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Impact of Rare Earth Elements in sediments on the growth and photosynthetic efficiency of the benthic plant *Myriophyllum aquaticum*

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Abstract

Purpose Rare Earth Elements (REEs) are becoming more present in our everyday life. With this work, we aimed to study and compare the toxic responses of the REEs lanthanum (La), cerium (Ce), neodymium (Nd), and gadolinium (Gd) to the macrophyte *Myriophyllum aquaticum*. The scope was to evaluate if these elements trigger a response on the photosynthetic system (PSII), which causes inhibition of the growth rate of the plant.

Methods We measured the fluorescence yield by pulse-amplitude-modulated chlorophyll fluorometer (PAM) which enabled simultaneous high-resolution fluorescence measurements of the whorls daily for the whole duration of the test (10 days) and fresh weight change (FWC) at the end of the test.

Results Our findings suggest that La significantly decreased FWC at the highest concentration (500 mg kg^{-1}) but did not cause any significant effects on the fluorescence yield. Ce and Nd significantly decreased the chlorophyll fluorescence between days 2 and 4, and after that the yield was not significantly different with respect to the control. Of all the REEs tested in this study, Gd showed the most negative effect as the whorls exhibited chlorosis/necrosis and the fresh weight at the end of the test decreased significantly compared to the same plant at day 0. The yield of *M. aquaticum* showed time-dependent effects for Gd at the highest concentration.

Conclusion Gd was the most toxic REE, strongly affecting both the yield and FWC. The measurement of the fluorescence yield of the PSII is a useful effect observation and of high environmental importance. The difference in sensitivity between the functional and growth endpoints may give hints about the mode of action of contaminants to aquatic plants.

Keywords Rare earth elements · Aquatic plant · Chlorophyl fluoresence · Fresh weight change

1 Introduction

Rare earth elements (REE) are a group of 17 metals, including the lanthanide series and the elements scandium (Sc), and yttrium (Y). They are naturally present in the environment, constituting a chemical group sharing similar characteristics (Feng et al. 2013). REEs are not individual native metals but occur together in numerous ore/accessory minerals as minor or major constituents. Though they are termed "rare," REEs are found in soils worldwide (Hu et al. 2006). The classification of "rare" solely refers to the fact that they are not found on large ores like silver and gold (Carpenter et al. 2015). REE are not widely known to the public, although they are becoming a highly valuable commodity because of their increasing use in emerging technologies, especially renewable energy (Lambert and Ledrich 2014). REEs have become essential in high—and green technologies (e.g., wind turbines, solar panels, electric vehicles), but their supply capacity is below the increasing demand. Thus, REEs are considered critical raw materials (European Commission 2011). Cerium (Ce) is one of the most abundant elements among REEs, displaying a wide range of human applications. Chloride and nitrate forms of Ce and lanthanum (La) are the main constituents of REE microfertilizers used in China since the 1970s to improve crop yield (Hu et al. 2004). In addition, REEs utilization in agriculture, animal husbandry, and medicine are well known

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(Tommasi and d'Aquino 2017). The presence of anthropogenic REE in aquatic systems was first demonstrated in 1996 with the release of gadolinium (Gd) contained in contrast agents used in magnetic resonance imaging (MRI) (Bau and Dulski 1996). There is limited data on other REEs available, notably on neodymium (Nd) (Blinova et al. 2020). However, some data indicate that their presence is increasing (Sa'eed and Mahmoud, 2014). Even though REEs exhibit similar chemical and physical properties, the toxicity of individual REEs can vary depending on several factors. The solubility of REE compounds in water influences their bioavailability and potential toxicity, andalthough REEs have received increased attention recently, little is known about their effects on the aquatic biome and aquatic organisms.

Aquatic macrophytes play an important functional and structural role in freshwater ecosystems by influencing the carbon and nutrient cycle, forming primary productivity, and providing food and habitat for other organisms. Especially in oligotrophic ponds and lakes, streams, and wetland communities, submerged, floating, and emersed macrophyte species are essential to harbor diverse organism communities (Wetzel 2001). Regardless of the causes, any significant reduction in macrophytes can be expected to strongly impact the whole ecosystem (Lewis 1995). *Myriophyllum spp*. is widely considered a suitable bioassay plant model for the detection of herbicidal activity (Forney and Davis 1981; Paterson and Wright 1987; Hanson et al. 2002; Turgut 2005) and has been used as a potential candidate for pesticide toxicity, as a dicot- and sediment-rooting macrophyte. The accumulation of REEs in water is restricted by multiple mechanisms, such as the absorption of hydroxides of polyvalent metals (Fe, Mn, Co) and phosphorus compounds (Borzenko et al. 2017). The ability of lanthanides to form complexes with inorganic and organic ligands controls their flow in natural processes.

