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ORIGINAL ARTICLE

Rising temperatures decrease rare earth element bioavailability and ecological risk in coastal sediments

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Abstract
Rare earth elements are sedimentary pollutants of increasing health concern, yet the effect of global warming on their bioavailability and toxicity is unknown. To test this, we applied the diffusive gradients in thin films technique to assess the bioavailability of 15 rare earth elements, including lanthanides and yttrium, in sediments at temperatures ranging from 0 to 40 °C. We modeled the ecotoxicological risk to aquatic organisms using the species sensitivity distribution–probabilistic risk assessment–inclusion–exclusion principle. Results show that the bioavailability of all rare earth elements decreases by 40% to 70% as temperature increases from 0 to 40 °C, indicating reduced mobility and enhanced sediment adsorption. Similarly, the calculated ecotoxicological risk is reduced from 1.75 to 0.08%. This is the first evidence of temperature-driven attenuation of rare earth element risk in sediments, suggesting that global warming should decrease the toxicity of some rare earth elements.

Keywords Rare earth elements · Bioavailability · Ecotoxicological risk · Temperature effects · Diffusive gradients in thin films · Coastal sediments

Introduction

Rare earth elements, including lanthanides and yttrium (Y), are critical components in many modern technologies due to their unique chemical properties [1–3]. These elements are widely used in electronics, renewable energy technologies, and various industrial processes [1, 2, 4, 5]. However, their increasing production and utilization have led to their release into the environment, where they can accumulate in soils, water bodies, and sediments [2, 6, 7]. Coastal sediments, in particular, serve as key sinks for rare earth elements and may pose ecological risks to aquatic ecosystems [2, 8, 9]. Yet, the ecological implications of rare earth elements in these environments remain insufficiently understood.

Climate change introduces an additional layer of complexity, particularly in coastal zones, which are both biodiversity hotspots and human activity hubs [10–14]. Rising temperatures are expected to alter the environmental behavior of pollutants, including rare earth elements, by affecting processes such as speciation, mobility, and bioavailability [15–17]. However, the specific effects of temperature on rare earth elements bioavailability and associated ecotoxicological risks to aquatic organisms remain largely unexplored.

The ecotoxicological risks of rare earth elements are directly related to their bioavailable fractions, which are influenced by sediment characteristics and environmental conditions such as pH, redox potential, and temperature [9, 18–21]. Among these, temperature is particularly significant in the context of global climate change. Despite increasing recognition of rare earth elements as emerging contaminants, few studies have addressed how temperature fluctuations impact their bioavailability in marine sediments.

This study addresses this gap by applying the diffusive gradients in thin films (DGT) technique to assess the bioavailability of 15 rare earth elements (yttrium [Y], lanthanum [La],

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cerium [Ce], praseodymium [Pr], neodymium [Nd], samarium [Sm], europium [Eu], gadolinium [Gd], terbium [Tb], dysprosium [Dy], holmium [Ho], erbium [Er], thulium [Tm], ytterbium [Yb], and lutetium [Lu]) in the coastal sediments of Daya Bay under a temperature gradient (0 °C – 40 °C). The objective is to quantify the relationship between temperature and rare earth element bioavailability and to evaluate the associated ecotoxicological implications. These findings will contribute to understanding pollutant dynamics under climate change and support the development of effective environmental management strategies.

Experimental

This study investigated the effects of rising temperatures on the bioavailability and ecological risks of rare earth elements in coastal sediments. Surface sediment samples collected from 24 sites in Daya Bay were subjected to temperature-controlled laboratory experiments. The bioavailable fractions of rare earth elements were determined using the DGT technique. Ecotoxicological risks were evaluated using an integrated risk assessment model (referred to as the SPI model), which combines species sensitivity distribution (SSD), probabilistic risk assessment (PRA), and the inclusion–exclusion principle (IEP) (Fig. S3). Detailed descriptions of the sampling procedures, sediment particle size analysis, experimental setup, DGT deployment and retrieval, laboratory analyses, SPI model procedures, model calculations, and statistical methods are provided in the Supplementary Material.

