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A meta-analysis of metal biosorption by suspended bacteria from three phyla

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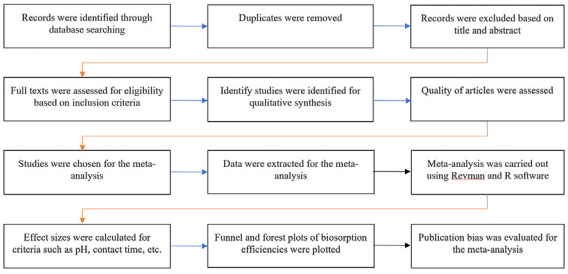
HIGHLIGHTS

- First meta-analysis on biosorption of heavy metals by suspended bacterial strains.
- 56 studies were included in this meta-analysis according to the inclusion criteria.
- Optimum bacterial phyla and operational conditions for biosorption were evaluated.
- Order of biosorption efficiencies of bacterial strains were: Cd > Cr > Pb > Zn > Cu > Ni > Mn.
- The mean biosorption capacity of bacteria was between 71.26 and 125.88 mg g ^{1}.

GRAPHICAL ABSTRACT



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ABSTRACT

Biosorption of heavy metals by bacterial biomass has been the subject of significant research interest in last decades due to its efficiency, relatively low cost and minimal negative effects for the surrounding environment. In this meta-analysis, the biosorption efficiencies of different bacterial strains for Cu(II), Cd(II), Zn(II), Cr(III), Mn(II), Pb(II) and Ni(II) were evaluated. Optimum conditions for the biosorption process such as initial metal concentration, temperature, pH, contact time, metal type, biomass dosage and bacterial phyla, were evaluated for each heavy metal. According to the results, the efficiencies of bacterial biomass for removal of heavy metal were as follows: Cd(II) > Cr(III) > Pb(II) > Zn(II) > Cu(II) > Ni(II) > Mn(II). Firmicute phyla showed the highest overall (living and dead) biosorption efficiency for heavy metals. Living biomass of Proteobacteria had the best biosorption performance. Living bacterial biomass was significantly more efficient in biosorption of Cu(II), Zn(II) and Pb(II) than dead biomass. The maximum biosorption efficiency of bacterial strains for Cd(II), Pb(II) and Zn(II) was achieved at pH values between 6 and 7.5. High temperatures (>35 C) reduced the removal efficiencies for Cu(II) and Zn(II) and increased the efficiencies for Cd(II) and Cr(III) ions. The maximum biosorption efficiency of non-essential heavy metals occurred with short contact times (<2 h). Essential metals such as Zn and Cu were more efficiently removed with long biosorption durations (>24 h). The mean biosorption capacity of bacterial biomass was between 71.26 and 125.88 mg g ^{1}. No publication bias existed according to Egger's and Begg's test results.

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1. Introduction

The rapid growth of industrialization in past decades has led to contamination of the environment especially water bodies (Ali et al., 2019; Khatri and Tyagi, 2015). Contamination caused by industry can be categorized as inorganic, organic and biological. Heavy metals are considered to be the most toxic environmental contaminants in low concentrations (Tchounwou et al., 2014; Jaishankar et al., 2014). Heavy metals are continuously discharged to catchments, and this has resulted in their incorporation into natural systems, direct toxicity to life and bioaccumulation (Anyanwu et al., 2018; Javed and Usmani, 2019). Arsenic (As), lead (Pb), zinc (Zn), selenium (Se), cobalt (Co), chromium (Cr), nickel (Ni), mercury (Hg), cadmium (Cd), copper (Cu) and magnesium (Mn) are some of the highly toxic heavy metals used in industry by human society (El-Sheikh and Alshamaly, 2020; Wuana and Okieimen, 2011; Azeh Engwa et al., 2019). Toxicity of heavy metals is due to their accumulation in organisms and animal tissues, which can eventually enter the human body through food consumption (Singh et al., 2011; Tchounwou et al., 2012; Li et al., 2015). Although heavy metals can be found naturally in the environment, anthropogenic processes are considered as the most important sources of heavy metal release to the environment (El-Sheikh et al., 2018; Cimbolakova et al., 2019; Algul and Beyhan, 2020). Industries such as leather processing, metallurgy, mining, pesticides, petrochemicals, steel and photography are some of largest producers of anthropogenic heavy metals (Smiljanic et al., 2019; Ojedokun and Bello, 2016; Abdoli et al., 2015).

Soil, water and air contamination by heavy metals has become of serious concern around the world in recent years (Masindi and Muedi, 2018; Rai et al., 2019). Heavy metals are generally conveyed via contaminated municipal and industrial runoff and find their ways into water and soil catchments. Heavy metals are not degradable; thus, microbial and chemical degradation do not reduce their concentrations in contaminated catchments (Kirpichtchikova et al., 2006; Tasharrofi et al., 2018). Moreover, even low concentrations of heavy metals in soil and water present a hazard to the environment and human life due to accumulation and their persistent presence in food chains, direct ingestion and plant uptake (Rigby and Smith, 2020). To reduce the negative impacts of heavy metal contamination on receiving ecosystems, several physical and chemical metal remediation technologies have been employed over the years. The most globally accepted and routinely used heavy metal remediation methods are adsorption, precipitation, filtration, ion exchange, biosorption, coagulation and cementation (El-Sheikh et al., 2019a; Kanamarlapudi et al., 2018; Murnane et al., 2019; Kapahi and Sachdeva, 2019).

Biosorption is a physio-chemical process in which heavy metals are removed from contaminated water by ion exchange, surface complexation, chelation and coordination of metal ions using biological adsorbents (Michalak et al., 2013). In general, biosorption is considered to be an efficient, cheap and environmentally friendly remediation method for removal of heavy metals from contaminated water (Bilal et al., 2018). Living and dead microbial cells of bacteria, algae and fungi are the most frequently used biosorbents. The cell walls of biosorbents consist of various functional groups such as amino, carboxyl, hydroxyl and carbonyl groups, that remove metal ions from aqueous solutions by forming a chemical complex (Ramrakhiani et al., 2016; Li et al., 2018). Various living and dead bacterial strains have been investigated and reported to be efficient for the biosorption of heavy metals (Quinton et al., 2017, Boeris et al., 2018; Vishan et al., 2019; Podder et al., 2017; Lu et al., 2018). Biosorption of heavy metals by bacterial biomass processes have been reported to be affected by several physiochemical parameters such as pH, temperature, biomass dosage, initial metal concentration, contact time, type of heavy metal and type of biosorbent. Temperature can alter the structure of proteins and functional groups available on the surface of the biosorbent. pH influences the solubility of heavy metals ions as well as active binding sites of the biomass. Various studies have examined the biosorption efficiencies and capacities of different bacterial strains, and have addressed the effect of the influential parameters described above, on the process. However, there is a lack of concise focus on the biosorption of heavy metals by bacterial strains that could provide information on the most efficient bacterial biosorbent and optimum physio-chemical conditions for the removal of each heavy metal based on published data.

Based on the described research requirements, in this study, data from previous studies were subjected to a meta-analysis. Meta-analysis is a valid, scientific and subjective method to analyze and combine the results of different studies with the same goals and objectives to better understand the subject (Ahn and Kang, 2018). Many researchers have successfully used meta-analysis technique and tools in various fields of studies (Burnes et al., 2019; De Meuse, 2019; Gayed et al., 2018; Riley et al., 2015; Cornell et al., 2014; Orsini et al., 2012). However, the present study is the first meta-analysis for biosorption of heavy metals by bacterial strains. Results were extracted from selected articles based on search terms and inclusion and exclusion criteria to provide an overall understanding of the biosorption process of seven heavy metals (Cu, Cd, Zn, Cr, Mn, Pb and Ni) applied to bacterial biomass. This meta-analysis aimed to provide an overview of researches on the removal of metal ions by bacterial strains in the previous decade (2010–2020) and provide suggestions for future studies.

The general hypothesis of the present study is that type of bacterial biomass from different phyla, their state (living or non-living), environmental factors (temperature, pH, etc), type of heavy metal (Cu, Cd, etc) and associated concentration have a statistically significant effect on the efficiency of biosorption in wastewater treatment process. The results of the present study will help researchers and industries to select the most appropriate bacterial phyla, bacterial state, experimental and process conditions to achieve the optimum biosorption efficiencies according to the contaminated water and wastewater conditions. To evaluate the hypothesis, research aims of the present meta-analysis were as follows:

- To evaluate the biosorption efficiencies of different bacterial biomass for different heavy metals in the last decade
- To identify and evaluate the factors affecting the biosorption process such as initial metal concentration, temperature, pH, contact time, metal type, biomass dosage and the represented bacterial phyla
- Comparative and descriptive analysis of data from selected studies in terms of important physiochemical parameters
- To suggest the optimal biosorption conditions and biosorbent for removal of Cu (II), Cd, Zn, Cr, Mn, Pb and Ni
- To identify knowledge gaps in the field of biosorption by bacterial biomass.

