Dead biomass of *Morganella morganii* acts as an efficient adsorbent to remove Pb(II) from aqueous solution in different aeration–agitation and pH conditions

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Abstract

Lead (Pb) removal from industrial effluent using physicochemical methods, though efficient, poses economic and environmental challenges due to high cost and generation of toxic wastes as by-products. Biosorption using dead microbial biomass, on the other hand, offers economic feasibility and environmental safety, but its application is limited because it relies on specific pH and agitation conditions. To address these issues, we used wastewater of a drain containing effluent from nineteen industries and isolated Pb-tolerant strains of *Morganella morganii* (ND1 and ND2). We demonstrated that the dead biomass of *M. morganii* ND1 and ND2 maintains a high biosorption potential at pH ranging from 3 to 5 in both shaking (89.96–89.99 mg/g) and static conditions (89.99–84.05 mg/g). Adsorption of Pb(II) from *M. morganii* ND1 and ND2 follows pseudo-second-order kinetic model and chemisorption as a dominant underlying mechanism in aqueous media. Fourier-transform infrared spectroscopic analyses of dead biomass before and after Pb(II) biosorption revealed the involvement of phosphoryl, hydroxyl, amide, carbonyl, and phosphate functional groups during biosorption. We demonstrated the potential of *M. morganii* ND1 and ND2 in developing a cost-effective biosorption technology for removing Pb in industrially relevant pH, and both agitation and static conditions.

Keywords Bioremediation · Heavy metal pollution · Industrial effluent · Environmental application

1 Introduction

Lead (Pb), a key heavy metal in the history of civilization and economic development, gained significance as a driver of development and concern of public health in the fastest growing economies of today [1, 2]. Though Pb occurs naturally, anthropogenic activities, such as mining and other industrial operations, contribute significantly to its global cycling. Developing countries rely on Pb for acid batteries (electric vehicle, mobile, and household electronic equipment), infrastructure development (roofing and gutters), electroplating, pigments, and ammunition. With an estimated worth of \$75 billion by 2024, the battery

industry alone uses ~85% of global Pb demand and serves as the primary source of Pb pollution in the environment [3, 4]. Being mutagenic and carcinogenic, Pb ranks second in the US ATSDR “Priority List of Hazardous Substances 2017” [5]. At any level, Pb is considered unsafe to humans; for example, USEPA and World Health Organization (WHO) formulated the permissible limits of Pb in drinking water as low as 0.015 mg/l and 0.01 mg/l, respectively [6, 7].

Though children and pregnant women form the most vulnerable groups, Pb remains toxic to both the genders of all age groups. Pb accumulates in the body after long-term exposure and damages nervous, cardiovascular, renal, gastrointestinal, and hematologic systems in humans [3, 8,

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9]. However, children represent a highly vulnerable group because children accumulate four to five times more Pb than adults. Also, the children with high levels of Pb show lower life expectancy and poor work efficiency and indulge in violent crime in adulthood due to impaired cognitive potential [10–12]. Pregnant women, on the other hand, may experience miscarriage, premature birth, and fetal malformations due to prolonged exposure to Pb [13, 14]. In the human body, Pb persists for a long time and continues to cause toxicity because its residence time in bones and teeth ranges in decades, and its continuous release damages different organ systems [15].

Pb pollution has emerged as a significant challenge to sustainable health globally. In 2016, Pb pollution led to 540,000 deaths and 13.9 million years of healthy life lost (disability-adjusted life years) worldwide [16]. Developing countries with low- and middle income bear the highest burden of Pb-induced mortality and morbidity as ~ 90% of children with elevated levels of Pb in blood live in these countries [17, 18]. Given Pb toxicity as a significant threat to sustainability, policymakers recommend developing cost-effective methods for remediation and recovery of Pb from contaminated wastewater.

