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Toxicity of lanthanum oxide (La_2O_3) nanoparticles in aquatic environments†

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This study demonstrates the acute toxicity of lanthanum oxide nanoparticles (La_2O_3 NP) on two sentinel aquatic species, fresh-water microalgae *Chlorella* sp. and the crustacean *Daphnia magna*. The morphology, size and charge of the nanoparticles were systematically studied. The algal growth inhibition assay confirmed absence of toxic effects of La_2O_3 NP on *Chlorella* sp., even at higher concentration (1000 mg L^{-1}) after 72 h exposure. Similarly, no significant toxic effects were observed on *D. magna* at concentrations of 250 mg L^{-1} or less, and considerable toxic effects were noted in higher concentrations (effective concentration [EC_{50}] 500 mg L^{-1}; lethal dose [LD_{50}] 1000 mg L^{-1}). In addition, attachment of La_2O_3 NP on aquatic species was demonstrated using microscopy analysis. This study proved to be beneficial in understanding acute toxicity in order to provide environmental protection as part of risk assessment strategies.

Environmental impact

Nanomaterials attracted significant attention on potential adverse effects on aquatic organisms due to their mass production and ubiquitous applications. Researchers have begun exploring lanthanum oxide nanoparticles, among other rare earth elements, for potential uses in widespread applications and, subsequently, potential hazards. Results presented here demonstrate enhanced growth of *Chlorella* sp. with exposure to lanthanum oxide nanoparticles. In contrast, lanthanum oxide nanoparticles caused severe toxicity effects to *Daphnia magna*, including mortality. These observations demonstrate the toxic effects of lanthanum oxide nanoparticles upon release into aquatic environments.

1. Introduction

In recent decades use of nanoparticles (NPs) in many industrial and household applications has been extensive, such as sunscreens, cosmetics, paints and construction materials.[1–4] Consequently, aquatic environments are considered vulnerable to diverse NP releases, for which subsequent impacts have not been clearly defined.[5] Inevitable releases have gained significant attention due to adverse effects on the environment and human health.[6–8] However, owing to the differential nature of NPs compared to soluble chemicals, minimal information is available on their interaction with aquatic organisms. It has been found that transformations, agglomerations and surface properties play a vital role in determining NP toxicological and bioavailability properties, once they are released into aquatic environments.

Numerous studies on the ecotoxicity of NPs used a variety of algae, microorganisms, invertebrates and fish as model aquatic organisms.[9–14] However, the underlying ecotoxicological effects on diverse aquatic organisms remain unclear. *Daphnia magna* and *Chlorella* sp. are considered excellent biomonitoring aquatic species owing to their critical role in the aquatic food chain and sensitivity to various pollutants.[15,16] The use of *D. magna* and microalgae for ecotoxicological studies has been highly recommended in various standard regulatory guidelines,[17–20] and many studies were carried out on these species to evaluate the toxicity potential of NP.[21–29]

Due to their unique chemical nature and exceptional catalytic, magnetic and electronic properties, the rare earth elements (REE) have been widely used in various industries as well as biotechnology applications.[30,31] Among REE applications, lanthanum oxide nanoparticles (La_2O_3 NP) have been exploited for use in sensors, electronics, fuel cells, magnetic data storage, antimicrobials, catalysis, automobiles, water treatment, phosphate removal and biomedicine.[32–34] Because of

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widespread and growing applications, how these NP affect the environment and human health is a major research focus.

The aim of the present study is to evaluate the toxicity of La_2O_3 NP in aquatic organisms *Chlorella* sp. and *D. magna*. We investigated the impacts of La_2O_3 NP on behavioral change and ecotoxicity, and determined effective concentration (EC_{50}) and lethal dose (LD_{50}) values. The attachment and accumulation of La_2O_3 NP in aquatic organisms was investigated using optical microscopy (OM) and scanning electron microscopy (SEM).

2. Materials and methods

2.1 Nanoparticle characterization

The La_2O_3 NP used in this study was donated by the CECRI, Karaikudi, Tamilnadu, India. Transmission electron microscopy (TEM; Tecnai G2 F30, FEI) was used to determine the morphology and chemical composition. Mean particle size and surface charge of La_2O_3 NP were studied by using a zeta sizer (Nano ZS, Malvern) in test media (ISO test medium, pH 7.6, and BG 11 medium, pH 7.5). X-ray diffraction (XRD) patterns of La_2O_3 NP were obtained using the PANalytical X'Pert Multipurpose X-ray diffractometer with Cu Kα radiation. The surface composition of La_2O_3 NP was studied by X-ray photoelectron spectroscopy (XPS; Thermoscientific, K-alpha).