2. Materials and methods

2.1. Data source and search strategy

The literature in this study was extracted according to Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. Electronic databases including Elsevier, PubMed and Wiley were systematically searched for studies between January 1, 2010 and January 1, 2020. The survey strategy included the use of Medical Subject Headings (MeSH) terms of 'Biosorption' OR 'Biosorptions' OR 'Biosorptive' OR 'Removal' AND 'Bacteria' OR 'Bacterias' OR 'Bacteriae' OR 'Microbiology' AND 'Heavy metal' OR 'Metal' OR 'Ion' to search the electronic databases.

2.2. Inclusion and exclusion criteria

EndNote X9.2 (Thompson Reuter, CA) was used to remove duplicate literature matches extracted from the databases. In the next step, the titles and abstracts of the remaining records were assessed and irrelevant studies were excluded. Inclusion and exclusion criteria were applied after assessing the full text of remaining studies. Afterwards, data were extracted from the selected records according to parameter extraction sheets. Inclusion and exclusion criteria in this study were:

a) Original papers on biosorption of different heavy metals by various bacterial phyla, in English, published in peer reviewed journals between 2010 and 2020.
b) Papers with inadequate experimental criteria data and consistent methodologies were excluded.
c) Conference papers, book chapters, posters, review papers were excluded from this study.
d) Papers that did not report the sample size in their full text were excluded from the meta-analysis.

2.3. Data extraction and methodology quality assessment of records

The authors designed the data extraction method including: 1) type of heavy metal, 2) bacterial species, 3) bacterial state, (living or dead organisms) 4) biomass dosage, 5) initial heavy metal concentration, 6) temperature, 7) contact time, 8) pH and 9) equilibrium concentration or biosorption capacity. One author extracted the data and another author checked and evaluated the data. If different decisions were reached on the selected studies and extracted data, they reassessed the data sheet together, making a final mutual decision. The quality of selected papers was assessed according to the method proposed by Azari et al. (2020), based on number of the 9 criteria mentioned above. Papers with 5 or more criteria included were considered high quality and included in the final meta-analysis. Papers with lower quality, according to the inclusion and exclusion criteria, were excluded in this study to reduce the risk of publication bias. Corresponding authors of all selected papers with high quality and no sample size reported in the manuscript, were contacted and asked for the missing information to meet the criteria 4 in section 2.2.

2.4. Statistical analyses

The meta-analysis in this study was carried out using RevMan 5 software (Cochrane, London). In order to evaluate the capacity and efficiency of various bacterial strains to remove heavy metal ions from aqueous solution, the type of heavy metal, bacterial taxon, bacterial state, biomass dosage, initial heavy metal concentration, temperature, contact time, pH and equilibrium concentration in each study were compared. To achieve this goal and eliminate the methodological differences between selected studies such as initial heavy metal concentrations, the R parameter (Hedges et al., 1999) which was used to evaluate the effect sizes of different bacterial strain biosorption efficiencies. This parameter was calculated as follows:

$$R = Ln(X_e / X_c)$$

where X_e is the equilibrium adsorbed heavy metal concentration after the biosorption by the bacteria and X_c is the initial heavy metal concentration before the biosorption process. Bacterial species with higher R value are more efficient in biosorption of heavy metals from aqueous solutions (Nguyen et al., 2017).

The meta-analysis was conducted according to the calculated R value, sample size and biosorption capacities of different bacterial strains. Quantitative tools of Tau^2 and I^2 were used to evaluate the statistical heterogeneity of the studies, in the present meta-analysis. Tau^2 is a tool that RevMan software presents to estimate the between-study variance in a random-effects meta-analysis and I^2 is an index to quantify the dispersion of effect sizes in the meta-analysis. Where an I^2 value more than 75% is considered to show high heterogeneity. An I^2 value more than 50% is an indicator of substantial heterogeneity (Cochrane Handbook). Mean effect sizes and 95% confidence intervals (CI) were calculated using RevMan software to evaluate the statistical significance. A 95% confidence interval is a range of values that you can be 95% certain contains the true mean of the population. A P value of less than 0.05 was considered as statistically significant and figures were generated using Microsoft Excel. P value is the evidence against a null hypothesis. When heterogeneity was significant, a random effect model was used to analyze the data. However, in the case of low heterogeneity (I^2<50%), a fixed effect model was utilized. R software (4.0) was used to provide Funnel plots to evaluate the publication bias by using Egger's and Begg's tests (Zhang et al., 2020).

3. Results and discussion

3.1. Selected studies and extracted data

In the initial search of the databases, a total number of 3388 papers were identified which included 2108, 642 and 638 records from Elsevier, PubMed and Wiley, respectively. Supplementary Figure 1 (Fig S1) illustrates the process of selecting papers for the meta-analysis in this study. According to this figure, 614 records were excluded due to duplication using EndNote software. In the next step, according to PRISMA guidelines, the titles and abstracts of remaining studies were assessed and 1855 articles were omitted for being unrelated to this study, non-English language, not original research and with different experimental conditions. Full texts of the remaining records were screened carefully and according to the inclusion criteria of this study, 355 articles were eligible for further evaluation. From these, 277 studies were excluded due to simultaneous biosorption of different heavy metals, a lack of reported data and a limited focus on factors affecting the biosorption process (for example, pH, temperature). 22 papers from 78 remaining records were further omitted due to low quality (reporting less than 5 of the necessary research criteria) and finally 56 records were selected to be included in the meta-analysis. Supplementary Material 1 includes details and data from all 56 selected records in this study. As described above, in order to eliminate the differences in initial concentration used in different studies, the R parameter was calculated for all 56 studies that were chosen for this research. R-values, sample sizes, effect sizes and references of studies selected for meta-analysis are shown in Table 1.

3.2. Effect of key factors on biosorption process

Biosorption of heavy metals by bacterial biomass is affected by factors such as type of heavy metal, type and phylum of bacteria, pH, contact time, initial metal concentration, temperature, biomass dosage and state (Tan and Chen 2012; Oves et al., 2013; Ahmad et al., 2014; Khadivinia et al., 2014; Varia et al., 2014; Abu Hasan et al., 2016; Munoz et al., 2016). Contaminated water and runoff are thought to be treated by biosorption processes using bacteria. Despite this, the mechanisms of biosorption in stormwater have not been fully explored and the attenuation of soluble contaminants in drainage systems is generally not well understood. Therefore, it is important to identify the effect of factors influencing the attenuation of soluble metals in stormwater using published data, and report the optimum conditions for biosorption of various heavy metals using different bacterial strains.

3.2.1. Heavy metal type

As shown in Table 1, a total number of 56 studies were selected to evaluate the biosorption of heavy metals, including Cu(II), Cd(II), Zn(II), Cr(III), Mn(II), Pb(II) and Ni(II). As illustrated in the data extraction form in Supplementary Material 1, selected articles provided 111 data sources for the heavy metals in this study. Pb had the most records with 21 data sources. Mn was the least reported

Table 1
Bacterial species and phylum, Effect Size, Sample size and references of studies included in the meta-analysis.

