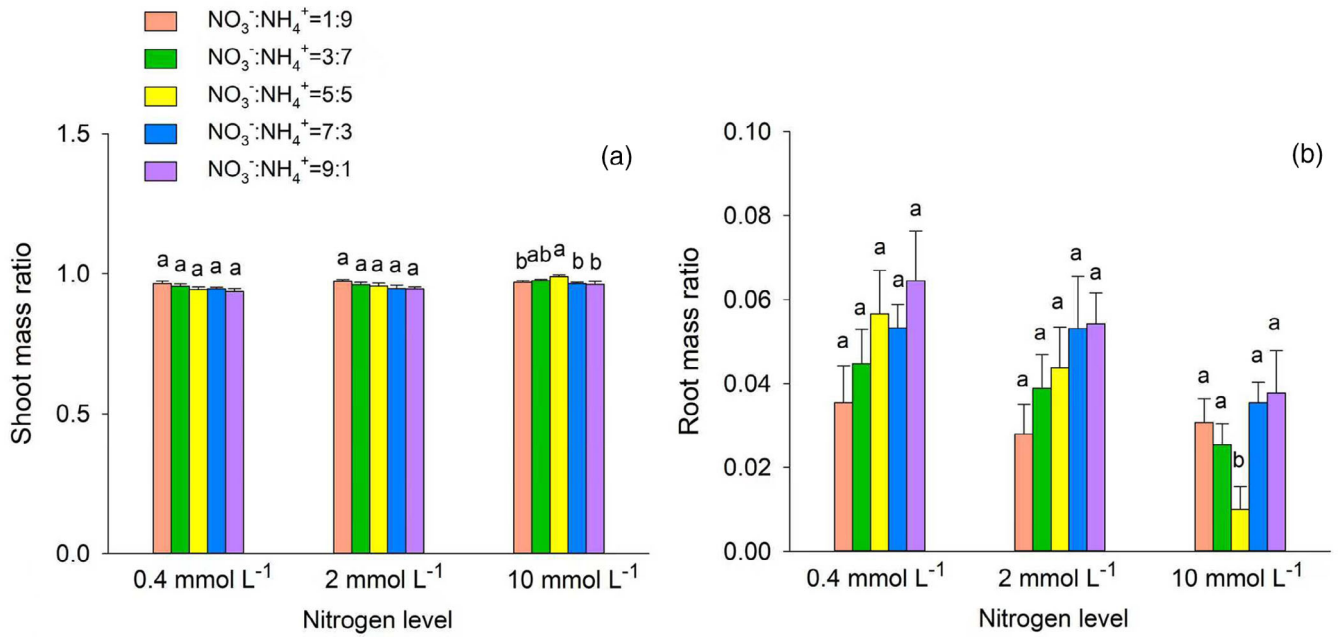


FIGURE 3 Effects of nitrogen level and the ratio of nitrate to ammonium on shoot mass ratio (a) and root mass ratio (b) of *Alternanthera philoxeroides* in cadmium polluted water. Bars and vertical lines are means and SE. Different small letters above bars indicate significant differences among the five ratios of nitrate to ammonium within each of the three nitrogen levels.

conduit for resource and chemical signal transmission (Alpert, 1996; Caraco & Kelly, 1991). The maintenance of node number despite stem shortening suggests *A. philoxeroides* prioritizes ramet initiation over internode elongation under N enrichment in Cd polluted environments (Dong et al., 2010; Zhang, Chen, Li, et al., 2023). However, this strategy carries functional compromises: while reduced stem length may enhance nutrient transmission efficiency, the diminished stem volume likely reduces carbohydrate storage capacity and limits architectural complexity (Dong et al., 2010; Dong et al., 2012; Zhang, Chen, Lyu, et al., 2023). The most severe inhibition was observed at a 5:5 NO_3^--N to NH_4^+-N ratio, suggesting synergistic toxicity under Cd stress when both NO_3^--N and NH_4^+-N serve as codominant N sources. This synergistic toxicity may result from conflicting N assimilation pathways that compete for energy and redox resources, as well as potential cation-anion imbalances that disrupt cellular homeostasis (Yang et al., 2019; Zhang et al., 2022; Zhu et al., 2018).