Industries though use physicochemical methods for Pb removal, have been expressing interest in biological methods, which are not only cost-effective but also safe to humans and the environment. Physicochemical methods, such as electrodialysis, ion exchange, reverse osmosis, adsorption, solvent extraction, and chemical precipitation, have been in practice. However, these methods are not only chemically intensive and dependent on high capital investment but also produce toxic sludge [19–22]. Consequently, the physicochemical methods remain unpopular in developing countries where regulations are relaxed and unorganized sectors dominate in Pb-based battery recycling industries. Though biological methods, like using microbes, plants, or enzymes, offer attractive alternatives, the pH condition and sensitivity of microbes, plants, or enzymes to high level of pollutants limit their efficacies [23–26]. Biosorption or use of dead microbial biomass offers a sustainable solution to remediate Pb from wastewater as fragmented cell membrane immobilizes Pb, which remains independent of the metabolic status of the cell [27, 28]. Using dead bacterial biomass also reduces the concern of introducing alien microbes, a possible risk of microbial infection, and the cost of maintenance. Besides this, dead biomass inherently possesses the ease of transport and convenience of long-term storage without compromising with its activity [29]. Biosorption of Pb, using dead bacterial biomass, therefore, serves as a cost-effective and environment-friendly approach [30].

Morganella, a rod-shaped, gram-negative bacterium with metabolic versatility, belongs to Enterobacteriaceae

that commonly occurs in the aerobic and anaerobic environment of the gut of reptiles and mammals, including humans. Live cells of *Morganella morganii* have been studied for the remediation of explosives [TNT (2,4,6-trinitrotoluene) and RDX (hexahydro-1,3,5-trinitro-1,3,5-triazine)] from the soil, water, and oil spills [31, 32], industrial dyes [33, 34], and bioaccumulation and biosorption of Cr(VI) [35, 36]. However, the potential of dead biomass of *Morganella* in biosorption of heavy metals is yet unknown. Our study, therefore, aims to (i) isolate a biosorbent for Pb removal from an industrial drain and ascertain the efficacy of biosorption for potential application in low agitation, or static conditions, and in different pH, and (ii) characterize Pb adsorption of the biosorbent by determining its rate constant and equilibrium capacity. We report Pb-tolerant strains of *Morganella* from one of the most polluted industrial drain of India and show biosorption potential of its biomass to remove Pb from synthetic wastewater.

2 Materials and methods

2.1 Bacterial isolation and culture conditions

Pb-tolerant bacteria were isolated on nutrient agar (HiMedia, India) using the standard procedure [37]. Wastewater was sampled from Najafgarh drain, Delhi (28°41'49" E, 77°12'32" E), receiving huge loads of untreated effluent from different industries. One milliliter of the wastewater was diluted to 10 ml with sterile distilled water. Fifty microliter of diluted wastewater was uniformly spread on nutrient agar supplemented with 1500 ppm Pb and incubated at 28 ± 2 °C. Two well-isolated bacterial colonies with distinct morphology developed after 2–3 days were purified by transferring onto freshly prepared nutrient agar plate 4–5 times. Purified bacterial isolates were designated as ND1 and ND2 till identification, and their stocks were prepared in 50% glycerol following standard procedure and stored at -80 °C till further use [38].

2.2 Bacterial identification using 16S rRNA sequencing

Pb-tolerant bacterial isolates (ND1 and ND2) were identified using 16S rRNA sequence analysis [39, 40]. Genomic DNA was isolated using guanidium thiocyanate method, and 16S rRNA gene was amplified by polymerase chain reaction (PCR) using primers: 27F 5'-AGAGTTTGATCC TGGCTCAG-3') and 1492R (5'-TACGGYTACCTTGTTACG ACTT-3'). PCR-amplified DNA product was purified using QiaGene gel extraction kit as per manufacturer's protocol, and sequencing reactions were performed using universal primers. 16S rRNA gene sequences were analyzed

by the BLAST algorithm for comparison of a nucleotide query sequence against the public nucleotide sequence database (GenBank), and closely related match of bacteria (homologous sequences) was determined. Gene sequences of ND1 and ND2 were submitted to NCBI GenBank (accession numbers MN148804 and MN148805).

2.3 Production and preparation of biosorbent

For biomass cultivation, the cell culture of each isolate was raised in 2000 ml Erlenmeyer flask containing 800 ml nutrient broth and shaking at 120 rpm and $28 \pm 2^\circ\text{C}$ in an incubator shaker (NewBrunswick, USA). Bacterial cells were harvested at the stationary phase by centrifugation at $10,000 \times g$ and 4°C for 15 min (Biofuge Stratos, Heraeus, Germany). The cell pellet was washed five times with sterile distilled water and finally suspended in sterile distilled water (2 mg/l). Cells were sonicated at 50% duty cycle, 2 bursts per second for 5 min at 4°C (Sonics Vibra-Cell, USA) [41]. Cell fragments were pelleted down by centrifuging at $12,000 \times g$ and 4°C for 15 min and washed thoroughly with sterile distilled water and used for biosorption assays.