Species with Actinobacteria phylum	Heavy metal: Sample size, R	Reference
Arthrobacter viscosus	Cr: 3, 0.598	Hlihor et al., 2016
Curtobacterium sp. *FM01*	Ni: 3, 0.123, Pb: 3, 0.271	Masoumi et al., 2017
Leucobacter sp. *N-4,*	Ni: 3, 0.149	Qu et al. (2011)
Micrococcus luteus	Pb: 3, 0.447, Cu: 3, 0.291	Puyen et al. (2012)
Mycobacterium sp.	Cr: 3, 1.609	Aryal and Liakopoulou-Kyriakides (2014)
Rhodococcus erythropolis	Cu: 6, 0.545	Baltazar et al., 2018
Rhodococcus opacus	Pb: 6, 0.133	Bueno et al. (2011)
Rhodococcus opacus	Ni:5, 1.204	Cayllahua and Torem (2011)
Streptomyces ciscaucasicus	Zn: 3, 0.328	Li et al. (2010)
Streptomyces K11	Zn: 3, 0.162	Sedlakova-Kadukova et al., 2018
Streptomyces lunalinharesii	Zn: 3, 0.198, Cu: 3, 0.198	Veneu et al. (2013)
Streptomyces roseorubens SY	Ni: 5, 0.236	Long et al. (2018)
Tsukamurella paurometabola A155	Zn: 3, 0.223, Cd: 3, 0.371	Limcharoensu et al. (2015)
Species with Firmicutes phylum		
Acinetobacter baumannii SCE3	Pb: 3, 0.266	Mathew and Krishnamurthy (2018)
Bacillus anthracis SCE2	Pb: 3, 0.773	Mathew and Krishnamurthy (2018)
Bacillus cereus	Pb: 6, 0.061, Mn: 6, 1.021	Abu Hasan et al. (2016)
Bacillus cereus RC-1	Cd: 6, 0.073	Huang et al. (2013)
Bacillus coagulans R11	Pb: 3, 0.235	Xing et al. (2018)
Bacillus SP	Cd: 3, 0.867, Cr: 3, 0.151, Mn:3, 0.654, Pb: 3, 0.198	Garcia et al. (2016)
Bacillus sp. *Putida*	Mn: 6, 0.357	Hasan et al. (2012)
Bacillus sp. *PZ-1*	Pb: 5, 0.105	Ren et al. (2015)
Bacillus thuringiensis	Cr: 3, 1.119, Ni: 3, 1.455, Cd: 3, 0.310, Cu: 3, 0.159, Pb: 3, 0.105	Oves et al., 2012
Bacillus toyonensis SCE1	Pb: 3, 0.166	Mathew and Krishnamurthy (2018)
Bacillus toyonensis SCE4	Pb: 3, 0.426	Mathew and Krishnamurthy (2018)
Bacillus toyonensis SCE5	Pb: 3, 0.467	Mathew and Krishnamurthy (2018)
Bacillus xiamenensis	Pb: 3, 0.357	Mohapatra et al. (2019)
Lysinibacillus sp. *BA2*	Ni: 3, 0.173	Prithviraj et al. (2014)
Paenibacillus polymyxa	Cu: 3, 0.654 Ni: 3, 1.059	Çolak et al. (2013)
Pediococcus pentosaceus	Cd: 3, 0.631	Le et al. (2019)
Species with Proteobacteria phylum		
Acidiphilium symbioticum H8	Cd: 3, 0.315	Chakravarty and. Banerjee (2012)
Acinetobacter baumannii SCE3	Pb: 6, 0.266	Mathew and Krishnamurthy (2018)
Acinetobacter junii	Cr: 5, 0.094	Paul et al. (2012)
Acinetobacter sp.	Zn: 3, 0.594	Tabaraki et al. (2013)
Brevundimonas sp. *ZF12*	Cd: 3, 0.477	Masoudzadeh et al. (2011)
Burkholderia vietnamiensis	Cu: 6, 0.419	Zhou et al. (2014)
Cupriavidus metallidurans CH34	Cu: 5, 0.116, Cr: 5, 0.041	Fan et al. (2014)
Cupriavidus taiwanensis E324	Zn: 3, 0.545, Cd: 3, 0.562	Limcharoensuk et al. (2015)
Halomonas	Cd: 6, 0.123	Manasi et al. (2014)
Klebsiella sp.	Zn: 6, 0.032	Muñoz et al. (2018)
Ochrobactrum intermedium LBr	Cu: 5, 0.198, Cr: 5, 0.139	Fan et al. (2014)
Ochrobactrum MT180	Cu: 5, 0.030	Peng et al. (2019)
Ochrobactrum sp	Cd: 5, 0.230	Khadivinia et al. (2014)
Pectobacterium Sp.	Cd: 3, 0.136, Cu: 3, 0.041, Zn: 3, 0.545, Pb: 3, 0.077	Liu et al. (2018)
Providencia sp	Pb: 3, 0.211, Cr: 3, 0.128, Cd: 3, 0.105, Cu: 3, 0.092, Mn: 3, 0.579, Zn: 3, 0.513	Li et al. (2020)
Pseudomonas aeruginosa	Zn: 3, 0.223	Joo et al. (2010)
Pseudomonas aeruginosa B237	Zn: 3, 0.274, Cd: 3, 0.288	Limcharoensuk et al. (2015)
Pseudomonas azotoformans	Cu: 3, 0.635, Pb: 3, 0.211, Cd: 3, 1.108	Choinska-Pulit et al., 2017
Pseudomonas sp	Cd: 3, 0.474, Pb: 3, 0.194	Huang et al. (2013)
Pseudomonas sp	Cu: 5, 1.003	Andreazza (2010)
Pseudomonas sp. *I3*	Pb: 3, 0.139	Li et al. (2017)
Pseudomonas sp	Mn: 3, 1.122	Gialamouidis et al. (2010)
Pseudomonas sp. *375*	Cd: 5, 0.029	Xu et al., 2019
Rhizobium leguminosarum bv. Viciae	Cd: 3, 0.568	Abd-Alla et al., 2011
Rhodobacter sphaeroides SC01	Pb: 3, 0.041, Cd: 3, 0.462	Su et al., 2019
Stenotrophomonas maltophilia	Cu: 3, 0.105	Ghosh and Saha (2013)

with 5 data sources. Cd(II), Cu(II), Ni(II), Cr(III) and Zn(II) had 17, 14, 7, 8 and 10 data sources. The effect sizes of different heavy metals were calculated according to R values and sample sizes and are presented in Fig. 1. The higher values of effect size, represent higher biosorption efficacies. According to Fig. 1, Pb had the highest number of data with 107, and with an effect size less than 0.5. The order of efficiency was Cd(II) > Cr(III) > Pb(II) > Zn(II) > Cu(II) > Ni(II) > Mn(II) which revealed that biosorption of Cd was the most efficient (ES =− 0.31). Mn had the lowest efficacy (ES =− 1.46). Cd(II), Cr(III) and Pb(II) had effect sizes lower higher than 0.5, Cu(II) and Zn(II) showed effect sizes between 0.5 and 1.0, Ni(II) and Mn(II) had effect sizes lower than 1.0. This observation revealed that bacterial strains had the highest biosorption efficiencies for Cd(II), Cr(III) and Pb(II). This efficiency reduced for Cu(II), Zn(II) and showed the lowest efficiencies for Mn(II) and Ni(II).

The considerable differences in bacterial biosorption capacities for different heavy metals, can be explained by various factors such as molecular weight, ionic radius and the oxidation state of the metal ion (Park et al., 2010, Tsezos et al., 2006). Moreover, properties of the biosorbent such as the functional groups available on the surface and the bacterial state (living or dead microbes) influence the biosorption process (Xingjie et al., 2018). Biosorption of heavy metals by bacterial biomass occurs through the relatively quick processes of ion exchange, complexation, chelation, coordination, reduction, physical adsorption and precipitation. The process of metal active transport to the inside of the bacterial cell is slower (Mrvcic et al., 2012). Complexation takes place by the formation of a complex between functional groups available on the surface of the bacterial cells and the metal ion (El-Sheikh et al., 2019b; Wu et al., 2012). Functional groups have various complexation process for different heavy metals which will lead to different biosorption capacities. Carboxyl, hydroxyl and amine groups are the main functional groups that have been reported to be responsible for the biosorption of heavy metals by bacterial strains (Shamim, 2018). Functional groups are also involved in the exchange of binary metal ions during the biosorption process. Heavier metal ions have a closer affinity with functional groups available on the bacterial cells, during the complexation process (Becker and Peiffer, 1997). Pb(II) and Cu(II) ions have larger cation sizes than other metals in this study, showed a higher biosorption capacity. This phenomenon is in line with the pattern in Fig. 1. Lighter heavy metal ions of Mn(II) and Ni(II) had less affinity with the biosorbent functional groups and as a result showed a lower adsorption capacity.

3.2.2. Bacterial phyla and state

One of the factors influencing the complexation of heavy metals in biosorption processes is the composition of the bacterial community (Mustapha and Halimoon, 2015). Different species of bacteria produce their own specific Extracellular Polymeric Substance (EPS) layer with functional groups that alter the bacterial biosorption capacity (Wei et al., 2016). In this study, the biosorption data from selected studies were categorized to three main bacterial phyla: the Firmicutes, Actinobacteria and Proteobacteria. These 3 particular bacterial phyla were chosen for inclusion in this study, due to the lack of data on other bacterial types in selected records. Effect sizes and the sample size of different bacterial phyla, used for biosorption of seven heavy metals in this study are presented in Fig. 2a. The phylum Proteobacteria was of most interest to researchers in the last decade with 47 recorded data points. From these 47 data points, 23 used living proteobacteria for biosorption, which was more records of living microbe biosorption than the other phyla. Actinobacteria and Firmicutes had 22 (4 living) and 42 (14 living) data points, respectively. Proteobacteria showed the best overall biosorption capacity with an effect size of 0.44.