The mode of action of REEs in *Myriophyllum aquaticum* is not completely understood. These elements cause leaf chlorosis and abnormal growth responses in *Arabidopsis thaliana*, typical of many plant growth regulators (Ma et al. 2013). The loss of photosynthetic pigments is also a common response of plants which has been observed after metal treatment in various species of *Myriophyllum* genus such as *M. heterophyllum* (Sivaci et al. 2008), *M. spicatum* (Grudnik and Germ 2010) and *M. alterniflorum* (Delmail et al. 2011). However, it is indicated that REE could greatly increase the activities of the photosynthetic system II (PSII) –protein complex in wheat (Fashui 2002). Chlorophyll fluorescence analyses, as one of the most sensitive parameters of plant photosynthetic capacity, showed that terbium inactivated the performance of reaction centers in PSII, causing the decrease in the photosynthetic capacity on *Lemna minor* (Alp et al. 2023). As monitoring of the photosynthetic status over time for every single exposed plant is time-consuming, the pulse-amplitude-modulated chlorophyll fluorometer (PAM) enables simultaneous high-resolution fluorescence measurements of whole plants and plant sections in multiwell plates in parallel. Few studies were done using this method to evaluate the effect of REEs on different plant models (Gomez-Garay et al. 2014; Goecke et al. 2015).

The aim of this study was to compare the effects of La, Ce, Nd, and Gd on the photosynthetic efficency and evaluate the responses of the macrophyte *M. aquaticum* to the phyto-toxicity induced by these REEs. It is hypothesized that these elements trigger a response on the PSII, which causes inhibition of the growth rate of the plant. This hypothesis was tested through observation parameters of the terminal measure of the fresh weight change and the non-invasive measure of the photosynthetic status of the exposed macrophytes over time.

2 Materials and methods

2.1 Maintenance and pre-culture preparation of *Myriophyllum aquaticum*

The stock culture of *M. aquaticum* (parrot feather) was obtained from the German Federal Institute of Hydrology (BfG, Koblenz, Germany). Non-axenic pre-cultures of *M. aquaticum* were grown vegetatively in artificial sediment following the instructions for toxicity determination on the ISO 16191 2013. The sediment was saturated with modified Steinberg medium (DIN EN ISO 20079 2006) containing 350 mg l^{-1} KNO_3; 295 mg l^{-1} Ca $(NO_3)_2$ •$4H_2O$; 90 mg l^{-1} KH_2PO_4; 12.6 mg l^{-1} K_2HPO_4; 100 mg l^{-1} $MgSO_4$•$7H_2O$; 120 µg l^{-1} H_3BO_3; 180 µg l^{-1} $ZnSO_4$•$7H_2O$; 44 µg l^{-1} Na_2MoO_4•$2H_2O$; 180 µg l^{-1} MnCl2•$4H_2O$; 760 µg l^{-1} $FeCl_3$•$6H_2O$; 1500 µg l^{-1} EDTA Disodium salt •$2H_2O$, with pH = 5.5 ± 0.2, under defined growth conditions in a growth chamber. The artificial sediment consisted of 74% quartz sand (average grain size 170 µm), 20% kaolinite clay, 5% peat, and 1% calcium carbonate (OECD 218 2004). The pre-culture was maintained in glass pots at 24 ± 1 °C with a light exposure of 16:8 h light/dark and a light intensity of 80 µE m^{-2} s^{-1}. A new pre-culture was prepared biweekly from the head and the three whorls below from 3- to 4-week-old *M. aquaticum* plants.

2.2 Spiking of sediment

The spiking solution for the artificial sediment (OECD 218 2004) was prepared as follows: Ce, Nd, La and Gd-salts ($CeCl_3$•$7H_2O$, $NdCl_3$•$6H_2O$, $GdCl_3$•$6H_2O$ and $LaCl_3$•$7H_2O$, 99% purity; Sigma Aldrich) were dissolved in modified Steinberg medium and added to the sediments to reach a final concentration of 50, 250, and 500 mg kg^{-1} dry weight. 100 mg kg^{-1} 3.5-dichlorophenol (DCP, 97% purity; Sigma

Aldrich) and 700 µg kg^{-1}diuron (3-(3.4-Dichlorphenyl)-1.1-dimethyl-harnstoff, 98% purity; Sigma Aldrich) were used as positive controls and acetone was used as the solvent solution for DCP. The spiked sediments were conditioned statically in glass pots with the growth media solution as supernatant in the ratio: 1 part (mass) mixed sediment plus a maximum of 0.5 parts (volume) nutrient solution and sealed with Parafilm® "M" (American National Can, Chicago, USA) for one week under exposure conditions of 24 ± 1 °C and 80 µmol m^{-2} s^{-1} of continuous light, prior to use in the bioassay.

