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Optimizing Nickel Phytoremediation in Alternanthera ficoidea (L.) R.Br.: Chemical-Assisted Enhancement Strategies

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Abstract*: Nickel (Ni) contamination is recognized as a significant environmental concern on account of its poisonous nature and recycling in the biological systems of soil and water. Phytoremediation offers considerable promise as a way to tackle pollution of Ni, being a green and sustainable process for the disposal of foreign substances through plants. Outlining further methodologies of respective chemicals to enhance Ni recovery occurred in Alternanthera ficoidea (L.) R.Br. is hence the interest of the current study. Chemical treatments like chelating agents (ethylene diamine tetra acetic acid, or EDTA) and surfactants (sodium dodecyl sulphate) were tested in thefield trial for their effectiveness in increasing the nickel uptake and accumulation in plant tissues. Via the chelators and surfactants, an improved performance of Ni uptake within Alternanthera ficoidea (L.) R.Br. was comparatively found. It was finally clear by this work that the combined results were a good improvement to create synergy between EDTA and SDS. The significance of this study is scarred by the identification of chemicals as an aid to improved phytoremediation efficacy for sites aloft with Ni contamination. However, environmental impacts, sustainability, and cost-effectiveness need special attention by the industrial plants to embed these strategies practically. On the whole, the study produces unprecedented insights into the improvement of phytoremediation applications and the development of a more sustainable environmental management strategy to address contamination by metals such as heavy metals.*

Keywords: Nickel, SDS, EDDS, Phytoremediation

I. INTRODUCTION

Soil and aquatic environment nickel contamination is subject to severe concern due to persistence and toxicity of the metal (Ali et al., 2021) Major nickel releases in the environment propelling ecosystem health losses and adverse effects on humans such as mining, metallurgy, and waste disposals (Prasad et al., 2021). Remediation techniques prescribed in traditional procedures are generally characterized by exorbitant costs as well as the involvement of invasive ways, which make them typically unsuitable for large-scale contamination scenarios. On the other hand, due to its resilient changing features, the wide distribution of *Alternanthera ficoidea* (L.) R. Br has shown appreciable potential for Ni phytoremediation (Bhat, Abbasi, and Abbasi, 2023). Several traits are witnessed in the species, such as fast growth, development of an extensive root system, and the capability to accumulate high metal concentrations in its tissues, making it an apparent candidate among those for which the adoption of such a milling method would be hard for the upsurge of its phytoremediation potential. However, the augmentation of Ni uptake for *Alternanthera ficoidea* (L.) R.Br. 's remains a constraining task at hand. For this purpose, researchers have indeed explored the use of chemicals to enhance Ni uptake in *Alternanthera ficoidea* (L.) R.Br. Although these chemicals include chelating agents, surfactants, and other chemical amendments to change soil properties and increase the solubility of nickel and its availability for uptake by plants, they would render nickel highly bioavailable in the rhizosphere, aiding its translocation from soil to plant tissue and are considered one of the promising methods for enhancing the phytoremediation efficiency of *A. ficoidea*

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To explore the global potential of Ni accumulation in *A. ficoidea*. the significance of chemical-assisted prospects has taken a central focus by undergoing the characterization of methods and chemical agents based on these Ni uptake mechanisms. Chelator EDTA and surfactant SDS play a key role in investigating Ni uptake mechanisms and determining the type of method-injection, soil applied, or foliar applied-under different concentrations of chemical amendments. A series of controlled greenhouses and field trials will help in identifying optimum chemical amendments and optimize application methods to minimize plant biomass production and maximize Ni removal efficiency. This research study is expected to open up new possible strategies for future phytoremediation of nickel-contaminated sites considered far too often from a cost perspective. In conclusion, the answers to the mechanism of chemical-assisted nickel uptake by *Alternanthera ficoidea* (L.) R.Br. in this research will impact how phytoremediation can be improved and will involve itself in future remediation strategies. Finally, if implemented, these interventions will address the issue of nickel pollution and thus restore ecosystem health and promote sustainable environmental management practices.