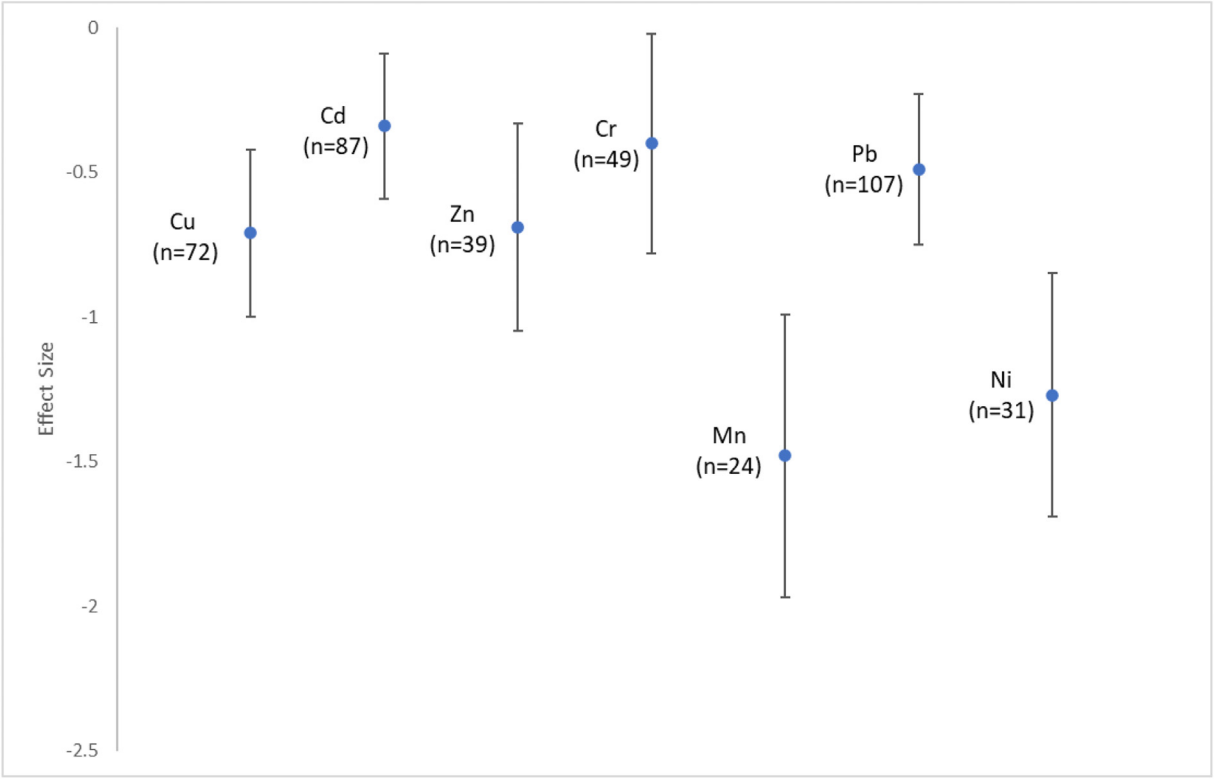

Fig. 1. Effect sizes of bacterial biosorption of different heavy metal ions. Error bars are ±95% CI. n represents number of samples. Heterogeneity of the pooled data was $P < 0.001$.

Actinobacteria had an effect size of 1.36 which indicated that this phylum provided the least capacity for removal of heavy metals. Firmicutes had an overall effect size of 1.15 which presented a medium efficiency in the total number of samples. The living and dead bacterial biomass revealed that although Proteobacteria had the best overall (living and dead) biosorption performance, dead strains of Proteobacteria showed the lowest effect size (1.77) for all bacterial phyla. In terms of all dead bacterial strains, Firmicutes had the highest effect size and as a result a better biosorption efficiency. Considering the living strains, Proteobacteria showed a noticeable higher performance in comparison to Firmicutes and Actinobacteria. This observation can be due to differences in cell structure between bacterial phyla. Proteobacteria are gram-negative bacteria, whereas Firmicutes and Actinobacteria are gram-positive (Rizzatti et al., 2017; Barka et al., 2016; Davey et al., 2016). The cell wall thickness of gram-negative bacteria is 8–10 nm which provides an easier and quicker route for a living bacterial cell to absorb the heavy metal ions, compared with gram-positive bacterial cells which typically have 20–80 nm thick walls (Huang et al., 2008; Silhavy et al., 2010). Peptidoglycan layers in gram-negative bacteria provide a single thin layer that is favourable for the intracellular diffusion of metal ions (Vollmer et al., 2008). The peptidoglycan layer is a thick multilayer in gram-positive bacteria, providing a more complicated barrier preventing living organisms from absorbing the metal ion. The rigid and thick peptidoglycan layer of gram-positive bacteria consists of carboxyl, amide and phosphate functional groups which have been reported to be active in the biosorption process (Jiang et al., 2004; Barreteau et al., 2008). The lack of a thick peptidoglycan layer in gram-negative Proteobacteria, assists active living bacteria biosorption, but, for dead bacteria less functional groups resulted in a lower adsorption capacity. The fundamental cell structure differences between gram-positive and negative bacteria, explains the difference in performance of living cells of Proteobacteria in the biosorption of the heavy metal ions, in comparison with Firmicutes and Actinobacteria.

Previous studies have reported different biosorption efficiencies for living and dead bacterial biomass (Hlihor et al., 2017, Hu et al., 2020, Malkoc et al., 2015; Contreres-Cortes et al., 2020). In order to evaluate the efficacy of both bacterial states (living or dead) in biosorption processes, a total of 86, 62, 107, 24, 51, 42 and 25 results included in this meta-analysis, were extracted for Cd, Cu, Pb, Mn, Cr, Zn and Ni, respectively. The effect sizes of using living and dead biomass for the removal of heavy metals are shown in Fig. 2b. Effect sizes were calculated with ±95% confidence interval and heterogeneity of $P < 0.001$. According to Fig. 2b, living bacterial strains were more efficient for the removal of 6 out of 7 heavy metals studied in this meta-analysis, except for Mn that had a higher effect size for dead biomass. According to Fig. 1, the overall (living and dead) performance of bacterial biomass in biosorption of heavy metals was in the following order: Cd(II) > Cr(III) > Pb(II) > Zn(II) > Cu(II) > Ni(II) > Mn(II). As shown in Fig. 2b, in the case of living bacteria, the order of biosorption efficiency was Cr(III) > Cu(II) > Cd(II) > Pb(II) > Zn(II) > Mn(II) (the dataset for Ni(II) was not large enough for inclusion). For dead bacterial biomass, the order of biosorption efficiencies was: Cr(III) > Cu(II) > Ni(II) > Cd(II) > Mn(II) > Cu(II) > Pb(II). In both dead and living bacterial biomass, the highest effect sizes and efficiencies were achieved for Cr(III). This observation can be explained by the multistep removal mechanism of functional groups for Cr(III) which starts with adsorption, continues with complexation and the final step is reduction (Zhang et al., 2018). This three-step mechanism does not need the organism to be living and active and as a result, the Cr(III) removal by both states of bacterial biomass was high and not altered significantly. The living or dead state did not have a significant effect on the Cr(III) or Cd(II) biosorption capacities, of the bacterial biomass. However, Zn(II) and Cu(II) showed a significant reduction in effect size and biosorption rates with a dead bacterial state. One explanation of this difference between Cr(III), Cd(II) and Zn(II) and Cu(II), is the fact that Zn(II) and Cu(II) are essential heavy metals and bacterial cells actively absorb Zn(II) and Cu(II) ions for their metabolism (Arif et al., 2016). Therefore, active living bacterial biomass showed higher effect sizes, and as a result, had higher removal capacity for Zn(II) and Cu(II) in comparison to dead bacterial strains. However, a dead or living state did not alter the biosorption capacity of bacterial biomass for non-essential Cr(III) and Cd(II) ions. Living bacterial biomass are significantly altered by the environmental conditions such as pH, temperature and initial concentrations of heavy metals (Fathollahi et al., 2020; Al-Homaidan et al., 2014). These conditions affect organism metabolism and can result in a reduction in their biosorption capacities. In the following sections the effect of pH temperature and other conditions will be discussed.

3.2.3. Bacterial phyla and heavy metal type

As described in section 3.2.2, the bacterial taxonomy has a significant effect on the efficiency of biosorption in the removal of heavy metals in aqueous solution. In this section, the biosorption capacity of Firmicutes, Actinobacteria and Proteobacteria phyla for removal of 7 heavy metals were evaluated. Effect sizes and number of samples for each heavy metal are presented in Fig. 3. For Cd(II) there was not sufficient data available for Actinobacteria; effect sizes for Firmicutes and Proteobacteria were not significantly different. This revealed that biosorption of Cd(II) is not altered by the type of bacterial phylum. For Cd(II) ions, as described in section 3.2.2, the state of the bacteria did not affect the biosorption capacity, which was due to the non-essential nature of the cadmium ions. The type of phylum had a considerable effect on levels of Cu(II) removal efficiency. Proteobacteria showed the highest effect size (0.71) and Actinobacteria phyla had the lowest effect size (2.19). For Pb(II) ions, the effect sizes of Firmicutes, Actinobacteria and Proteobacteria phyla were 1.24, 1.56 and 1.59, respectively, which was not significant. In a similar pattern, differences in bacterial phyla did not have a significant effect on the biosorption efficiency of Mn, with less than 0.15 change in effect sizes. However, bacterial phyla showed the greatest influence (among 7 heavy metals in this study) on the effect size of Cr(III) biosorption. Firmicutes had the highest effect size (0.93) and the lowest effect size was for Proteobacteria (2.21). For Zn(II), Proteobacteria had a higher biosorption efficiency than Actinobacteria. However, Ni was the only heavy metal for which Actinobacteria had a higher effect size (0.96) and as a result, higher biosorption efficiency than Firmicute phyla (1.36).