2.4 Adsorbate preparation and Pb estimation

Adsorbate Pb(II) stock solution (2000 ppm) was prepared by using $\text{Pb}(\text{NO}_3)_2$ (Merck, Germany). Stock solution was filter-sterilized using $0.2 \mu\text{m}$ filter (Sartorius, Japan) and stored in a tightly closed flask at 4°C till further use. Pb concentration at different steps of biosorption assays was monitored by using atomic absorption spectrophotometric assays (Analytic Jena, Germany). A standard curve was prepared by diluting 1000 ppm Pb standard (AAS grade, Merck Germany) with 0.1 M HNO_3 in the range of 1–5 ppm.

2.5 Biosorption experiment

Biosorption efficacy of dead biomass of ND1 and ND2 isolates was assessed in a batch mode in 100 ml flask containing 50 ml of 500 ppm Pb(II) and 2 mg/l of biomass. The effect of environmental parameters (pH, temperature, agitation/static condition, and contact time) on Pb biosorption was also analyzed. An aliquot of biosorption reaction mixture treated under different environmental parameters was sampled at 0 min, 3 h, 6 h, 9 h, 12 h, and 24 h. Adsorbed dead biomass was pelleted down by centrifugation, and Pb(II) concentration in the supernatant was estimated as described in Sect. 2.4.

2.5.1 Effect of temperature

Effect of temperature on biosorption by dead biomass of bacterial isolates ND1 and ND2 was analyzed at 30°C and

35°C under static and shaking conditions. The pH of the adsorbate was adjusted to 5.0 just before the experiment using 0.1 M NaOH and 0.1 M HNO_3 . Before conducting the biosorption assay, the adsorbate solution was equilibrated to the desired temperature for 30 min.

2.5.2 Effect of pH on biosorption

To determine the effect of pH on biosorption efficacy, the adsorbate solution was adjusted to pH of 3, 4, and 5 using 0.1 M NaOH and 0.1 M HNO_3 just before adding the dead biomass of ND1 and ND2. Biosorption assays were avoided at pH higher than 5.0 to prevent Pb precipitation as hydroxide [42].

2.5.3 Effect of agitation/static condition

The effect of agitation on biosorption efficacy of bacterial dead biomass was analyzed by biosorption assays conducted in batch mode in both static and shaking (120 rpm) conditions at pH 3–5 and temperature 30°C and 35°C .

2.5.4 Adsorption characterization

To predict the rate constants of adsorption, equilibrium capacity of adsorption, and mechanism of adsorption, we conducted a kinetic study. We used three kinetic models, i.e., pseudo-first-order, pseudo-second-order, and intra-particle diffusion models [43–45]. In the kinetic study, dead bacterial biomass (2 g/l) was exposed to Pb (500 ppm) at 30°C , and Pb concentration in the supernatant was estimated. Kinetic parameters of Pb biosorption were analyzed following different kinetic models.

The pseudo-first-order model in linearized form is expressed as [43]:

$$\ln(q_e - q_t) = -k_1 t + \ln q_e \quad (1)$$

The pseudo-second-order model in linearized form is expressed as [45]:

$$1/q_t = 1/(k_2 q_e^2 t) + 1/q_e \quad (2)$$

The intra-particle diffusion model is expressed as [44]:

$$q_t = k_p t^{0.5} + C \quad (3)$$

where q_e (mg g^{-1}) is the Pb adsorbed by dead biomass at equilibrium state, q_t is Pb adsorbed at any time, k_1 (min^{-1}) is the pseudo-first-order rate constant, k_2 ($\text{g mg}^{-1} \text{min}^{-1}$), k_i ($\text{g mg}^{-1} \text{min}^{0.5}$), and C is the intercept reflecting boundary layer effect.

The values of pseudo-first-order rate constant (k_1), pseudo-second-order rate constant (k_2), and intra-particle

diffusion rate constant (k_f) were obtained by plotting $\log(q_e - q_t)$ versus time (t), t/q_t versus t , and q_t versus $t^{0.5}$, respectively.