II. MATERIALS AND METHOD

1. *A. ficoidea*seedlings were sourced from a reputable nursery. The selected seedlings were of a similar size and health to minimize any given variability in the experiments.
2. Soil Preparation: The soil was collected from a Ni- contaminated site, air and slightly air dried, mixed well, and then sieved to measure <2 mm into homogeneity. It was analysed for Ni content using standard analytical methods.
3. Experimental Design: Pots with *A. ficoidea* species, grown in Ni-contaminated soil, treated with different chemical amendments.
4. Chemical Treatment: Three chemical treatments were under study, and they are as listed:

A- Control Ni-contaminated soil (without chemical treatment).
B- EDDS A treatment (Ni-contaminated soil, amended with Ethylenediaminedisuccinic acid).
C-SDS treatment (Ni-contaminated soil, amended with drag).

5. Experimental Setup:The soil was filled in pots, and planting was done in *A. ficoidea* field put in each document. The pot arrangements were placed in a greenhouse environment, which was under control of temperature, humidity, and light.
6. Plant Growth Studies and Analysis of Ni Uptake:The biomass length and length were taken to study the growth parameters during the given growth period. Plant tissues were harvested; washed, dried however; and digested by standard methods.
7. Statistical Analysis:Data of growth parameters and Ni uptake as well as comparisons of treatments were subjected to analysis of variance to reveal the significant differences among treatments, within which post hoc tests like Duncan's Multiple Range Test were used to differentiate between the specific treatments. Statistical analyses were conducted in certain standard software (SPSS).

III. RESULT AND DISCUSSION

Table 1. represents the effect of Nickel exposure on biomass, length of *A. ficoidea* under 5% SDS. Data represent mean values ± SD of 3 replicates; each experiment was repeated thrice.

Nickel (ppm)	Biomass (g)	Length (cm)
Control	3.65±0.1[a]	11.01±0.61[a]
20	3.41±0.4[ab]	10.77±0.3[a]
40	3.2±0.37[b]	9.3±0.1[ab]
80	3.01±0.3[b]	9.1±0.5[ab]
120	2.3±0.02[cd]	6.7±0.3[de]
160	2.01±0.01[cd]	5.2±0.3[e]
200	1.82±0.5[d]	4.23±0.1[h]

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Table 2. represents the effect of Nickel exposure on biomass, length of *A. ficoidea* under 15% SDS. Data represent mean values ± SD of 3 replicates; each experiment was repeated thrice.

Nickel (ppm)	Biomass (g)	Length (cm)
Control	3.65±0.1a	11.01±0.61a
20	3.21±0.4a	10.07±0.03ab
40	3.03±0.7ab	9.3±0.05b
80	2.84±0.5bc	7.22±0.01d
120	2.23±0.02c	6.37±0.3ef
160	1.9±0.01d	4.2±0.3gh
200	1.62±0.5d	3.87±0.02h

Table 3. represents the effect of Nickel exposure on biomass, length of *A. ficoidea* under 25% SDS. Data represent mean values ± SD of 3 replicates; each experiment was repeated thrice.

Nickel (ppm)	Biomass (g)	Length (cm)
Control	3.65 ± 0.1^{a}	11.01 ± 0.61^{a}
20	3.31 ± 0.2^{a}	8.07 ± 0.4^{b}
40	2.9 ± 0.3^{b}	7.2 ± 0.2^{bc}
80	2.1 ± 0.01^{bc}	5.61 ± 0.3^{de}
120	1.8 ± 0.01^{bc}	4.32 ± 0.02^{ef}
160	1.51 ± 0.02^{bc}	3.3 ± 0.23^{fg}
200	1.3 ± 0.01^{c}	3.01 ± 0.01^{g}

Table 4. represents the effect of Nickel exposure on biomass, length of *A. ficoidea* (under 5% EDTA. Data represent mean values ± SD of 3 replicates; each experiment was repeated thrice.

Nickel (ppm)	Biomass (g)	Length (cm)
Control	3.65 ± 0.1^{a}	11.01 ± 0.61^{a}
20	3.24 ± 0.1^{ab}	10.3 ± 0.08^{ab}
40	3.1 ± 0.3^{ab}	9.7 ± 0.3^{b}
80	2.81 ± 0.5^{b}	8.71 ± 0.06^{bc}
120	2.2 ± 0.52^{cd}	7.92 ± 0.9^{cd}
160	1.91 ± 0.01^{d}	7.5 ± 0.05^{ef}
200	1.73 ± 0.5^{de}	7.15 ± 0.03^{ef}

Table 5. represents the effect of Nickel exposure on biomass, length of *A. ficoidea* under 15% EDTA. Data represent mean values ± SD of 3 replicates; each experiment was repeated thrice.