According to Fig. 3 Firmicutes showed the highest biosorption efficiency for Cr ions. The order of biosorption efficiency for Firmicute phyla was as follows: Cr(III) > Cd(II) > Cu(II) > Pb(II) > Ni(II) > Mn(II). Actinobacteria was the most efficient phylum in biosorption of Ni ions. Pooled data from selected studies revealed that the efficiency order of Actinobacteria for heavy metals was Ni(II) > Cr(III) > Pb(II) > Cu(II) > Zn(II) and the order for Proteobacteria was Cu(II) > Cd(II) > Zn(II) > Pb(II) > Mn(II) (Hussein et al., 2004; Kanamarlapudi et al., 2018; Redha 2020). Fig. 3 shows that the most efficient phyla for Cu, Ni and Cr were Proteobacteria, Actinobacteria and Firmicutes, respectively. Phylum Firmicutes was the most efficient for biosorption of Cd(II), Pb(II), Mn(II) and Cr(III). Proteobacteria was most efficient in the biosorption of essential heavy metals (Cu(II) and Zn(II)). This observation can be explained by the structure of Proteobacteria phyla. As described in section 3.2.2, cell wall of gram-negative bacteria is thinner than gram-positive bacteria which provides a quick route for bacterial cell to

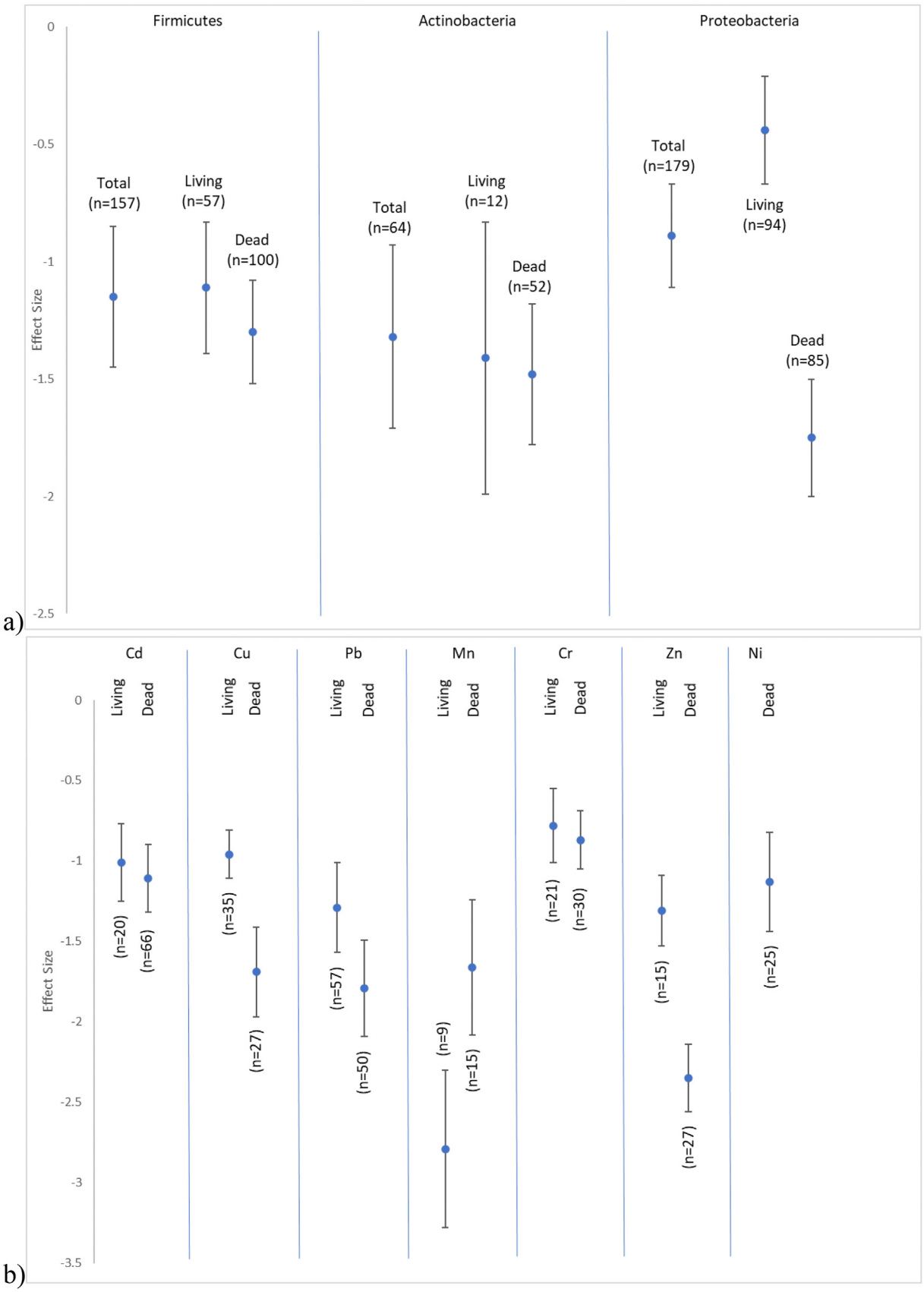

Fig. 2. a) Effect sizes of different bacterial phyla and states on heavy metal adsorption. b) Effect sizes of bacterial states on biosorption of heavy metals. Error bars are ±95% CI. n represents number of samples. Heterogeneity of the pooled data was $P < 0.001$.

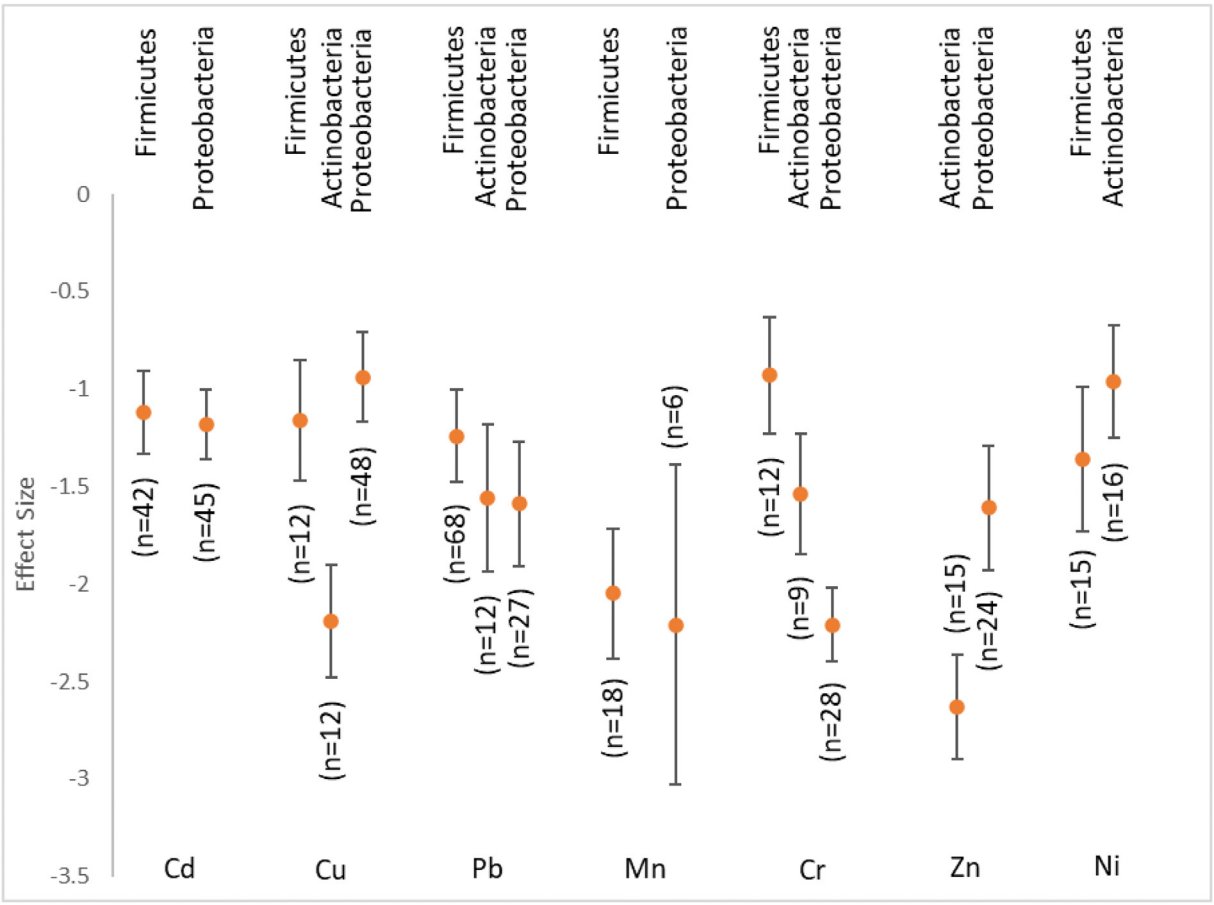

Fig. 3. Effect sizes of bacterial phyla on biosorption of heavy metals. Error bars are ±95% CI. n represents number of samples. Heterogeneity of the pooled data was $P < 0.001$.

absorb the heavy metal ions. The peptidoglycan layer in gram negative bacteria is a single thin layer that is favourable for intracellular diffusion of metal ions. As a result, thinner cell walls of Proteobacteria showed a higher efficiency in biosorption of essential heavy metals (Bakkaloglu et al., 1998; Mishra 2014, Kılıç et al., 2014).