2.2 Algal growth inhibition assay

2.2.1 Test species and culture conditions. First, isolation of the green algae *Chlorella* sp. from the water supply was carried out in Sorgun, Yozgat, Turkey.[35] The medium BG 11 was used to conduct the algal growth inhibition assay based on the OECD 201.[20,36] The microalgal cultures were inoculated at 0.1 g L^{-1} dry weight biomass and flasks illuminated by cool-white fluorescent lamps at 25 μmol m^{-2} s^{-1} (1750 lx) light intensity at 25 ± 2 °C with 100 r min^{-1}.

2.2.2 Treatment and analytical methods. Exponentially growing algal cells were propagated in Erlenmeyer flasks containing La_2O_3 NP at 10, 50, 100, 250, 500 and 1000 mg L^{-1} of the BG11 medium. In addition, the control medium consisted of flasks without La_2O_3 NP. All experiments were carried out twice in triplicate. Flasks were maintained at 25 ± 2 °C under continuous illumination in a shaker (100 r min^{-1}). While exposed to various concentrations of La_2O_3 NP, the growth of *Chlorella* sp. was monitored by measuring optic density, dry weight and specific growth rate parameters for the samples collected at 0, 24, and 72 h. At the end of the study, colony counts were taken into account to elucidate toxicities of the various treatments involved.

Optical density was calculated with a Shimadzu UV 1800 model spectrophotometer at 600 nm. Microalgae were centrifuged at 3421 × g = 5000 rpm for 10 min (Hettich Universal 320 R model centrifuge), and resulting pellets were collected and dried at 80 °C overnight at the MMM-MedCentre Ecocell model sterilizer, in order to preserve dry weights. Maximum biomass productivity (P_{max}) was calculated according to eqn (1):

$$P_{max} = (X - X_0)/(t - t_0) \quad (1)$$

where X is the final biomass concentration and X_0 the initial biomass concentration (g L^{-1}), and t is the final time and t_0 the initial time of the culture. Specific growth rate (μ_{max}) was calculated as follows:

$$\mu_{max} = (\ln X_2 - \ln X_1)/(t_2 - t_1) \quad (2)$$

X_2 and X_1 are the dry cell weight concentrations (g L^{-1}) at time t_2 and t_1, respectively.[37] The concentration for chlorophyll was obtained at 646.6 nm and 663.6 nm for chlorophyll a and b, respectively.[38] SEM (Quanta 200 FEG, FEI) and OM were used to observe and image attachment of microalgae with La_2O_3 NP. Before SEM observation and energy dispersive spectroscopy (EDS) mapping, a drop from the 1000 mg L^{-1} culture solution was air dried on a copper stage and subsequently coated with a layer of gold to confirm the attachment of La_2O_3 NP with the microalgae. Similarly, a drop of dried culture solution on a clean glass slide was used for OM observation.

2.3 Acute immobilization test

2.3.1 Test species and culture conditions. We used freshwater flea *D. magna* neonates as the test species in this study. Fed with suspensions of green algae (*Chlorella* sp.), the daphnids were maintained at a constant temperature of 20 ± 1 °C and a 16 : 8 h light : dark cycle.

2.3.2 Treatment. The acute immobilization test was conducted based on the OECD 202 guideline.[19] Seven concentrations of La_2O_3 NP (0, 25, 50, 100, 250, 500 and 1000 mg L^{-1}) were prepared in the ISO test medium to determine the sensitivity of *D. magna*. A total of 20 daphnids were divided in four replicates for each concentration tested. Following the 24 and 48 h exposures, daphnids were studied for immobilization effects, with simultaneous comparison with controls. The experiment was repeated to ensure consistency of the results. The pH of the culture medium was measured throughout the experiment. Changes in morphology, La_2O_3 NP attachment on exterior surfaces and accumulation in the intestinal tract of *D. magna* were examined using SEM and OM techniques.

3. Results and discussion

3.1 Nanoparticle characterization

The TEM image in Fig. 1 shows that the particles are irregular spheres and less than 100 nm in size. Further, the EDS spectra confirmed the presence of lanthanum and oxygen at 61.96% and 38.03%, respectively (Fig. S1†). Results of the zeta sizer revealed mean particle size of La_2O_3 NP at 59 nm and 61 nm in ISO test medium and BG 11 medium, respectively (Fig. S2†). Similarly, the zeta potential value was 14.5 mV in ISO test medium and 14.9 mV in BG 11 medium. No significant differences in diameter and surface charge were observed in test media at different pHs.