2.3 Sediment contact assay

A sediment contact test with *M. aquaticum* (Feiler et al. 2004) was adapted for application in six well multiwell plates (VWR International, 734–1599). Each well was half-filled (10 g) with the respective exposure sediment for the miniaturized sediment contact assay. Sediment in the wells was water saturated with modified Steinberg medium if necessary (usually every 3–5 days) and the stem of the *M. aquaticum* whorl was inserted into the sediment (one whorl per well). Before whorls from 3- to 4-week-old *M. aquaticum* were exposed to the sediment, the fresh weight of each whorl was determined. Only whorls with a fresh weight between 10 and 20 mg were used for experiments (ISO 16191 2013). For the test, all six wells of one plate had the same exposure sediment acting as replicates. The plates were incubated under controlled standardized conditions at 24 ± 1 °C, under continuous lighting (neutral white), for 10 days. Light intensity was homogeneous within the range of 60 µmol m^{-2} s^{-1} to 75 µmol m^{-2} s^{-1}. After 5 days of exposure, the modified Steinberg medium was added to the sediment in each slot to accommodate for evaporation loss. At the end of the 10 days of exposure, the plants (whorl, roots, and shoots) were removed from the sediments, rinsed in Steinberg medium, pat dried and weighted. DCP and diuron were used as a positive control for the growth and chlorophyll fluorescence, respectively, on the same plate. Each experiment was repeated at least twice.

2.4 Measurement of the photosynthetic yield

Measurements of the photosynthetic yield were carried out as described by Küster and Altenburger (2007) in the six-well plates using a maxi-imaging pulse-amplitude-modulated chlorophyll fluorometer (I-PAM) (Walz, Effeltrich, Germany). The I-PAM employs pulse-modulated measuring light for fluorescence excitation plates, which were measured every 24 h for the whole duration of the test (10 days). Hereby, the maximum fluorescence yield (Fm′) is measured under actinic light during a saturation pulse. The momentary fluorescence yield (F) is determined between the pulses. The fluorescence parameter Y(II) was calculated according to Schreiber et al. (2011). After the preparation of the multiwell plates, the effective quantum yield of the PS II (Y(II)) of each whorl in the multiwell plate was determined via I-PAM measurement. A circle enclosing the entire whorl was used as the area of interest. During the exposure time of 10 days, the Y(II) of each whorl was determined every 24 h. The measurements were performed during the application of saturation light pulses to samples adapted to an actinic illumination of 80 µE m^{-2} s^{-1} every 30 secs for ten measurements. A circle enclosing the entire whorl was used as the area of interest. All whorls of the six-well plate were analyzed, and only the last six measurements per slot were used for estimating the median Y(II) at each time point, as a dark-adapted sample is important. The following measurement settings were used: pulse-modulated measuring light (ML) = 1, photosynthetically active radiation (PAR) = 35, gain = 2, actinic light (AL) = 3, saturation pulse = 10.

2.5 Inhibitory effects calculation

In the sediment contact assay, two parameters were considered: the inhibition of fresh weight change (FWC) and the inhibition of Y(II) in *M. aquaticum* whorls exposed to artificially spiked sediments in comparison to whorls grown under negative and positive control conditions. The FWC (in%) was calculated from the mass gain in fresh weight on day 10 of exposed *M. aquaticum* (Eq. 1).

$$FWC = \left(\frac{m_{d10} - m_{d0}}{m_{d0}} \right) x\,100, \tag{1}$$

where m_{d0} is the fresh mass of a single plant at day 0 and m_{d10} is the fresh mass of a single plant at day 10.

To calculate the inhibitory effects of REE on the FWC of the whorls (I_{FWC} in %), the FWC of exposed whorls (FWC_T) and of the control whorls (FWC_C) were calculated according to Eq. 2.

$$I_{FWC} = \left(1 - \frac{FWC_T}{FWC_C} \right) x\,100 \tag{2}$$

Similarly, the inhibitory effect ($I_{PSII,\,dx}$ in%) of spiked sediments to the Y(II) of *M. aquaticum* whorls at day x (dx) was calculated. (Eq. 3) The Y(II) of treated whorls ($Y(II)_{T,\,dx}$) and of the control whorls ($Y(II)_{C,\,dx}$) at dx is the average of the last six measurements from the I-PAM (data not shown).

$$I_{PSII,dx} = \left(1 - \frac{Y(II)_{T,dx}}{Y(II)_{C,dx}} \right) x\,100 \tag{3}$$

The growth performance of the plants in the control sample must meet a minimum mean growth rate of 0.090 (ISO 16191 2013).