3.2.4. pH

During biosorption, the pH of an aqueous solution has a significant effect on the speciation of the metal ions, electrostatic charges and functional groups available on the biosorbent surface and degree of ionization (Fears et al., 2009). In order to evaluate the optimum pH value for biosorption of seven heavy metals in this study by bacterial biomass, 86, 66, 31, 107, 24, 54 and 42 data were pooled for Cd(II), Cu(II), Ni(II), Pb(II), Mn(II), Cr(III) and Zn(II), respectively. pH values of <6, between 6 and 7.5, 7.5, which were classified as low, medium and high, respectively. There were very few studies using alkaline conditions for the biosorption process and as a result data were not sufficient for meta-analysis. This can be due to lower solubility of heavy metals in pH conditions higher than 8 which is known to interfere with biosorption (Chaudhuri et al., 2013). Fig. 4a illustrates the effect sizes of low and medium pH on the biosorption of seven heavy metals in this study. 6 out of 7 heavy metals showed a higher effect size at medium pH values. Cr was the only metal which was more efficiently removed at pH less than 6. The maximum efficiency of bacterial strains in biosorption of chromium at low pH (2–4) has been previously reported by several studies (Tarangini and Satpathy 2009; Rasheed et al., 2020; Sethuraman and Balasubramanian, 2010; Nguema et al., 2014). This revealed that acidic conditions are optimum for Cr removal by bacterial biomass. The decrease of removal percentages in higher pH can be a result of the shift of monovalent $HCrO_4$ to divalent $Cr_2O_7^{2}$ and CrO_4^{2} ions in metal solutions (Palmer et al., 1994). For the rest of the heavy metals, the effect size and as a result the biosorption capacity of the biomass increased at medium pH (6–8). This increase may be due to the reduction in the number of H^+ in aqueous solution at higher pH levels, which leads to less competition between heavy metal ions and protons to bond with the active binding site on the biosorbent surface (Pagnanelli et al., 2000; Beena Lahari et al., 2011; Fontana et al., 2016). The solution pH changes the composition of bacterial cell walls and metabolism of the living biomass and metal transport patterns, leading to a change in the biosorption capacity of the biosorbent (Krulwich et al., 2011; Ramstedt et al., 2014). The greatest increase in effect size at medium pH was for Cd(II), Pb(II) and Zn(II). The optimum pH of between 6 and 7.5 for Cd(II), Pb(II) and Zn(II) has been reported by several studies (Tarbaoui et al., 2016; Park and Chon, 2016; Kaya et al., 2009; Malkoc et al., 2015; Hu et al., 2014). At pH values between 6 and 7.5, the speciation of Pb changes from Pb^{2+} to $Pb{-}OH_2$ which is a species with low solubility. This process leads to the precipitation of Pb(II) ions and interferes with the biosorption process, resulting in higher removal efficiency (Wei et al., 2016; Kariuki et al., 2017). According to the present meta-analysis results, Cd(II), Pb(II) and Zn(II) were more efficiently treated by bacterial biomass at pH between 6 and 7.5. Low and medium pH did not show significant difference in effect sizes or biosorption efficiencies for Cu(II), Ni(II), Mn(II) and Cr(III).

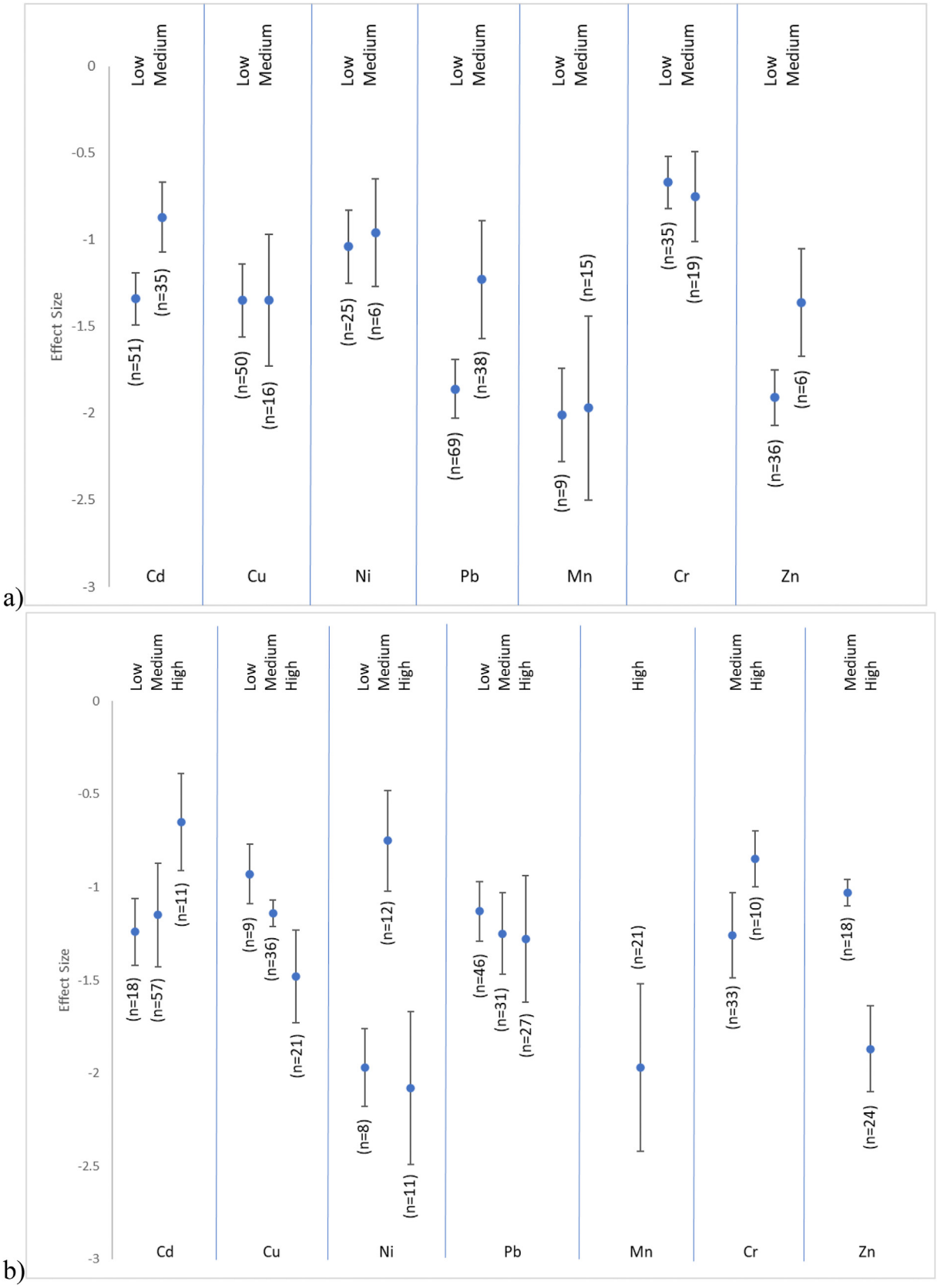

Fig. 4. a) Effect sizes of pH on biosorption of heavy metals by bacterial biomass. b) Effect sizes of different temperatures on biosorption of heavy metals. c) Effect of different contact time on biosorption of heavy metals. Error bars are ±95% CI. n represents number of samples. Heterogeneity of the pooled data was $P < 0.001$.