Results and discussion

Temperature effect on the bioavailability of rare earth elements

Details of the particle size distribution of surface sediment samples are provided in supplementary material (section S1.3). This study applied DGT technology to analyze the variation in bioavailability of rare earth elements in Daya Bay sediments with temperature changes. The bioavailability of these rare earth elements progressively decreased as the temperature increased from 0 to 40 °C (Table 1, Table S2, Fig. S4). This trend was evident across all analyzed rare earth elements, indicating that temperature was a key environmental factor affecting their bioavailability.

To quantitatively assess this trend, a quadratic polynomial Eq. (1) was fitted to the experimental data.

$$y = a + bx + cx^2 \quad (1)$$

where y represents the bioavailability of a specific rare earth element, x is the temperature (°C), and a, b, and c are the fitting constants (Table 1, Table S2, Fig. S4). The fitting results showed that all rare earth elements' equations had high R^2 values ($R^2 > 0.94$), demonstrating a strong correlation between temperature and rare earth element bioavailability (Table 1). These high R^2 values confirmed the reliability of the quadratic model in predicting changes in rare earth elements'bioavailability under varying temperature conditions. These findings further confirmed that, with global warming and rising ocean temperatures, the rare earth elements in Daya Bay coastal sediments became more stable, with decreased bioavailability. This reduction in bioavailability suggests a lower potential for rare earth element uptake by benthic organisms, which may alter biogeochemical cycling and trophic transfer within the ecosystem. This trend might have been related to temperature-induced changes in chemical equilibrium within the sediments, such as alterations in the adsorption–desorption behavior of rare earth elements at the sediment–water interface. Additionally, temperature changes might have affected the chemical composition of pore water in sediments, further altering the solubility and biological availability of rare earth elements.

Table 1 Regression equations and coefficients of determination (R^2) for the linear relationships between diffusive gradients in thin films (DGT)-measured bioavailability and temperature (0 to 40 °C) of rare earth elements in Daya Bay sediments

Element	R^2
Y	0.98
La	1.00
Ce	1.00
Pr	0.97
Nd	0.99
Sm	0.98
Eu	0.96
Gd	0.99
Tb	0.94
Dy	0.98
Ho	0.96
Er	0.96
Tm	0.97
Yb	0.97
Lu	0.96

Importantly, this study provides the first quantitative evidence that increasing temperature significantly reduces the combined probabilistic ecotoxicological risk of rare earth elements in sediments, as assessed by in situ DGT techniques. Specifically, the risk probability declined sharply from 1.75 at 0 to 0.08% at 40 °C, highlighting temperature as a key modulator of ecological risk under climate warming scenarios.

Furthermore, these findings have practical implications for environmental risk assessment and management. Understanding the temperature dependence of rare earth element bioavailability can help predict the mobility and ecological impact of rare earth elements under future climate change scenarios. Therefore, such knowledge is crucial for regulatory frameworks related to rare earth element contamination and for developing strategies to mitigate potential ecological risks in coastal ecosystems.

Temperature effect on the ecotoxicological risk of rare earth elements to aquatic biota

The risk probabilities for each rare earth element to aquatic biota at temperatures of 0° C, 10, 20, 30, and 40 °C are detailed in Fig. S5. This figure illustrates a gradual decrease in risk probability with increasing temperature, which is further depicted in Table 2, Table S4, and Fig. S6. The ecological risk trends for these elements could be fitted using a linear model, while the remaining rare earth elements also showed a decreasing trend. This reduction in risk probability was likely due to increased adsorption of rare earth elements at the sediment–water interface with higher temperatures, which reduced their solubility and bioavailability. Elevated temperatures may have also altered the chemical equilibrium in sediment pore water, such as reducing the ion exchange capacity of rare earth elements or modifying their interactions with organic matter and inorganic particles. Additionally, temperature-driven changes in microbial activity and redox conditions within sediments may have influenced rare earth element speciation, leading to enhanced precipitation or complexation, further lowering their bioavailable fractions. These changes likely further decreased rare earth element solubility and bioavailability, thereby reducing their ecological risk. These findings underscore the critical role of temperature as an environmental variable in regulating rare earth element bioavailability and ecological risk, highlighting its importance for predicting the environmental behavior and potential impacts of these elements under climate change scenarios. From a practical perspective, these results provide valuable insights for environmental risk assessments and regulatory decision-making. By integrating temperature-dependent risk models, policymakers and environmental managers can better anticipate potential changes in rare earth element contamination risks and implement adaptive strategies to protect aquatic ecosystems in a warming climate.