2.6 Statistical analysis

The data presented are the mean of at least three different replicates. All analyses were run separately for each REE evaluated. One-way ANOVA followed by Dunnett's multiple comparisons test was performed using GraphPad Prism version 9.0 (GraphPad Software, San Diego, CA, United States). Statistical significance was accepted at $p < 0.01$ (*), $p < 0.001$ (**) and $p < 0.0001$ (***).

3 Results

3.1 Plant growth

The FWC of *M. aquaticum* whorls in the negative control sediment showed a significant gain of more than double the fresh weight during exposure in all sequential 4 experiments (see Fig. 1a–d). The FWC of the whorls within the control varied between 110 and 170% at the end of the 10 day experiment. Whorls treated with Ce and Nd did not show a significant FWC at any concentrations tested. La induced a significant decrease on FWC (around 28%) at the highest concentration, while the lowest concentrations did not induce any changes compared to the respective control. Gd showed the highest effect of all REEs tested at 250 and 500 mg kg^{-1}. At 500 mg Gd kg^{-1}, all whorls had entered a visually detectable state of chlorosis/necrosis, with a decrease in FWC of 101% compared to the control. As a result, the mean fresh weight of the whorls at this treatment decreased from 28 mg at the onset of the experiment to 27 mg at the end of the exposure. When treated with 250 mg kg^{-1}, the FWC of the whorls decreased by 50% compared to the respective control. At 50 mg kg^{-1} the FWC was not significantly different. Acetone, used as a suitable solvent for DCP to spike the sediment, did not affect the growth rate (SM, Table 1).