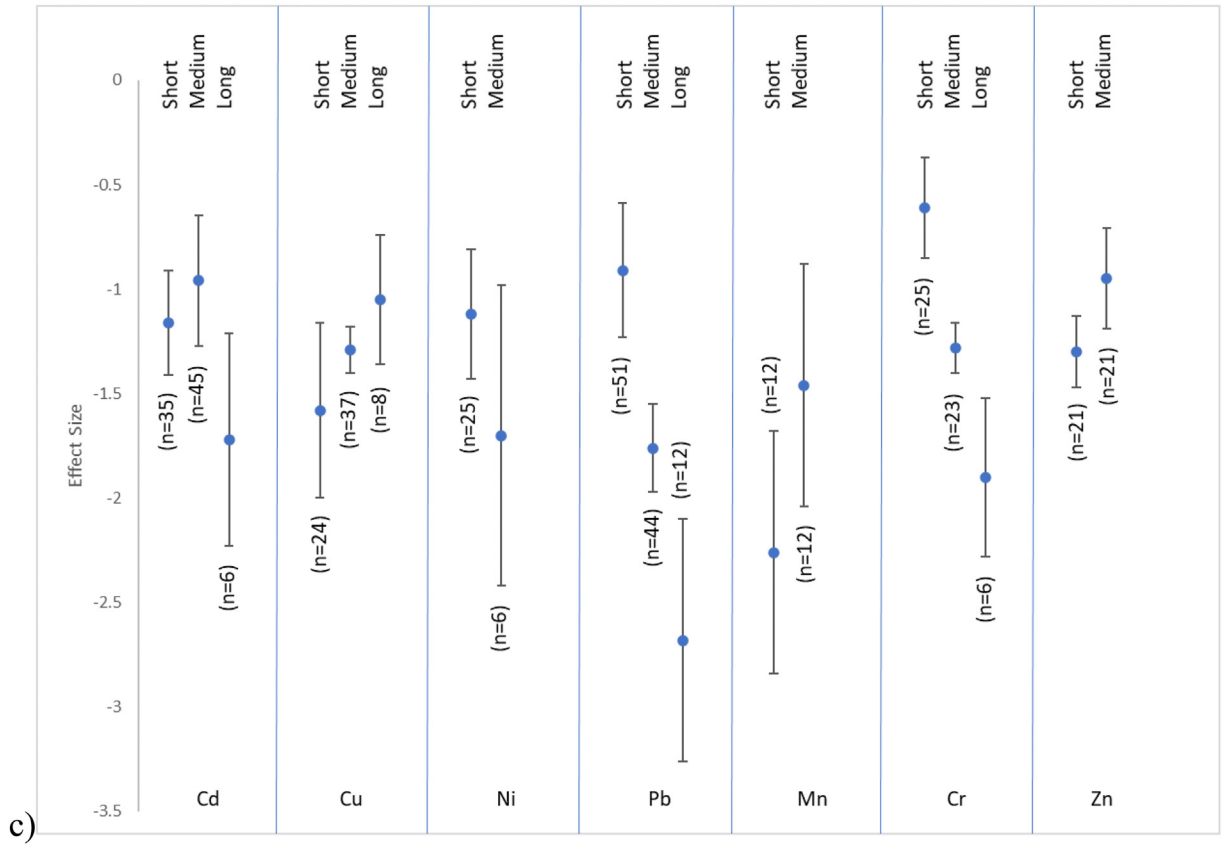

Fig. 4. (*continued*).

3.2.5. Temperature

Temperature is one of the main factors influencing the thermodynamics of the biosorption process and should be studied to find the optimal biosorption conditions (Osasona et al., 2013; Ali and Alrafai 2016). A total of 23, 16, 9, 28, 5, 13 and 13 data points were pooled for Cd(II), Cu(II), Ni(II), Pb(II), Mn(II), Cr(III) and Zn(II), respectively, to evaluate the effect of temperature on bacterial biomass biosorption efficiency. The experimental temperature used in the selected studies in this meta-analysis were categorized into Low (<27 C), Medium (27 C T 35 C) and High (>35 C). Effect and sample sizes of pooled data for seven heavy metals are illustrated in Fig. 4b. The temperature effect size on biosorption of Cd(II) ions decreased with the increase of temperature which revealed that bacterial biomass biosorption efficiency for removal of Cd(II) ions was the highest at temperatures >35 C. The same pattern was observed for Cr(III) ions with an effect size of 0.85 at temperatures >35 C which has been previously reported in several studies (Rezaei and Mazzola, 2013;Jobby et al., 2019). The effect size of temperature on Ni biosorption by bacterial strains increased at medium temperatures (0.74) and showed a good biosorption efficiency. However, at higher temperatures (>35 C) a rapid decrease in effect size (2.08) and biosorption capacity was observed. The increase in biosorption capacity of the bacterial biomass at temperatures between 27 C and 35 C, can be attributed to the increase in the number of active binding sites on the surface of biomass. Additionally, high temperatures may reduce the thickness of the boundary layer on bacterial cells which leads to a lower mass transport resistance of the layer against Ni ions (Alpat et al., 2010). The change of effect size with the increase of temperature, followed a different pattern for Zn(II) and Cu(II) ions, which revealed an inefficient biosorption by bacterial strains at high temperatures. As described in section 3.2.2., living biomass showed a high biosorption capacity for Cu(II) and Zn(II) and on the contrary, the dead biomass showed a considerably lower efficiency (Fig. 2a). As the experimental temperature in the majority of studies that had used living bacteria for biosorption was less than 30 C and the fact that the living biomass showed a higher biosorption efficiency, it can be concluded that the reason for the observed decrease in effect size may be attributed to the lack of using living biomass at temperatures higher than 35 C. However, the decrease in bacterial metabolism and the destruction of active binding sites on bacterial cells at high temperatures, may also be a reason for the decrease of biosorption capacity of bacterial biomass for Cu(II) and Zn(II) ions. No significant change of effect size was observed for Pb at high temperatures and the data for low and medium temperatures were not sufficient for meta-analysis.

3.2.6. Contact time

The majority of biosorption studies have reported a fast initial adsorption rate, before the process slows and reaches an equilibrium concentration (Garcia et al., 2016; Kalita and Joshi, 2017; Gupta and Balomajumder, 2015; Podder and Majumder, 2018; Mathew and Krishnamurphy, 2018; Carvajal et al., 2012; Fang et al., 2014). The reason for the fast removal rate at the start of the biosorption process, is due to more vacant and unoccupied active biosorption sites available on the biomass surface. These active binding sites are filled with metal ions during the biosorption process, which leads to a slower rate of adsorption before reaching the saturation point and ultimately an equilibrium state (Tsai and Chen, 2010; Das et al., 2014; Kumar et al., 2019). In this meta-analysis, contact times of <2, 2 < T < 24 and >24 h were considered as short, medium and long, respectively. To evaluate the effect

of contact time on biosorption of seven heavy metals by bacterial biomass, 23, 17, 9, 29, 6, 14 and 13 data points were extracted for Cd(II), Cu(II), Ni(II), Pb(II), Mn(II), Cr(III) and Zn(II), respectively. Data were pooled using ±95% confidence interval and heterogeneity of $P < 0.001$. Fig. 4c illustrates the effect of short, medium and long contact time on biosorption of different heavy metals. The results for Cd(II) ions showed that the medium contact time (2 h < T < 24 h) resulted in the most biosorption efficiency (effect size =− 0.96). By increasing the contact time to more than 24 h, the effect size and ultimately the removal efficiency for Cd(II), decreased. The observed decrease in biosorption capacity at longer contact times, may be due to the longer exposure and as a result higher toxicity of metal ions to the living bacterial strains (Ibuot et al., 2017; Igiri et al., 2018). At contact times longer than 24 h, with changes in the pH of the metal solution due to the metabolic processes of living bacteria, can affect the metal speciation, solubility and ultimately desorption or precipitation of metal ions (Ratzke et al., 2018; Xie et al., 2018). The same pattern was observed for Ni(II), Pb(II), and Cr(III) with the highest effect sizes of 1.12, 0.91 and 0.61 at short contact times (Fig. 4c). However, Cu(II) and Zn(II) showed higher effect sizes and biosorption efficiencies at both medium and long contact times. This increase of biosorption efficiency may be attributed to two main factors. Firstly, a bacterial medium with living cells is an active system in which microorganisms can reproduce. Bacterial reproduction can increase the number of colony forming units that contribute to the metal binding process and lead to a higher metal biosorption efficiency. Secondly, at longer contact times the rate of microorganism metabolism increases and as a result, more essential metal ions such as Cu(II) and Zn(II) are removed from the medium (Porcheron et al., 2013; Buracco et al., 2018; Stewart et al., 2019).