XRD patterns of La_2O_3 NP are shown in Fig. S3.† The diffraction peaks are consistent with values of the standard card JCPDS file 65-3185. The surface composition of La_2O_3 NP was investigated *via* XPS analysis. The survey spectrum confirmed that there were no metal element impurities present in the surface of the sample except for lanthanum (Fig. S4a†). The La 3d core level

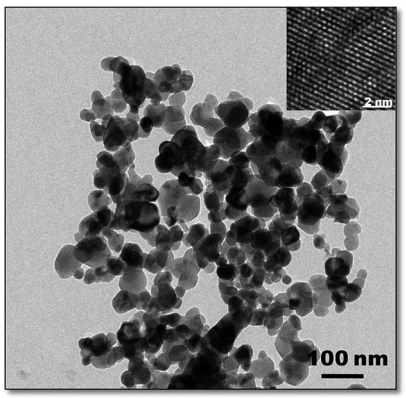

Fig. 1 TEM image of La_2O_3 NP. Particles are irregular spheres in shape and less than 100 nm. Inset shows lattice spacing (0.348 nm).

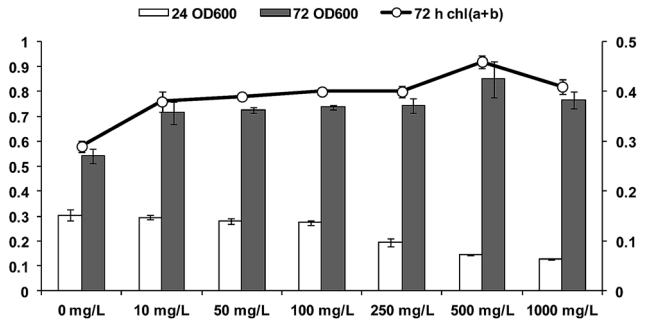

Fig. 2 Interactive effect on optical density (OD_{600}) and chlorophyll content of *Chlorella* sp. with La_2O_3 NP during the incubation period (24 and 72 h). The diagram represents algal growth inhibition at 24 h exposure and growth enhancement observed at 72 h. Results are mean values of triplicate cultures.

spectrum is shown in Fig. S4b.† The deconvoluted spectra show two peaks separated by ~4 eV. As shown in Fig. S4c,† the deconvoluted O 1s spectrum had three peaks (526.6 eV, 529.3 eV and 531.6 eV) associated with chemical bonding state of O–La–O (O_L) and hydrated phases from air exposure (O_H).[39]

3.2 Algal growth inhibition assay

The effects of La_2O_3 NP on growth parameters of *Chlorella* sp. were studied and analyzed after 24 and 72 h incubation periods. Initially, during the 24 h observation, it was found that with increasing nanoparticle concentrations, microalgal growth decreased. The highest growth was attained in the control culture at 0.133 g L^{-1} dry weight of microalgal biomass in 24 h. Nanoparticle concentration at 10 mg L^{-1} showed no toxic effects on *Chlorella* sp., as the biomass reached 0.130 g L^{-1}. At the 1000 mg L^{-1} nanoparticle concentration, the lowest biomass was recorded at 0.057 g L^{-1} (Table 1).

Enhanced growth of *Chlorella* sp. was observed at higher nanoparticle concentrations at 72 h. All treated cultures showed higher microalgal growth than the control culture. Maximum growth achieved by the control culture was recorded at 0.237 g L^{-1}, whereas the biomass in the culture containing 500 mg L^{-1} NP was 1.5 times higher than that of the control culture (Fig. 2). Thus, it was apparent that increasing nanoparticle concentration did not exhibit any toxic effects on the growth of *Chlorella* sp.