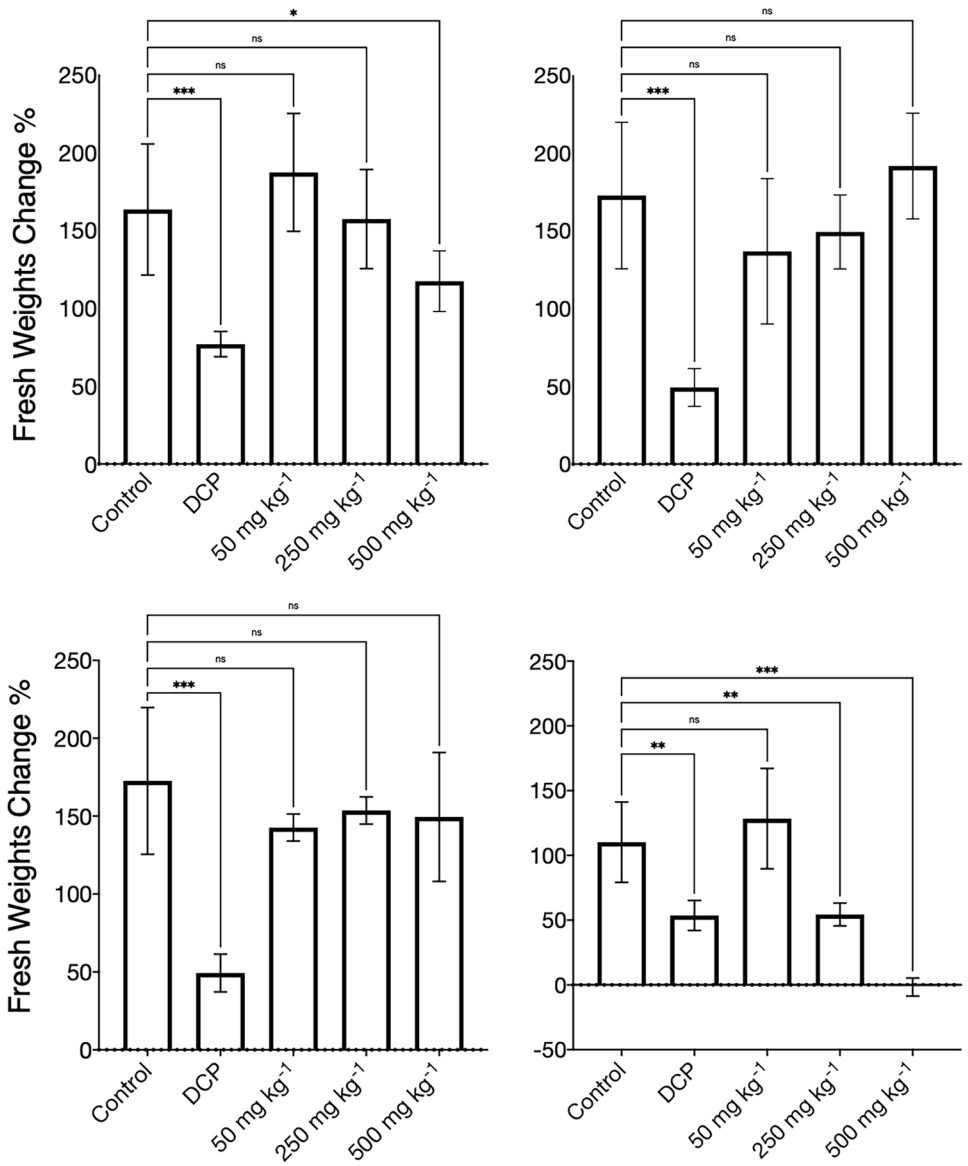

Fig. 1 Fresh weight change (%) (a-d) of *M. aquaticum* whorls in control and spiked sediments after a 10-day exposure. Sediments were spiked with La (a), Ce (b,) Nd (c) and Gd (d) at three concentrations. Data points of control and spiked sediments represent the mean value of four plants. Vertical bars indicate the SD of replicates in each treatment group. * Statistical significance at $p < 0.05$ (*); $p < 0.01$ (**); $p < 0.001$ (***)

3.2 Effects of different REE on the fluorescence yield

During the exposure of whorls of *M. aquaticum* to control and spiked sediments, the Y(II) was observed every 24 h for each whorl over the 10-day exposure period. For whorls treated with La, there was no significant difference from the control (Fig. 2a); at all concentrations there was a constant photosynthetic status. Whorls treated with Ce and Nd showed a significant decrease in yield between days 2 and 4 compared to the control, followed by no difference in yield for the duration of the experiment. (Fig. 2b, c; Supplementary Material (SM), Table 2). In contrast to the other rare earth metals, in Gd-spiked sediments, the Y(II) of *M. aquaticum* showed time and concentration-dependent effects (Fig. 3). For the highest concentrations investigated (500 mg kg^{-1}), almost immediate effects could be detected with a drop in Y(II) of 36% within 3 days reaching 90% at the end of the test (whorls were in necrosis). For 50 and 250 mg kg^{-1}, there was a lower decrease in Y(II) of the exposed whorls over the length of the experiment of 19% on day 10 (Fig. 2d).

3.3 Inhibitory effects

Table 1 reports the inhibition of REE-treated whorls for both the yield and FWC. Diuron and DCP were the positive controls for the yield and the FWC, respectively. Exposure to La at all concentrations did not cause inhibition except for the FWC at the two highest concentrations. Nd showed inhibition at all concentrations for both parameters. The same was recorded for Ce, except for no FWC inhibition at the highest concentration. Gd showed the strongest effects in both parameters measured, being more significant at the highest concentration. For the FWC at the highest concentration there is a complete inhibition.