Table 2 Regression equations and coefficients of determination (R^2) for the linear relationships between ecotoxicological risk of individual rare earth elements and temperature (0 to 40 °C) of rare earth elements in Daya Bay sediments

Element	R^2
Y	0.11
La	0.19
Ce	0.45
Pr	0.13
Nd	0.45
Sm	0.75
Eu	0.92
Gd	0.88
Tb	0.21
Dy	0.73
Ho	0.91
Er	0.94
Tm	0.91
Yb	0.87
Lu	0.82

Combined ecotoxicological risk decreases with temperature

The combined probabilistic ecotoxicological risk of 15 rare earth elements to aquatic biota in Daya Bay sediments was assessed at various temperatures (0 °C, 10, 20, 30, and 40 °C), yielding risk probabilities measured at 1.74, 1.01, 0.34, 0.68, and 0.08%, respectively (Fig. 1; Figs. S7–S9). This clear temperature-dependent decline in combined risk underscores the significant role of thermal conditions in modulating sediment-associated rare earth element toxicity at the ecosystem level. The observed trend of decreasing risk with increasing temperature suggests that higher temperatures may enhance the adsorption of rare earth elements to sediment particles, particularly finer sediments with higher silt and clay content, thereby reducing their bioavailability (Fig. 2; Fig. S2).

These findings highlight the significance of temperature as a modulating factor in the ecological risk assessment of rare earth elements. Given that finer sediments typically exhibit greater adsorption capacities for pollutants, the predominance of silt in the studied sediments (22.17 to 79.97%) may contribute to the observed decrease in rare earth element bioavailability at elevated temperatures. Elevated temperatures could potentially alter the physical and chemical interactions within sediments, leading to reduced bioavailability and ecological risk. Specifically, increasing temperature may promote stronger binding of rare earth elements with sedimentary organic matter and iron or manganese oxides, reducing their mobility. Moreover, temperature-driven changes in sediment characteristics, particularly in finer-grained sediments, may further influence the retention and desorption dynamics of rare earth elements. Furthermore, temperature-induced shifts in microbial metabolism and enzymatic activity may influence biogeochemical cycling processes, indirectly impacting the speciation and bioavailability of rare earth elements.

This insight emphasizes the importance of accounting for temperature effects in environmental models, particularly under scenarios of global climate change, which may influence the mobility and toxicity of rare earth elements in marine ecosystems. Considering the diverse grain size distribution of the sediment samples—where clay ranged from 2.49 to 26.99%, silt from 22.17 to 79.97%, and sand from 2.42 to 75.34%—future studies should further explore how

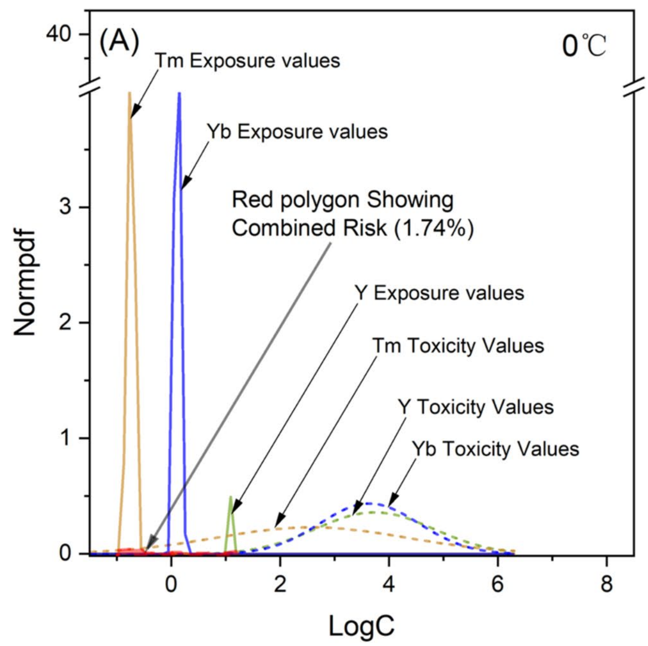

Fig. 1 Combined probabilistic ecotoxicological risk of rare earth elements to aquatic biota in Daya Bay sediments at temperatures 0 °C (**A**) and 40 °C (**B**). LogC: base-10 logarithm of exposure/toxicity concentration; Normpdf: normal probability density function