Overall, the shoot mass ratio increased with N concentration, peaking at a 5:5 NO_3^--N to NH_4^+-N ratio, while the root mass ratio declined, reaching its nadir at the same ratio. These findings suggest that elevated N, particularly when NO_3^--N and NH_4^+-N are codominant, may be toxic to roots or exacerbate Cd toxicity (Li et al., 2023; Si et al., 2020). Although *A. philoxeroides* can tolerate Cd by increasing root allocation under moderate nutrient availability (Wang, Zhang, et al., 2022), this adaptive strategy appears compromised at excessive N levels, especially with balanced NO_3^--N to NH_4^+-N ratios. This highlights a critical interaction: the detrimental effects of high N on root growth are most pronounced when NO_3^--N and NH_4^+-N are equally abundant, indicating that N content and form ratio synergistically influence clonal plant growth under Cd stress. Furthermore, while our study did not directly measure rhizosphere pH, the observed root inhibition at the 5:5 ratio in this experiment could potentially be attributed to NH_4^+-N absorption alter the local root zone pH at this specific ratio. The relatively high experimental temperature (24.3°C) may have further intensified this pH alteration, thereby enhancing Cd bioavailability (Drabesch et al., 2024). Future research should systematically investigate this interaction to confirm its role in root inhibition and Cd dynamics.

5 | CONCLUSION

The coexistence of multiple N forms (NO_3^--N and NH_4^+-N) may enhance the adaptive capacity of *A. philoxeroides* to elevated N concentrations in Cd polluted water. However, this adaptability is highly dependent on N concentration and N forms ratio. Our findings revealed a significant interaction between N concentration and the NO_3^--N to NH_4^+-N ratio in regulating the growth of *A. philoxeroides* under Cd stress, highlighting the

importance of considering both factors simultaneously. For ecological management, these results suggest that monitoring N form, rather than merely total N, is critical for predicting invasion dynamics of *A. philoxeroides* in Cd polluted waters. When developing habitat restoration strategies, the significant inhibitory effects of specific N concentrations and ratios on *A. philoxeroides* can be leveraged. Manipulating the N form ratio may not only suppress *A. philoxeroides* growth but also promote the growth of native species. In general, it remains to be explored whether native species prefer more diverse N compositions than invasive species like *A. philoxeroides*. Nevertheless, considering that native species often have varying N preferences, adjusting the N form ratio has the potential to create a more favorable environment for them, thereby enhancing overall ecosystem health. Future studies should investigate how these N-driven growth responses influence population dynamics, competitive interactions, and ecosystem services in Cd polluted wetlands. In summary, our study shows that the growth of *A. philoxeroides* in Cd polluted water is not determined solely by N concentration or N form ratio alone but by their synergistic interaction. These insights provide a foundation for developing more nuanced management strategies that account for the complex interplay between N nutrition, Cd toxicity, and invasive plant growth.

AUTHOR CONTRIBUTIONS

Zhi-Huan Chen: Investigation, methodology, formal analysis, writing—original draft, writing—review and editing. **Bing-Nan Zhao**: Methodology, formal analysis writing—review and editing. **Zhi-Hang Liu**: Investigation, methodology, formal analysis. **Xin-Yue Gu**: Investigation, methodology. **Zi-Qi Chen**: Investigation, methodology. **Zi-Yang Xie**: Investigation, methodology. **Rui Zhang**: Writing—original draft, writing—review and editing. **Chao Si**: Supervision, conceptualization, methodology, formal analysis, writing—original draft, writing—review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

Data are available from the corresponding author upon reasonable request.

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