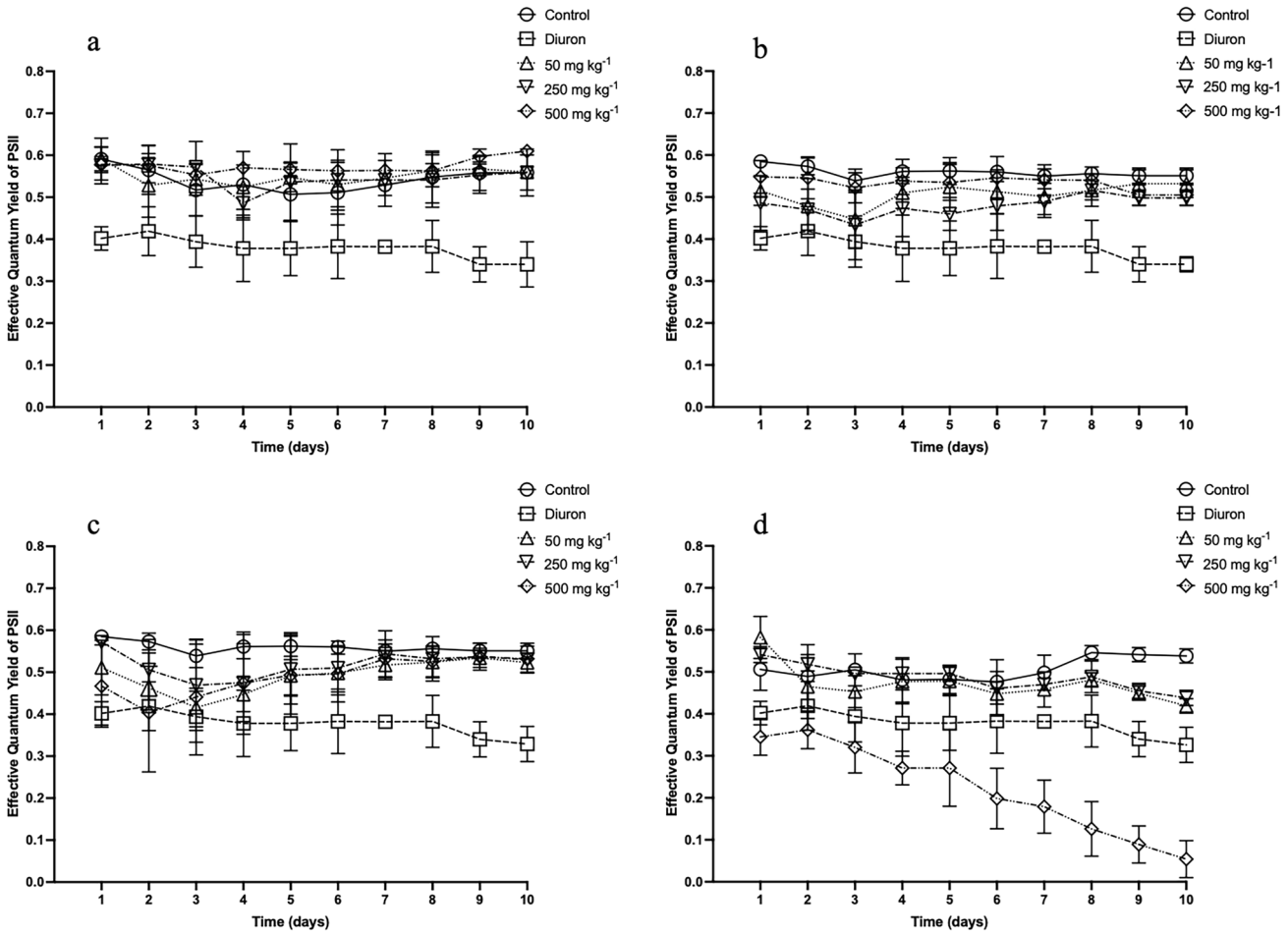

Fig. 2 Time course of the effective quantum yield of the PS II (a–d) of *M. aquaticum* whorls in control and spiked sediments during a 10-day exposure. Sediments were spiked with La (a), Ce (b,) Nd (c) and Gd (d) at three concentrations. Data points of control and spiked sediments represent the mean value of four plants and six measurements. Vertical bars indicate the SD of replicates in each treatment group