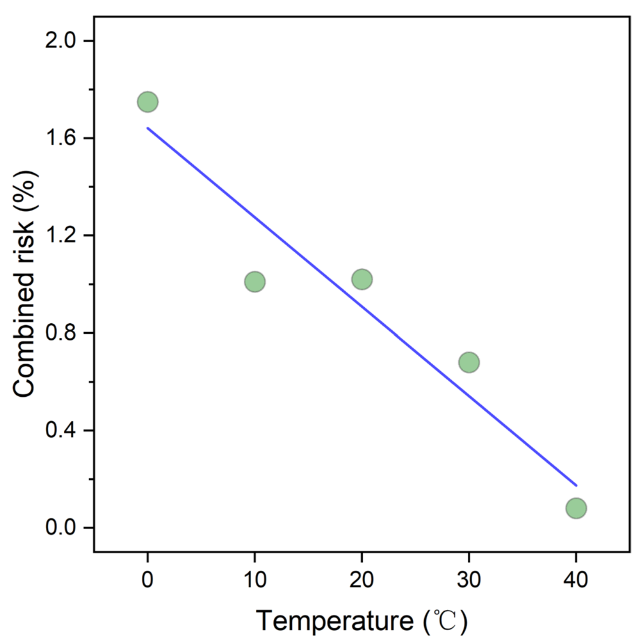

Fig. 2 Relationship between combined risk and temperature. The results illustrate a clear decrease in combined probabilistic ecotoxicological risk with rising temperature ($y = 1.642–0.037\ x$, $R^2 = 0.89$)

temperature interacts with sediment grain size in influencing the bioavailability of rare earth elements. From an environmental management perspective, understanding these mechanisms is crucial for refining risk assessment frameworks and developing adaptive mitigation strategies. Future studies should integrate temperature-dependent adsorption models and biogeochemical simulations to improve predictions of rare earth element behavior under changing climatic conditions.

Conclusion

This study demonstrates that rising temperatures reduce the bioavailability of 15 rare earth elements in coastal sediments, enhancing their adsorption to sediment particles and lowering their mobility. Consequently, the ecotoxicological risk of rare earth elements to aquatic biota decreases with increasing temperature. These findings highlight the critical role of temperature in modulating the ecological risk of rare earth elements and underscore the need for incorporating temperature effects into environmental risk assessments. As global temperatures rise, understanding these interactions will be essential for developing effective management strategies and regulatory guidelines for rare earth element contamination in marine environments.

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Author contributions Yang-Guang Gu contributed to the conceptualization, methodology, software development, validation, formal analysis, investigation, resources, data curation, writing of the original draft, review and editing of the manuscript, visualization, supervision, project administration, and funding acquisition. Yanpeng Gao contributed to validation, data curation, and funding acquisition. Richard W. Jordan contributed to data curation and writing—review and editing. Shi-Jun Jiang contributed to data curation and writing—review and editing. Hong-Hui Huang contributed to investigation.

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Data availability Data are available from the corresponding author upon request.

Code availability The code is available upon request from the corresponding author.

Declarations

Competing interests The authors declare no competing interests.

Ethics approval Not applicable; no human participants or animal experiments involved.