In addition, chlorophyll (a + b) concentrations of *Chlorella* sp. were also evaluated at 24 and 72 h. Following the 72 h exposure, the maximum chlorophyll (a + b) concentration was found to be 0.46 μg mL^{-1} at 500 mg L^{-1}, 13 times higher than in the control (Fig. 2). An image of enhanced chlorophyll content production appears in Fig. S5.†

Calculated μ_{max}, P_{max} and colony counts are presented in Table 1. As anticipated, 72 h values of maximum specific growth rate were lower than the 24 h values owing to incubation time. Under the effect of La_2O_3 NP, the maximum specific growth rate was 1.339 in the 10 mg L^{-1} concentration over 24 h. The obtained value was very close to the control culture value (Table 1). P_{max} was 0.116 at 500 mg L^{-1} for the 72 h exposure. Similarly, La_2O_3 NP exposure increased the viability of algal cells at 72 hours. Since no significant toxicity was observed under illumination, studying the effects of La_2O_3 NP under shading on algal growth was considered unnecessary. Using OM and SEM, the attachment of microalgae to La_2O_3 NP was precisely demonstrated (Fig. S6†). Further, EDS mapping of the treated *Chlorella* sp. confirmed the attachment of lanthanum on the surface of the microalgae without causing morphological changes (Fig. 3). Overall comparisons of chlorophyll and biomass production with La_2O_3 NP exposure over the control culture are presented in Fig. S7.†

Table 1 La_2O_3 NP effect on microalgae growth parameters during 24 h and 72 h exposures

Parameters	0 mg L^{-1}	10 mg L^{-1}	50 mg L^{-1}	100 mg L^{-1}	250 mg L^{-1}	500 mg L^{-1}	1000 mg L^{-1}
Dry weight (g L^{-1})[a]	0.133 ± 0.01	0.130 ± 0.004	0.124 ± 0.005	0.120 ± 0.003	0.085 ± 0.007	0.064 ± 0.001	0.057 ± 0.001
P_{max}[a]	0.108 ± 0.01	0.105 ± 0.004	0.099 ± 0.005	0.095 ± 0.003	0.060 ± 0.007	0.039 ± 0.001	0.032 ± 0.001
μ_{max}[a]	1.340 ± 0.003	1.339 ± 0.001	1.338 ± 0.001	1.337 ± 0.001	1.328 ± 0.002	1.322 ± 0.001	1.320 ± 0.001
Chlorophyll (μg mL^{-1})[a]	0.163 ± 0.012	0.159 ± 0.005	0.152 ± 0.062	0.147 ± 0.037	0.104 ± 0.087	0.078 ± 0.012	0.070 ± 0.012
Dry weight (g L^{-1})[b]	0.237 ± 0.01	0.314 ± 0.016	0.317 ± 0.004	0.323 ± 0.003	0.326 ± 0.01	0.373 ± 0.052	0.335 ± 0.012
P_{max}[b]	0.071 ± 0.01	0.096 ± 0.016	0.097 ± 0.004	0.099 ± 0.003	0.100 ± 0.010	0.116 ± 0.050	0.103 ± 0.012
μ_{max}[b]	0.455 ± 0.001	0.462 ± 0.001	0.462 ± 0.000	0.463 ± 0.000	0.463 ± 0.001	0.467 ± 0.004	0.464 ± 0.001
CFU (10^7 cells per mL)[b]	1.6 ± 0.040	2.2 ± 0.050	2.1 ± 0.070	2.6 ± 0.300	2.7 ± 0.090	3.3 ± 0.100	2.9 ± 0.500

[a] Denotes observation at 24 h. [b] Denotes findings at 72 h. Values are expressed as mean ± standard deviation.

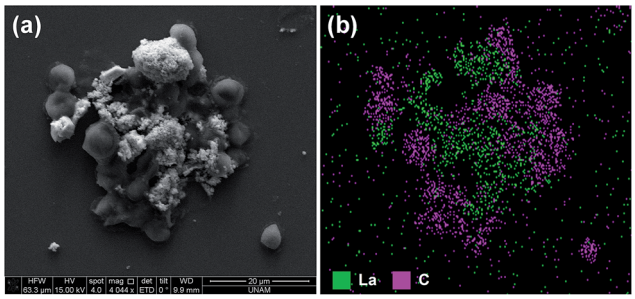

Fig. 3 (a) SEM image of *Chlorella* sp. following exposure to La_2O_3 NP (72 h; 1000 mg L^{-1}). (b) EDS dot map of corresponding SEM image, showing distribution of lanthanum and attachment to *Chlorella* sp. without morphological changes.