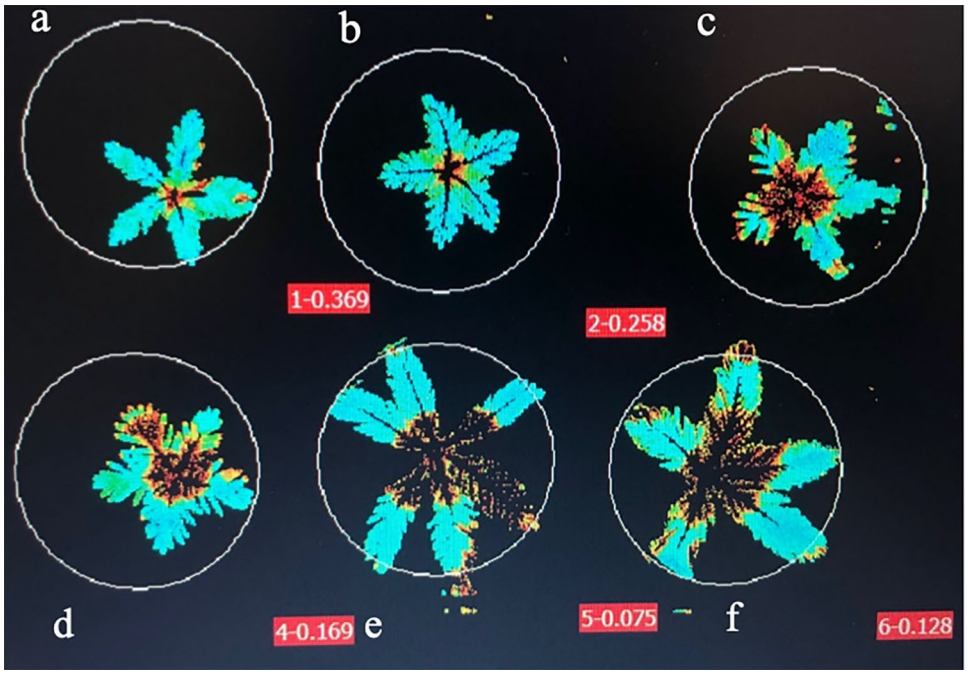

Fig. 3 Readings of the yield of the plants treated with Gd at 50 (a,b), 250 (c,d) and 500 (e,f) mg kg^{-1} on day 5 on the Maxi version of the Imaging – PAM. Darker areas show an effect on the PSII. Yield measurements were repeated every 24 h for the whole test duration

4 Discussion

The advantage of the *Myriophyllum* sediment contact test is that the plant grows directly in the sediment, without further addition of a water column. Thus, it is able to detect toxicity caused by contaminated sediment, especially as REE like to stick to sediment particles and fine organic matter (Herrmann et al. 2016; Gwenzi et al. 2018), making it very likely for *Myriophyllum* to be exposed to REE in nature as well. However, there are very few studies addressing the immobilization of REE to this plant model (Ostroumov et al. 2015) and as far as the authors know none on the effect. The results here reported showed that REE induced different effects on this species. In fact, La significantly decreased FWC at the highest concentration. However, it did not cause any significant effects on the fluorescence yield and, on the contrary, Ce and Nd significantly decreased the chlorophyll fluorescence between days 2 and 4, and after that the yield was not significantly different with respect to the control in accordance with reported by Selim and Haffner 2020. These data showed that PSII activity can be resumed in cells of *Synechococcus elongatus* that were recovering from Cu^{2+} treatment during chlorosis.

Gd showed the most negative effect among the REE tested in this work because the whorls exhibited chlorosis/necrosis (SM, Fig. 1) and the fresh weight at the end of the test decreased significantly compared to the same plant at day 0. The Y(II) of *M. aquaticum* showed time-dependent effects for Gd at the highest concentration, with almost immediate effects detected and a decrease in Y(II). The difference from the other REEs confirms previously data that reporting an increase of toxicity related to the molecular mass. In fact fact La, Ce and Nd are considered Light REE (LREE), while Gd is a Heavy REE (HREE). HREEs were preferentially translocated to leaves in the five *Phytolacca* species reported by Grosjean et al. (2019). This may also be the case with *M. aquaticum,* as only the leaves were considered when measuring the fluorescence yield. In future studies, it would be helpful to analyze the roots and evaluate the effects of REEs in different parts of the plants.

Table 1 Inhibition of the effective quantum yield of the PS II (Y(II)) and the inhibition of the FWC compared with control values of 10-day-old whorls exposed to spiked sediments. The inhibition was calculated using Eq. 2 and 3. Diuron and DCP values are from wells separate from the REE at concentrations 100 mg kg^{-1} and 700 µg kg^{-1} respectively

REE	*Yield inhibition*				*FWC inhibition*			
	50 mg kg-1	250 mg kg-1	500 mg kg-1	Diuron	50 mg kg-1	250 mg kg-1	500 mg kg-1	DCP
La	-0.18	0.00	-9.12	39.18	-14.6	3.74	28.18	52.88
Ce	3.45	9.62	8.35	38.29	20.75	13.54	-10.96	71.45
Nd	5.08	3.81	3.45	40.29	17.35	11.01	13.43	71.45
Gd	22.12	18.59	89.96	39.41	-16.52	50.64	101.52	51.36

The effects of REEs on photosynthesis are typical marker of plant stress; Li et al. (2013) reported that heavy metals damage plant chloroplast or photosynthetic organs and reduce photosynthetic efficiency. Results showed that when algae growth is inhibited by stress, it indicates that the photosynthetic system of algae has been damaged. Leaf photosynthesis could also be inhibited due to damage to PSII as indicated by changes in chlorophyll fluorescence under Cd stress (Ci et al. 2010). This is our hypothesis too; REEs induce a response on the PSII, which causes inhibition of the plant's growth rate. Gd and La are known to inhibit calcium (Ca) channels and disrupt calcium signaling pathways in plant cells (Barry and Meehan 2000; Herrmann et al. 2016; Han et al. 2019). Ca plays essential roles in various cellular processes, including signal transduction, enzyme activation, and cell wall synthesis (Kulaksız and Bau 2013; Gonzalez et al. 2014; Trapasso et al. 2021). Disruption of Ca homeostasis by Gd can lead to impaired plant growth, nutrient uptake, and other physiological processes (Xing et al. 2021). In this case, we could say that our hypothesis is not supported as Gd and La mechanisms primarily involve interference with ion uptake, rather than direct effects on photosynthetic machinery such as PSII. On the other hand, La can interfere with the uptake and assimilation of essential nutrients in plants (Xie et al. 2002). Imbalances in nutrient availability can disrupt metabolic processes, inhibit cell growth and division, and impair overall plant growth and development. This would also explain the effect of this REE on the plant growth.