References

1. Cheisson T, Schelter EJ (2019) Rare earth elements: Mendeleev's bane, modern marvels. Science 363:489–493. https://doi.org/10.1126/science.aau7628
2. Gu YG, Wang XN, Wang ZH, Jordan RW, Jiang SJ (2023) Rare earth elements in sediments from a representative Chinese mariculture bay: characterization, DGT-based bioaccessibility, and probabilistic ecological risk. Environ Pollut 335:122338. https://doi.org/10.1016/j.envpol.2023.122338
3. Wang P, Yang YY, Heidrich O et al (2024) Regional rare-earth element supply and demand balanced with circular economy strategies. Nat Geosci 17:94–102. https://doi.org/10.1038/s41561-023-01350-9
4. Gu YG, Ma C, Jordan RW, Jiang SJ, Wang M (2024) Nutrients and rare earth elements in surface sediments of Hongze Lake (China) using the DGT technique: spatial distribution pattern and probabilistic risk. ACS EST Water 4:2247–2258. https://doi.org/10.1021/acsestwater.4c00058
5. Morin-Crini N, Lichtfouse E, Liu G, Balaram V et al (2022) Worldwide cases of water pollution by emerging contaminants: a review. Environ Chem Lett 20:2311–2338. https://doi.org/10.1007/s10311-022-01447-4
6. Liu QY, Shi HD, An YF et al (2023) Source, environmental behavior and potential health risk of rare earth elements in Beijing urban park soils. J Hazard Mater 445:130451. https://doi.org/10.1016/j.jhazmat.2022.130451
7. Pereto C, Baudrimont M, Coynel A (2024) Global natural concentrations of rare earth elements in aquatic organisms: progress and lessons from fifty years of studies. Sci Total Environ 922:171241. https://doi.org/10.1016/j.scitotenv.2024.171241
8. Gu YG, Gao YP, Huang HH, Wu FX (2020) First attempt to assess ecotoxicological risk of fifteen rare earth elements and their mixtures in sediments with diffusive gradients in thin films. Water Res 185:116254. https://doi.org/10.1016/j.watres.2020.116254
9. Gu YG, Wang YS, Jordan RW, Su H, Jiang SJ (2023) Probabilistic ecotoxicological risk assessment of heavy metal and rare earth element mixtures in aquatic biota using the DGT technique in coastal sediments. Chemosphere 329:138592. https://doi.org/10.1016/j.chemosphere.2023.138592
10. Bellard C, Bertelsmeier C, Leadley P, Thuiller W, Courchamp F (2012) Impacts of climate change on the future of biodiversity. Ecol Lett 15:365–377. https://doi.org/10.1111/j.1461-0248.2011.01736.x
11. Wijffels S, Roemmich D, Monselesan D, Church J, Gilson J (2016) Ocean temperatures chronicle the ongoing warming of earth. Nat Clim Change 6:116–118. https://doi.org/10.1038/nclimate2924
12. Macreadie PI, Anton A, Raven JA et al (2019) The future of blue carbon science. Nat Commun 10:3998. https://doi.org/10.1038/s41467-019-11693-w
13. Blasiak R, Wynberg R, Grorud-Colvert K et al (2020) The ocean genome and future prospects for conservation and equity. Nat Sustain 3:588–596. https://doi.org/10.1038/s41893-020-0522-9
14. Rounce DR, Hock R, Maussion F et al (2023) Global glacier change in the 21st century: Every increase in temperature matters. Science 379:78–83. https://doi.org/10.1126/science.abo1324
15. Doney SC, Ruckelshaus M, Emmett DJ et al (2012) Climate change impacts on marine ecosystems. Annu Rev Mar Sci 4:11–37. https://doi.org/10.1146/annurev-marine-041911-111611
16. Kang B, Pecl GT, Lin LS et al (2021) Climate change impacts on China's marine ecosystems. Rev Fish Biol Fisher 31:599–629. https://doi.org/10.1007/s11160-021-09668-6
17. Trégarot E, D'Olivo JP, Botelho AZ et al (2024) Effects of climate change on marine coastal ecosystems—a review to guide research and management. Biol Conserv 289:110394. https://doi.org/10.1016/j.biocon.2023.110394
18. Khan AM, Bakar NKA, Bakar AFA, Ashraf MA (2017) Chemical speciation and bioavailability of rare earth elements (REEs) in the ecosystem: a review. Environ Sci Pollut R 24:22764–22789. https://doi.org/10.1007/s11356-016-7427-1
19. Piarulli S, Hansen BH, Ciesielski T et al (2021) Sources, distribution and effects of rare earth elements in the marine environment: Current knowledge and research gaps. Environ Pollut 291:118230. https://doi.org/10.1016/j.envpol.2021.118230
20. Trapasso G, Chiesa S, Freitas R, Pereira E (2021) What do we know about the ecotoxicological implications of the rare earth element gadolinium in aquatic ecosystems? Sci Total Environ 781:146273. https://doi.org/10.1016/j.scitotenv.2021.146273
21. Arciszewska Ż, Gama S, Leśniewska B et al (2022) The translocation pathways of rare earth elements from the environment to the food chain and their impact on human health. Process Saf Environ 168:205–223. https://doi.org/10.1016/j.psep.2022.09.056