3.3 Acute immobilization test

It was found that immobilization of *D. magna* following 48 h of exposure to various concentrations of La_2O_3 NP is concentration dependent. Results of immobilization on exposure to La_2O_3 NP are presented in Fig. 4. The no observed effect level (NOEL) and low observed effect level (LOEL) were calculated at 25 mg L^{-1} and 50 mg L^{-1}, respectively. The EC_{50} value of La_2O_3 NP against *D. magna* was found to be 500 mg L^{-1}. Also, about 70% mortality occurred in the daphnids when treated at 1000 mg L^{-1} concentrations after 48 h of exposure. Thus the LD_{50} concentration value was 1000 mg L^{-1} pH ranged from 7 to 8 throughout the experiment.

At higher concentrations, ingestion of La_2O_3 NP was observed in the daphnids toward 48 h of exposure. OM images show no accumulation of particles in the intestinal tract of control *D. magna*, whereas significant accumulation of La_2O_3 NP was observed at 1000 mg L^{-1} (Fig. S8†). Further, the SEM images also confirmed no change in morphology at 0 mg L^{-1}, compared to severe damage at 1000 mg L^{-1} (Fig. 5). Interestingly, the images indicate the attachment of La_2O_3 NP on the body surface of *D. magna*, including antenna, used mobility. Attachment of La_2O_3 NP was further confirmed *via* the EDS dot map, which demonstrates the distribution of lanthanum and oxygen (Fig. S9†).

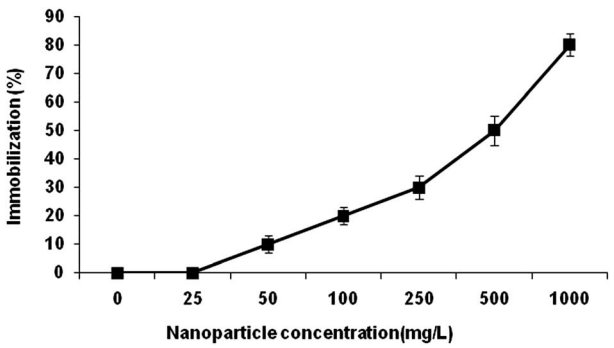

Fig. 4 Effect of La_2O_3 NP on mobilization nature of *D. magna* following 48 h exposure. Response curve shows that immobilization percentage is concentration dependent.

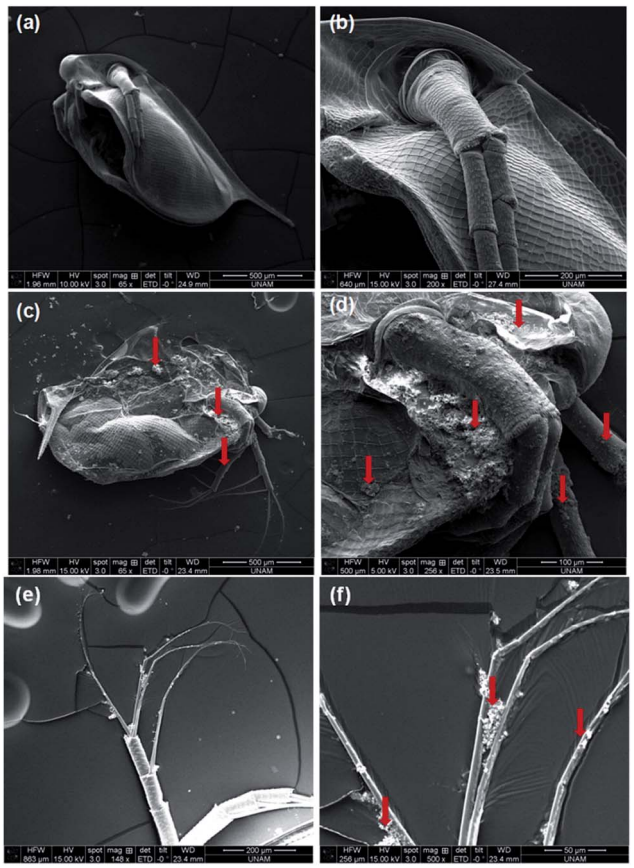

Fig. 5 SEM image of *D. magna* without La_2O_3 NP exposure, which shows no morphological changes (a and b). Treated with La_2O_3 NP (1000 mg L^{-1}) for 48 h (c–f). Images clearly illustrate change in morphology, adhesion of particles on body surface and antenna. Red arrows indicate attachment of La_2O_3 NP.