In soil and sediment, REE are often adsorbed onto surface of the soil and sediment particles, with 99% of all REE in aquatic systems ending up in the soil and sediment (Weltje et al. 2002). Therefore, even if the concentration of the element in soil and water is the same, the roots will take a different amount of the element from the growth media. It may be assumed that translocation of elements from roots to upper plant parts will also differ in the water-grown and soil-grown plants (Shtangeeva et al. 2022). Light rare earth elements (LREE, La – Eu) are more likely to form complexes with carbonates in the sediment, which makes it more likely for sediments to be enriched with LREE than with heavy rare earth elements (HREE, Gd – Y) (Smrzka et al. 2019).

La caused less damage to the plant system compared to Gd. The same can be said for plants treated with Ce and Nd. Ce can induce positive effects at low concentrations by activating beneficial physiological processes (Preetha et al. 2023), improving mineral nutritional content (Rico et al. 2015) and increasing shoot length and fresh weight (Jahani et al. 2019). The data suggest that Ce to induce hormetic effects on plants under certain conditions. Hormesis is a phenomenon where exposure to low doses of a stressor elicits a beneficial response, while higher doses may have negative effects. In the case of cerium, many studies have shown that low concentrations can indeed stimulate positive physiological responses in plants, which is characteristic of hormesis (Gjata et al. 2022).

The heterogeneous biological effects can also be explained by differences in test solution composition, which strongly influence REE speciation (i.e., the different chemical and physical forms of REE) and their bioavailability, and in consequence, induces different biological effects (Barry and Meehan 2000; Borgmann et al. 2005; Gonzalez et al. 2014; Vukov et al. 2016). While both Ce and La are bioavailable to aquatic organisms, La is often considered to be more bioavailable due to its increased solubility, environmental concentrations, and potential for uptake and accumulation in biological tissues (Herrmann et al. 2016). However, it is important to consider site-specific factors and the bioaccumulation potential of individual REEs when assessing their ecological risks and impacts in aquatic ecosystems.

This could explain the significant inhibition on the relative growht rate in plants treated with La compared to the ones with Ce. In water, mineral elements are present in more available to a plant form and can be easily taken by roots.

Further research is needed to better understand the underlying mechanisms and potential ecological implications of REE exposure on plant physiology and health.

5 Conclusions

Due to its ease of cultivation and handling, abundant growth, the fact that the species is not prone to contamination by algae and other organisms, and its acceptable variability and relative sensitivity, *M. aquaticum* should be considered a test model in environmental risk assessment. The measurement of the fluorescence yield of the PSII is a practical additional effect observation and of high environmental relevance. The difference in sensitivity between the functional and growth endpoints may give hints about the mode of action of contaminants in sediments, such as REE, to macrophytes and offer scope for an advanced hazard assessment. Gd was the most toxic REE, strongly affecting both measured endpoints. REEs affected photosynthetic activity, but their earliest effect was on the growth rate and development which, when compromised, resulted in an inhibition of the fluorescence yield. Further biochemical and physiological studies can be done to better understand the specific stress responses induced by these elements in plant. This will allow us to understand the mode of action of different REEs and identify potential biochemical markers that can minimize or neutralize the effects and counteract their toxicity.

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Author contributions Author contribution is in alphabetical order of surname. Isidora Gjata and Susanne Heise contributed to the study's conception and design. Material preparations were performed by Isidora Gjata and Chantal van Drimmelen. Data collection was performed by Isidora Gjata and Chantal van Drimmelen. The analysis was performed by Isidora Gjata. The first draft of the manuscript was written by Isidora Gjata; It was then reviewed and revised by Isidora Gjata, Susanne Heise, Chantal van Drimmelen, Franca Tommasi and Costantino Paciolla. All authors contributed to the review and discussion. All authors read and approved the final manuscript.

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Declarations

Conflict of interest The authors declare that they have no conflicts of interest regarding the publication of this paper.

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