Nickel (ppm)	Biomass (g)	Length (cm)
Control	3.65 ± 0.1^{a}	11.01 ± 0.61^{a}
20	2.4 ± 0.4^{bc}	9.08 ± 0.3^{b}
40	2.02 ± 0.7^{c}	8.3 ± 0.1^{bc}
80	1.9 ± 0.3^{cd}	7.06 ± 0.4^{c}
120	1.42 ± 0.02^{d}	6.01 ± 0.03^{cde}
160	1.01 ± 0.01^{de}	5.42 ± 0.4^{e}

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200	0.72±0.5^{e}	3.03±0.1^{fg}

Table 6. represents the effect of Nickel exposure on biomass, length of *A. ficoidea* (L.) R.Br.under 25% EDTA. Data represent mean values ± SD of 3 replicates; each experiment was repeated thrice.

Nickel (ppm)	Biomass (g)	Length (cm)
Control	3.65±0.1^{a}	11.01±0.61^{a}
20	2.72±0.09^{b}	6.67±0.19^{b}
40	2.16±0.07^{bc}	5.73±0.47^{cd}
80	1.41±0.1^{d}	4.63±0.02^{d}
120	1.29±0.11^{de}	4.27±0.27^{de}
160	1±0.01^{e}	4.13±0.32^{de}
200	0.74±0.11^{fg}	3.1±0.11^{e}

Table 7. represents the effect of Nickel exposure on biomass, length of *A. ficoidea*under 5% EDDS. Data represent mean values ± SD of 3 replicates; each experiment was repeated thrice.

Nickel (ppm)	Biomass (g)	Length (cm)
Control	3.65±0.1^{a}	11.01±0.61^{a}
20	3.12±0.1^{ab}	8.57±0.55^{b}
40	2.96±0.06^{bc}	7.37±0.39^{bcd}
80	2.72±0.09^{c}	6.67±0.19^{de}
120	2.65±0.08^{d}	5.6±0.35^{e}
160	2.16±0.07^{e}	4.97±0.07^{fg}
200	3.12±0.1^{b}	4.21±0.1^{g}

Table 8. represents the effect of Nickel exposure on biomass, length of *A. ficoidea.* under 15% EDDS. Data represent mean values ± SD of 3 replicates; each experiment was repeated thrice.

Nickel (ppm)	Biomass (g)	Length (cm)
Control	3.65±0.1^{a}	11.01±0.61^{a}
20	3.06±0.1^{ab}	8.30±0.03^{bcd}
40	2.6±0.16^{c}	7.8±0.42^{d}
80	2.02±0.27^{cd}	6.17±0.02^{e}
120	1.82±0.3^{ef}	5.21±0.03^{ef}
160	1.11±0.12^{f}	4.38±0.21^{f}
200	0.93±0.1^{fg}	4.05±0.04^{fg}

Table 9. represents the effect of Nickel exposure on biomass, length of *A. ficoidea* under 25% EDDS. Data represent mean values ± SD of 3 replicates; each experiment was repeated thrice.

Nickel (ppm)	Biomass (g)	Length (cm)
Control	3.65±0.1^{a}	11.01±0.61^{a}
20	1.23±0.08^{bcd}	6.6±0.35^{bc}
40	1.07±0.09^{cd}	3.12±0.1^{de}
80	0.88±0.07^{de}	2.96±0.06^{e}
120	0.81±0.1^{de}	2.72±0.09^{ef}

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160	0.62±0.1^{e}	2.65±0.08^{ef}
200	0.5±0.1^{ef}	2.16±0.07^{f}