2.6 Infrared (IR) spectral analysis

Fourier-transform infrared (FTIR) spectroscopy analysis was used to detect the main functional groups present on the surface of dead biomass of bacterial isolates ND1 and ND2 used in the biosorption of Pb(II). Briefly, dead biomass (control and Pb-treated) was dried overnight to avoid any interference due to hydroxyl groups on the surface. The functional groups responsible for Pb adsorption were identified by comparing FTIR spectra (Zn-Se ATR) of both control and Pb-treated biomass using the FTIR spectrometer (PerkinElmer Spectrum Two) at a wave number ranging from 400 to 4000 cm^{-1} .

3 Results and discussion

3.1 Bacterial identification

16S rRNA gene sequence analyses of bacterial isolates ND1 and ND2 against public nucleotide sequence database (GenBank) by BLAST algorithm showed close homology with *M. morganii* (ND1 99.58% and ND2 99.18%).

3.2 Effect of temperature, pH, contact time, and agitation/static condition on biosorption

As most of the developing countries are located in the tropics and subtropics where average temperature is around 28–35 °C, therefore adsorption efficiency of the *M. morganii* ND1 and ND2 dead biomass was assessed at

30 °C and 35 °C. The dead bacterial biomass showed the highest sorption of Pb(II) at 30 °C (Fig. 1); therefore, further experiments were performed at 30 °C. Though some studies reported temperature as a factor of low significance for biosorption by dead biomass [46], we still selected two values of temperature for the functioning of the biosorbent, which lie in the range of prevalent temperature in tropical conditions. In some biosorbent, the temperature higher than the ambient temperature causes physical damage; however, in others, the adsorption serves as an exothermic process [46]. In our case, the temperature of industrial effluent sourced for isolation of Pb-tolerant bacterial strains would be serving as an influencing factor for the performance of bacterial biosorbent as well. A high biosorption by dead biomass of *M. morganii* at ambient temperature enhances its potential for field application because it obviates the need for costly infrastructure for controlling the temperature, which also creates additional pressure on power. Developing countries need low-cost technologies, which remain functional without relying on the additional requirement of energy.

pH acts as a master environmental factor driving the biosorption because it determines the speciation of heavy metal (adsorbate) and surface properties of dead bacterial biomass (adsorbent) and governs the interaction between the two, the deciding factor for biosorption efficacy. Biosorption of Pb and other metal cations like Al, Cd, Co, Mn, Ni, and Zn generally increases at pH close to neutral because the degree of ionization of negative groups present on the biomass also increases. Pb removal by *M. morganii* ND1 and ND2 biomass was tested at pH 3–5. This range of pH was selected because at pH less than 3, metal sorption was reported to be lowered due to the positive charge density on the sites of biomass surface, and pH higher than 5, results in the formation of insoluble

Fig. 1 Lead removal by *M. morganii* ND1 and ND2 at 500 ppm initial Pb concentration, 2 mg/l biomass, temperature of 30 °C and 35 °C in **a** static and **b** shaking condition

metal hydroxides precipitates. Unlike dead biomass from different bacterial species, the biomass of both the bacterial isolates showed high biosorption efficacy at all the pH 3.0, 4.0, and 5.0 under both static and shaking conditions (Figs. 2, 3). Specific need of pH limits the efficacy and application of technology, as changes in pH will result in low adsorption of metal, and maintaining the pH of effluents for optimum results will increase the operational cost of the process. Irrespective of the pH, dead biomass of *M. morganii* ND1 and ND2 maintained high biosorption from pH 3–5, which increases its potential applicability as an efficient biosorbent for Pb removal from a variety of industrial effluents with varied pH; however, the pH optimum was at 5.0.

Irrespective of the pH and shaking or static conditions, *M. morganii* ND1 and ND2 showed > 90% biosorption of Pb(II) (Fig. 2) within 2½ h of contact time. Pb(II) biosorption continued to increase exponentially till entered equilibrium at 12 h. However in equilibrium, both the isolates maintained ~ 90% biosorption of Pb(II) both in shaking or static conditions. Such a pattern of biosorption suggests that with time, the sites available on the biosorbent (cell fragments) saturate and become unavailable for further biosorption via adsorption, complexation, binding, or ion exchange. Also, biosorption slows down with time due to the increase in repulsive forces between the Pb(II) adsorbed at the wall fragments and that present in the solution. Contact time and agitation/static conditions are

Fig. 2 Pb removal by dead biomass of *M. morganii* ND1 and ND2 (2 mg/l) at 500 ppm initial Pb concentration and 30 °C temperature; **a** pH 3 and static, **b** pH 3 and shaking, **c** pH 4 and static, **d** pH 4 and shaking, **e** pH 5 and static, and **f** pH 5 and shaking condition

Fig. 3 Comparison of Pb removal capacity of *M. morganii* ND1 and ND2 with other bacterial dead biomass-based biosorbents at pH 3, 4, and 5, respectively [47–55]

important parameters for designing the process of the wastewater treatment system and determining the economic feasibility of biosorption as maintaining the reaction process in stirring conditions further adds to infrastructural and the power cost of the treatment. Therefore, efficient removal of Pb (89.99–84.05 mg/g) by dead biomass of *M. morganii* ND1 and ND2 at ambient temperature, over a wide pH range, and in static condition can serve as an economic means of Pb removal from industrial effluent.