REE, including lanthanum, are extensively used as microfertilizers in agriculture due to capacity to enhance growth and productivity.[40–43] REE usage has significantly increased the chlorophyll content and production of the spinach plant.[44] Treatments of lanthanum at 12 mg L^{-1} have significantly increased the germination rate, germination index and vigour index in sorghum.[45] Lanthanum has supported the abscisic acid regulation and enhanced the root growth of *Arabidopsis*.[46] *Chlorella* sp. belong to the phylum chlorophyta and are considered eukaryotic photosynthesizers, as they contain chloroplasts, growth regulators (auxins, cytokinins, gibberellins, abscisic acid and brassino steroids) similar to plants.[47] Regulation of these enzymes also promotes microalgae growth. Myers reported that trace metals at minimum concentrations can provide nutrients, whereas at higher concentrations, they initiate interaction with proteins and affect enzymatic activities, leading to toxic effects.[48] In addition, it is speculated that lanthanide ions can also serve as isomorphic replacements for Ca^{2+} in biochemical systems.[49] Thus, similar to trace elements, in this study lanthanum served as a nutrient to algae and enhanced growth. The microalgae *chlorella* sp. may be used for metabolic phenomena to increase productivity like any other plant.

The initial inhibition observed during growth was found to result from toxic effects produced by La_2O_3 NP. With prolonged exposure, microalgae grow resistant, utilizing La_2O_3 NP for enhanced growth. At higher concentrations, nanoparticles formed aggregates, wrapping the algal cells around contributing to growth inhibition. It is also speculated that La_2O_3 NP are well known for inhibiting a broad range of microorganism growth by competing with available phosphates in the media. Hence, La_2O_3 NP restricted the availability of phosphates at higher concentrations and led to microalgal growth inhibition.[50] These phenomena serve as the basis for the observed decline in growth and biomass production at higher concentrations (1000 mg L^{-1}). Hence, lanthanide ions are considered responsible for enhanced growth with fresh water microalgae. Second, the regulation mechanism of lanthanum on *Chlorella* sp. enzymes also emerged as the reason for growth enhancement. Further, the attachment of La_2O_3 NP on microalgal cells could be attributed to electrostatic interaction between positively charged nanoparticles and negatively charged algae cell walls.[51,52] The electrostatic interaction of positively charged nanoparticles with different microorganisms and their effects are well reported.[53–56]

The remarkable feeding behavior of *D. magna* indicates ingestion and potential toxicity of NP. Mendonca *et al.* demonstrated the effect of ingested NP on *D. magna* gut cells.[57] In our study as well, it was expected that the ingested La_2O_3 NP might get mixed with food and interfere in intestinal adsorption at higher concentrations. In cases of chronic exposure, accumulation was noted at lower concentrations. Moreover, La_2O_3 NP are positively charged and known to adhere to negatively charged biological molecules. Balusamy *et al.* emphasized that bacterial toxicity against interaction of *S. aureus* is based on the electrostatic interaction between the NP and negatively charged cell wall content.[32] This assertion is also in agreement with the OECD Draft Guidance Document stating that hydrophobic substances are highly capable of becoming attracted to negatively charged biological materials.[58] In addition, it should be noted that La_2O_3 are well known for production of free radicals among diverse rare earth elements and their effect on hepatic nuclei and mitochondria have been reported.[59,60] Accordingly, we hypothesize that the observed toxicity against *D. magna* resulted from either mechanical disruption in feeding and carapace attachment of La_2O_3 NP, which leads to eventual immobilization and mortality or to production of reactive oxygen species (ROS), especially at higher concentrations. Again, this complements the findings of Asghari *et al.*[61] Likewise, experiments conducted in the shaking platform were found to be highly relevant to environmental conditions, considering natural water flow in aquatic environments.

4. Conclusion

Our research highlighted La_2O_3 NP treatment with *Chlorella* sp., emphasizing the absence of significant toxic effects, but enhanced growth rate and biomass production. On the contrary, the 48 h exposure acute toxicity test indicated significant toxicity at concentrations 500 and 1000 mg L^{-1} on *D. magna*. The EC_{50} and LD_{50} values of La_2O_3 NP in the acute immobilization test were determined as 500 and 1000 mg L^{-1}, respectively. Observed toxicity effects of La_2O_3 NP concentrations were found to be much higher than the regulatory recommendations. Therefore, the use of La_2O_3 NP in consumer products can be considered safe. But, the release of La_2O_3 NP requires greater attention at higher exposure levels since it has direct adverse effects on the environment. However, further research is needed to discover appropriate biological phenomena against toxicity and initiate the risk assessment process.

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