- **Effect of Nickel Exposure**: The results showed a dose-dependent response for synthesis in Ni uptake with increasing concentrations significantly decreasing biomass as well as the length of *A.ficoidea* By virtue, certain data sets do not show any changes in biomass amongst members although the corresponding data displayed slight seedling size reduction to an average dimensional extent at certain rates but not necessarily because stem growth was greatly obstructed. Notably, the data clearly reveal that at higher concentrations of Ni (≥120 ppm), a substantial decrease in the consent of biomass and length was observed, reflecting severe plants' resistance for phytotoxic effects (Khan et al. 2014). The finding is consistent with past studies that showed the sensitivity of plants to Ni contamination and its adversely affecting growth parameters.
- **Influence of SDS and EDTA**: According to (Kafle et al. 2022), the phytotoxic influence of Ni on *A. ficoidea* was enhanced by SDS and EDTA. A higher concentration of SDS and EDTA denoted a more drastic decrease in biomass and length, suggesting that the surfactant and chelating roles might confer to the enhancement of Ni bioavailability and endocytic uptake in the plant, an act of fostering its toxicity. This puts into perspective the need to undertake and realize efforts to mitigate heavy metals' impacts on plant growth via the application of soil amendments and practice management (Tables 1, 2,3,4,5,6,7,8, and 9).
- **Comparative Analysis**: In a comparison between SDS and EDTA, it was deduced that EDTA had a stronger impact on the decrease in biomass and length as compared with SDS at similar levels of heavy metal concentration of Ni (Garab 2012). This illustrates the stronger chelating properties of EDTA, promoting Ni solubilisation and uptake by the plant, causing higher toxicity. Differential responses of SDS and EDTA imply the importance of understanding steel mill removal interactions between heavy metals and chelating agents in soil systems.

BIOCHEMICAL PARAMETERS

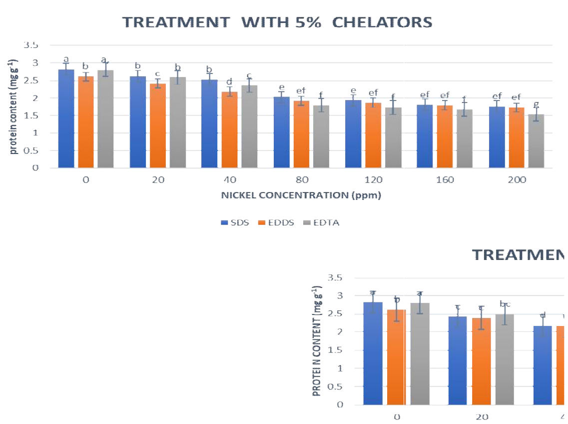

Figure 1. represents the effect of chelators on protein content under Nickel exposure in *Alternanthera ficoidea* (L.) R.Br. Data represent mean values ± SD of 3 replicates; each experiment was repeated thrice. Means with common letters are not significantly different at P ≤ 0.05 according to Duncan's multiple range test (DMRT).

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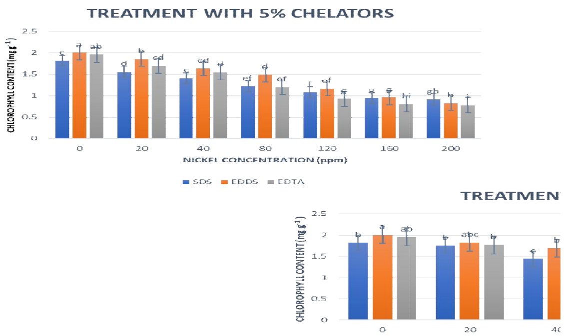

Figure 2. represents the effect of chelators on chlorophyll content under Nickel exposure in *Alternanthera ficoidea* (L.) R.Br. Data represent mean values ± SD of 3 replicates; each experiment was repeated thrice. Means with common letters are not significantly different at P ≤ 0.05 according to Duncan's multiple range test (DMRT).

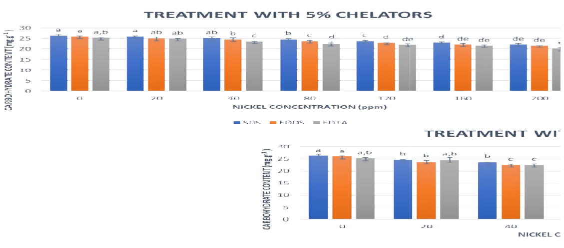

Figure 3. represents the effect of chelators on carbohydrate content under Nickel exposure in *Alternanthera ficoidea* (L.) R.Br. Data represent mean values ± SD of 3 replicates; each experiment was repeated thrice. Means with common letters are not significantly different at P ≤ 0.05 according to Duncan's multiple range test (DMRT).