3.3 Kinetics of biosorption

Adsorption kinetics provides the clue on underlying mechanisms of biosorption, which forms the basis of its industrial application. Kinetics of biosorption explains the rate of metal removal and helps in optimizing time for biosorption and controlling the adsorption process [4].

Table 1 provides a summary of three kinetic models, which have been widely used for determining the

underlying mechanism of biosorption. Because q_e calculated value (q_e^{cal}) was lower than the q_e experimental value (q_e^{exp}), we concluded that adsorption did not follow the pseudo-first-order kinetic model. In our case, the biosorption follows the pseudo-second-order model because q_e calculated value (q_e^{cal}) is close to the q_e experimental value (q_e^{exp}) and has an acceptable correlation coefficient ($R^2 \geq 0.95$). In the pseudo-second-order reaction, the rate-limiting step is a chemical reaction between the adsorbate and adsorbent [45]; therefore, we suggest chemisorption as the dominating mechanism of Pb(II) biosorption by *M. morganii* ND1 and ND2 dead biomass (Fig. 4). Chemisorption-based biosorption by microbial dead biomass results from complexation of metal ions with carboxyl, hydroxyl, amino, and phosphate groups of polysaccharides, proteins, and lipids present on the bacterial cell wall [29, 56]. Intra-particle diffusion, the third model tested, relies on the underlying assumption that intra-particle diffusion acts as the only rate-controlling step. In contrast, film

Table 1 Pseudo-first-order, pseudo-second-order, and intra-diffusion kinetic parameters of biosorption of Pb (initial metal ion concentration = 500 ppm, pH = 5.0, temperature = 30 °C)

<i>M. morganii</i>	Condition	<i>T</i> (Kelvin)	q_e^{exp} (mg/g)	Pseudo-first order			Pseudo-second order			Intra-particle diffusion		
				q_e^{cal} (mg/g)	k_1 (min ⁻¹)	R^2	q_e^{cal} (mg/g)	k_2 (g mg ⁻¹ min ⁻¹)	R^2	k_i (mg/gmin ^{0.5})	C	R^2
ND1	Shaking	303	89.96	9.49	0.65	0.91	67.57	0.02	0.95	18.27	21.19	0.76
ND2	Shaking	303	89.99	9.39	0.75	0.93	100	0.01	0.96	17.99	23.72	0.72
ND1	Static	303	89.99	10.87	1.11	0.99	52.91	0.04	0.95	18.80	19.76	0.78
ND2	Static	303	84.05	9.84	1.11	0.90	59.17	0.03	0.94	17.29	20.90	0.74

Fig. 4 Kinetic plots of **a–d** pseudo-first-order, **e–h** pseudo-second-order, and **i–l** intra-particle diffusion model for the adsorption of Pb onto dead biomass of *M. morgani* ND1 and ND2 (initial Pb concentration = 500 ppm, pH = 5.0, temperature = 30 °C)

diffusion plays a negligible role [57]. The intercept value (C) in the model is considered as the thickness of the boundary layer, which reveals the tendency of metal ions to get adsorbed onto the biomass or to remain suspended in the aqueous suspension. The higher the value of intercept, the greater will be the contribution of surface sorption in the rate-limiting step. The values of k_f and C obtained for ND1 and ND2 were 18.27 g mg⁻¹ min^{0.5}, 18.99 g mg⁻¹ min^{0.5}, 21.19, and 23.72, respectively, in shaking conditions with a correlation coefficient value of 0.76 and 0.72. The k_f and C values for ND1 and ND2 in static conditions were 18.80 g mg⁻¹ min^{0.5}, 17.29 g mg⁻¹ min^{0.5}, 19.76, and 20.90, respectively, with a correlation coefficient value of 0.78 and 0.74. The straight line obtained in the linear portion of q_t versus $t^{0.5}$ plot did not pass through the origin, which implies the rate-limiting effect of film diffusion rather than the intra-particle diffusion (Fig. 4).

3.4 FTIR analysis

Functional groups involved in the biosorption of Pb by bacterial biomass were identified using FTIR in order to elucidate the surface-bonding mechanism. FTIR spectrum for

M. morgani ND1 and ND2 biomass before Pb biosorption showed the characteristic absorption peaks at 3278.99, 2924.09, 1637.89, 1535.34, 1448.54, 1392.61, 1224.8, 1060.85 and 3269.60, 2921.09, 1629.46, 1541.12, 1397.53, 1336.72, 1231.01, 1060.86 cm⁻¹, respectively. These peaks were shifted to 3281.92, 2926.93, 1632.83, 1525.69, 1450.47, 1390.68, 1227.06, 1053.13 cm⁻¹, and 3277.06, 2926.01, 1639.49, 1529.55, 1384.89, 1312.26, 1219.01, 1039.63 cm⁻¹, respectively (Fig. 5) after Pb biosorption due to interaction between functional groups of biomass and Pb(II). Comparison of FTIR spectrum of biomass with or without Pb showed that the peaks of hydroxyl and amine groups shifted from 3278.99 to 3281.92 cm⁻¹ and 3269.60 to 3277.06 cm⁻¹ in ND1 and ND2 indicate the formation of more –OH and –NH by complexation. Interaction with the Pb shifted an anti-symmetric peak of –CH from 2924.09 to 2926.93 cm⁻¹ and 2921.09 to 2926.01 cm⁻¹. Shifting of peaks from 1637.89 to 1632.83 cm⁻¹ and 1629.46 to 1639.49 cm⁻¹; 1535.34 to 1525.69 cm⁻¹ and 1541.12 to 1529.55 cm⁻¹; 1448.54 to 1450.47 cm⁻¹ and 1397.53 to 1384.89 cm⁻¹; 1392.61 to 1390.68 cm⁻¹ and 1336.72 to 1312.26 cm⁻¹; 1224.80 to 1227.06 cm⁻¹ and 1231.01 to 1219.01 cm⁻¹ representing C=O stretching vibration in

Fig. 5 FTIR spectra of *M. morganii* ND1 dead biomass: **a** before Pb biosorption; **b** after Pb biosorption; and *M. morganii* ND2 dead biomass: **c** before Pb biosorption; **d** after Pb biosorption

carboxyl or amide group, C=C stretching, N–H bending; N–O stretching; C–H and O–H bending; C–H bending, C–O bending, S=O stretching; C–N stretching, C–O stretching, respectively, was also observed in the ND1 and ND2 due to Pb(II) biosorption. A shift of peaks from 1060.85 to 1053.13 cm^{-1} and 1060.86 to 1039.63 cm^{-1} in ND1 and ND2 represents PO_4^{3-} stretching and C–O stretching of alcohols and carboxylic acids. Taken these observations, we propose the involvement of functional groups such as N–H , COO^- , OH , C–N , C–O , C–H , C=O , and PO_4^{2-} the Pb(II) biosorption by ND1 and ND2 biomass; however, the carbonyl and hydroxyl groups remain the important functional groups in biosorption [29, 46].

4 Conclusions

Dead biomass of *M. morganii* not only showed high biosorption of Pb(II) at industrially relevant physico-chemical conditions but also exhibited biosorption

efficacy much higher than biosorbent reported from other bacteria. Biosorbents from *M. morganii* maintain high biosorption efficiencies in pH ranging from 3 to 5, which is in contrast with other reported effective biosorbents that show high biosorption only at a specific pH. Besides, this high Pb removal at 30 °C makes it cost-effective as this will reduce the infrastructural cost needed for maintaining a high temperature for the biosorption process. Efficient biosorption in a static condition also adds to the merit of *M. morganii* ND1- and ND2-based biosorbent. Adsorption kinetics of dead biomass of *M. morganii* ND1 and ND2 follows pseudo-second-order kinetic model suggesting chemisorption as an underlying mechanism of Pb(II) removal. Taken together, these properties of dead biomass of *M. morganii* serve as an ideal candidate to develop cost-effective and eco-friendly biotechnology for removing Pb(II) from wastewater. Such biosorption technology would be a step toward developing strategies for a circular economy.

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Compliance with ethical standards

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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