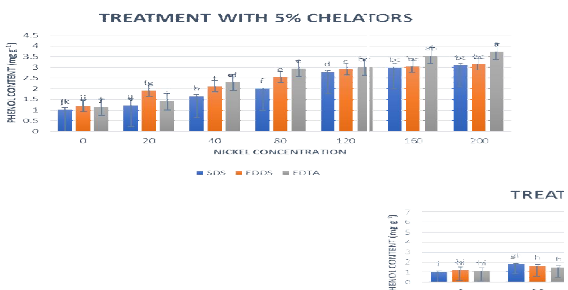

Figure 4. represents the effect of chelators on Phenol content under Nickel exposure in *A. ficoidea* (L.) R.Br. Data represent mean values ± SD of 3 replicates; each experiment was repeated thrice.

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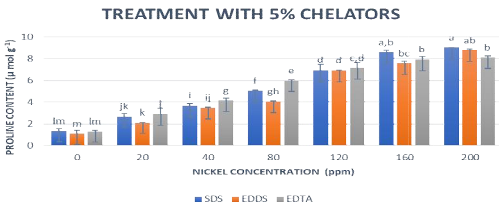

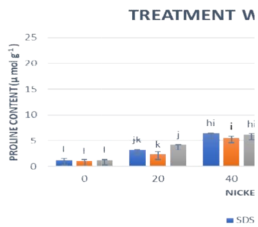

Figure 5. represents the effect of chelators on Proline content under Nickel exposure in *A. ficoidea* (L.) R.Br. Data represent mean values ± SD of 3 replicates; each experiment was repeated thrice.

Plants exhibit a reduction in proteins, chlorophyll, carbohydrates, and various other enzymatic activities under nickel(Ni) stress (Figure 1, Figure 2. Figure 3, Figure 4, Figure 5). These observations provide elementary details regarding the plant growth process; it encompasses physiological and biochemical responses activated under heavy metal stress(Wang, 2022). Through this, we aim to further understand the mechanisms that have condensed or buried any of the metabolic procedures or steps that may have been important to what we call Ni toxicity. These changes, which comprise an amplified level of phenol and proline in the treated versus control plants, are important for the plant's adaptive response in opposition to the stress imposed by various metals (Rasheed, Hassan, and Fahad 2021). They are important chemical modifications for plant defence mechanisms, osmotic regulation, and antioxidative defence.

Protein Degradation: Nickel exposure often brings about decreased protein content in tissues (Figure 1) (Helaoui et al. 2020). This phenomenon is attributable to several factors such as hampering of protein synthesis, increase in proteolysis, and enzyme inhibition. The nickel ions interfere with vital cellular processes like ribosomal functioning and protein folding and ultimately impair protein synthesis (Banerjee and Roychoudhury 2020). Furthermore, Ni-induced stress leads to oxidative stress, triggering the activation of proteolytic enzymes and hence protein degradation. The decline in proteins levels compromises various cellular functions like growth, development, and fighting mechanisms against stress, thus materializing into a major setback for plant survival and productivity (Zia et al. 2021).

Chlorophyll Degradation: Chlorophyll, which performs the ever-important photosynthesis task, is one which is especially responsive to the damage wrought by Ni-dominated degradations (Figure 2) (Baran and Ekmekçi 2021). Nickel ions, curtailed by negative legume output thresholds, detract from chlorophyll biosynthesis in that they noticeably decrease the productivity of enzymes involved in the metabolism of porphyrins like δ-aminolevulinic acid dehydratase and porphyrinogens oxidase (Jiang et al. 2022). Furthermore, Ni-influenced oxidative stress generates a lot of reactive oxygen species (ROS) which decays chlorophyll and causes its disintegration(Ashraf et al. 2023). The lessened chlorophyll throws a monkey wrench into their entire photosynthesis, resulting in less carbon strategy and lower energy production, which is most likely to consign plants to confined growth, compromised biomass accumulation, and hence, reduced stress resistance under Ni stress.

Carbohydrate Depletion: Nickel exposure, most of the time, leads to the draining of carbohydrate reserves in plant tissues (Figure 3) (Aguilar et al., 2023). Carbohydrates are crucial in supporting energy metabolism through being a carbon and energy source for the various physiological processes (Alghannam et al., 2021). Disturbances in photosynthesis and carbohydrate metabolism upon nickel stress all contribute to the imbalance in carbohydrate production and utilization, ultimately resulting in carbohydrate exhaustion (Moy and Nkongolo 2024). Moreover, Ni-induced oxidative stress apparently obscurely seems to degrade carbohydrates through the intensified respiration in association with the activation of carbohydrate-degrading enzymes. The carbohydrate reserve depletion in the plant deconsecrates plant growth and vigour, rendering it increasingly susceptible to environmental stress (Bhattacharya et al., 2022).

Phenol Accumulation: The major function of the phenolic compounds in flavonoids and phenolic acids to accumulate in plants is to act as an important part of the defence response against environmental stresses like heavy metal toxicity (Figure 4) (Tuladhar, Sasidharan, and Saudagar 2021). Nickel induces stress by upregulating the genes of the phenylpropanoid pathway, leading to the subsequent synthesis and accumulation of phenolic compounds (Jahan et al. 2020). Phenolics function as antioxidants to scavenge ROS that arise in Ni-stressed environments, minimizing oxidative damage to cellular constituents (Sachdev et al. 2021). The accumulation of phenolic compounds under Ni exposure forms an important adaptive plant survival strategy for survival under adverse environmental conditions.

Proline Accumulation: Proline is a non-proteinogenic amino acid that acts as a primary osmoprotectants and osmolyte for plants being exposed to various stresses such as heavy metals (Figure 5) (Zulfiqar, Akram, and Ashrov 2019). Forestalled stress through nickel results in the buildup and synthesis of proline by interacting with the overexpression of proline biosynthesis genes (Naji and Hassawi 2021). The proline accumulated is crucial for maintaining cell osmotic balance and stabilization of protein structures to prevent denaturation while under the stress of nickel (Alagoz, Lajayer, and Ghorbanpour 2023). Moreover, the role of proline as a ROS scavenger and a chelating agent for metal ions results in lowering the degree of oxidative damage and metal toxicity in the plant tissues (Badiaa and Topçuoğlu 2020). The enhancement of proline levels with the presence of nickel is a manifestation of the plant's adaptation to deal with osmotic stress and oxidative damage, thereby endowing an increased level of tolerance against stresses and chances of survival under hazardous contaminated conditions.

IV. CONCLUSION

This study was designed to investigate how chelating agents affect the purposeful use of chemical agents that may enhance the bioavailability of nickel in *Alternanthera ficoidea* (L.) R.Br. in order to increase the phytoremediation efficacy. In controlled studies and field trials, chelating agents (like EDTA) and surfactants (like SDS) were used, respectively. The measured research concludes that the catchy jargon of chemical amendments, namely EDTA and SDS, increased the uptake of Ni by the *Alternanthera ficoidea* (L.) R.Br. Even more eye-widening is the fusion of treatments ecological and combined, since EDTA and SDS combined produced the highest accumulation in plant tissues. This implies that chemical amendments should produce, if well selected, an increase in bioavailability to plants and thus aid to attain greatly high phytoremediation efficiency. The outcomes from this study imply that future efforts aimed at efficient and sustainable redevelopment of Ni-contaminated sites could be supported. If we are to have views that hold that they can design phytoremediation programs using these conclusions aimed at swishing Ni pollution and raise the health of ecosystems, support in real-world experimental work for further understanding should come. In conclusion, a technique developed that in-hence can be successful in combining the potential for the best alternative for the immobilizing nickel plays a very important role in this phytoremediation process. Extra research that strengthens the applications of such bulky-pharmaceutical amendments and tests that are highly represented at the desk study should further iterate our roadmap toward phytoremediation and environmental management.

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Conflict of interests

The authors declare that there is no competing interest.

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