3.2.7. Initial heavy metal concentration

The initial metal concentration is an important factor that influences the biosorption process. Active binding sites and functional groups, available on the biosorbent surface, are affected by the initial concentration of metal ions (Hong and Simon, 2007; Tu et al., 2018). Higher concentrations of heavy metals possess higher toxicity for living bacterial biomass (Rathnayake et al., 2013; Fashola et al., 2016, Sankarammal et al., 2014). To evaluate the effect of metal concentration on bacterial biomass, the biosorption efficiency of seven heavy metals in this study, 23, 14, 9, 29, 6, 13 and 14 data points were extracted for Cd(II), Cu(II), Ni(II), Pb(II), Mn(II), Cr(III) and Zn(II), respectively. Data were pooled using ±95% confidence interval and heterogeneity of $P < 0.001$. In this meta-analysis, initial metal concentration of <50, 50 < T < 250 and >250 mgL ^{1} were considered as low, medium and high, respectively. The effect sizes of initial metal concentrations on biosorption efficiencies of different heavy metals are presented in Fig. 5a. The effect sizes for Cd(II) and Cr(III) were increased for both medium and high metal concentrations. This may be due to the enhanced driving force in favour of the biosorption process initiated by high metal concentration (Wang et al., 2010). For Ni(II) and Pb(II), the effect sizes and biosorption efficiencies, were decreased at higher initial metal concentrations. This observation was due to the lack of available active binding sites on the surface of the biosorbent at higher concentrations, which led to a lower effect size and biosorption efficiency (El-Naggar et al., 2018; Satya et al., 2020). The maximum effect sizes for Zn(II) (0.56) and Cu(II) (0.98) were achieved at low concentrations. The effect sizes for both metals decreased by increasing the initial concentrations. Two main reasons can explain these observations. Firstly, although Zn(II) and Cu(II) are essential for microbial growth, when the amount of metal ions in the bacterial medium exceeds its toxicity threshold, the bacterial state and metabolism can be altered and lead to a lower biosorption efficiency (Utgikar et al., 2003; Samanovic et al., 2013; Braymer and Giedroc, 2014). Another reason for the lower effect sizes can be the lower ratio of metal concentration to available active binding surfaces at higher concentrations which results in a higher number of Zn(II) and Cu(II) ions remaining in the metal solution (Osasona et al., 2013; Jin et al., 2017).

In general, the pooled data showed that by increasing the heavy metal concentrations the biosorption capacity of the bacterial strains increased due to the enhanced driving force imposed by higher numbers of metal ions. However, due to the toxicity of higher metal concentrations, metabolism and bacterial state were altered and led to a lower biosorption efficiency. This reduction of efficiency was also attributed to less available active binding sites at higher concentrations of heavy metal ions.

3.2.8. Biosorbent dosage

The number of active binding sites available on the biosorbent surface has a significant effect on the efficiency and capacity of heavy metal removal by bacterial biomass (Velkova et al., 2018; Sayago et al., 2020). The effect of low (less than 1 gL^{-1}), medium (1–5 gL^{-1}) and high (more than 5 gL^{-1}) bacterial biomass dosage on removal efficiency of seven heavy metals was assessed in this study, 86 (Cd), 66 (Cu), 31 (Ni), 107 (Pb), 24 (Mn), 54 (Cr) and 42 (Zn) data sets were pooled via heterogeneity of $P < 0.001$ and an ±95% confidence interval and effect sizes are presented in Fig. 5b. According to this figure, for all seven heavy metals in this study, a biomass dosage between 1 and 5 g/L ^{1} showed a higher effect size and biosorption efficiency, in comparison with a low biomass dosage. This is due to the larger number of active binding sites on the surface of the biosorbent in the medium biomass dosage, which led to higher metal removal efficiencies. Pb showed the same trend for high biomass dosage, with an effect size of 0.97. However, for Cd(II) and Cu(II) the effect sizes were reduced at high biomass dosages (Fig. 5b). This reduction of biosorption efficiency at high biomass dosage, may be attributed to the shell effect mechanism which protects the biosorbent active binding sites and stops the metal ions occupying a proportion of the sites (Al-Homaidan et al., 2014; Gitipour et al., 2015; Kucuker et al., 2017).

In summary, the biosorption efficiency of heavy metals by the bacterial biomass increased at higher biosorbent dosage to a certain limit, after which the biosorption capacity decreased. Meta-analysis showed that a medium biosorbent dosage (1–5 gL^{-1}) delivered the highest removal efficiencies for Cu(II) and Cd(II). For Ni(II), Pb(II), Mn(II), Cr(III) and Zn(II) the removal efficiencies increased at medium bacterial dosage, however, due to the lack of data for high dosage (>5 gL^{-1}) the optimum range of dosage for the described heavy metals was not attained.

3.3. Biosorption capacity forest plots

To have a visualization of biosorption capacities and 95% CI of selected studies in the present meta-analysis, forest plots were prepared and presented in Fig. 6. All studies are plotted using dot and error bars, representing 95% CI of the study. A summary of biosorption capacities and 95% CI of all 56 studies is also presented in the figure (polygram). According to forest plot in Fig. 6, the mean biosorption capacity reported by the selected studies was between 71.26 and 125.88. The maximum reported biosorption capacity over all studies was 508.01 (95% CI = 2.17) which used *Bacillus toyonensis* for biosorption of Pb at pH 7, 25 C and 180 min contact time. The minimum removal capacity was 0.46 mg g ^{1} (95% CI = 2.36). This study used *Bacillus* sp. for the removal of Mn(II) from aqueous solution at 27 C and 120 min contact time. 17 out of 56 (30.3%) studies showed a higher than average biosorption capacity (98.12 mg g ^{1}).

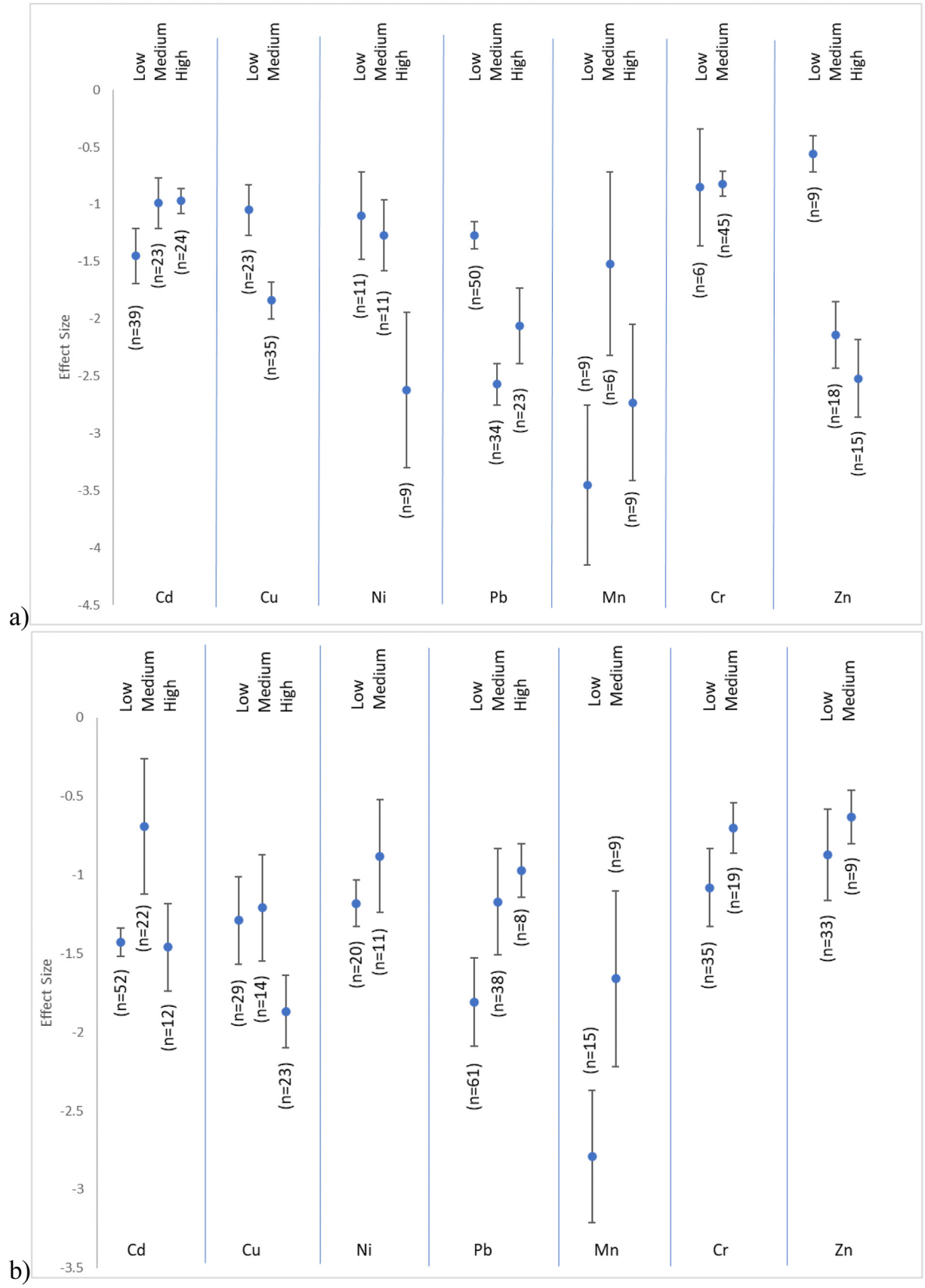

Fig. 5. a. Effect sizes of different initial heavy metal concentrations on biosorption of heavy metal by bacterial biomass. b) Effect sizes of biomass dosage on biosorption of heavy metals. Error bars are ±95% CI. n represents number of samples. Heterogeneity of the pooled data was $P < 0.001$.

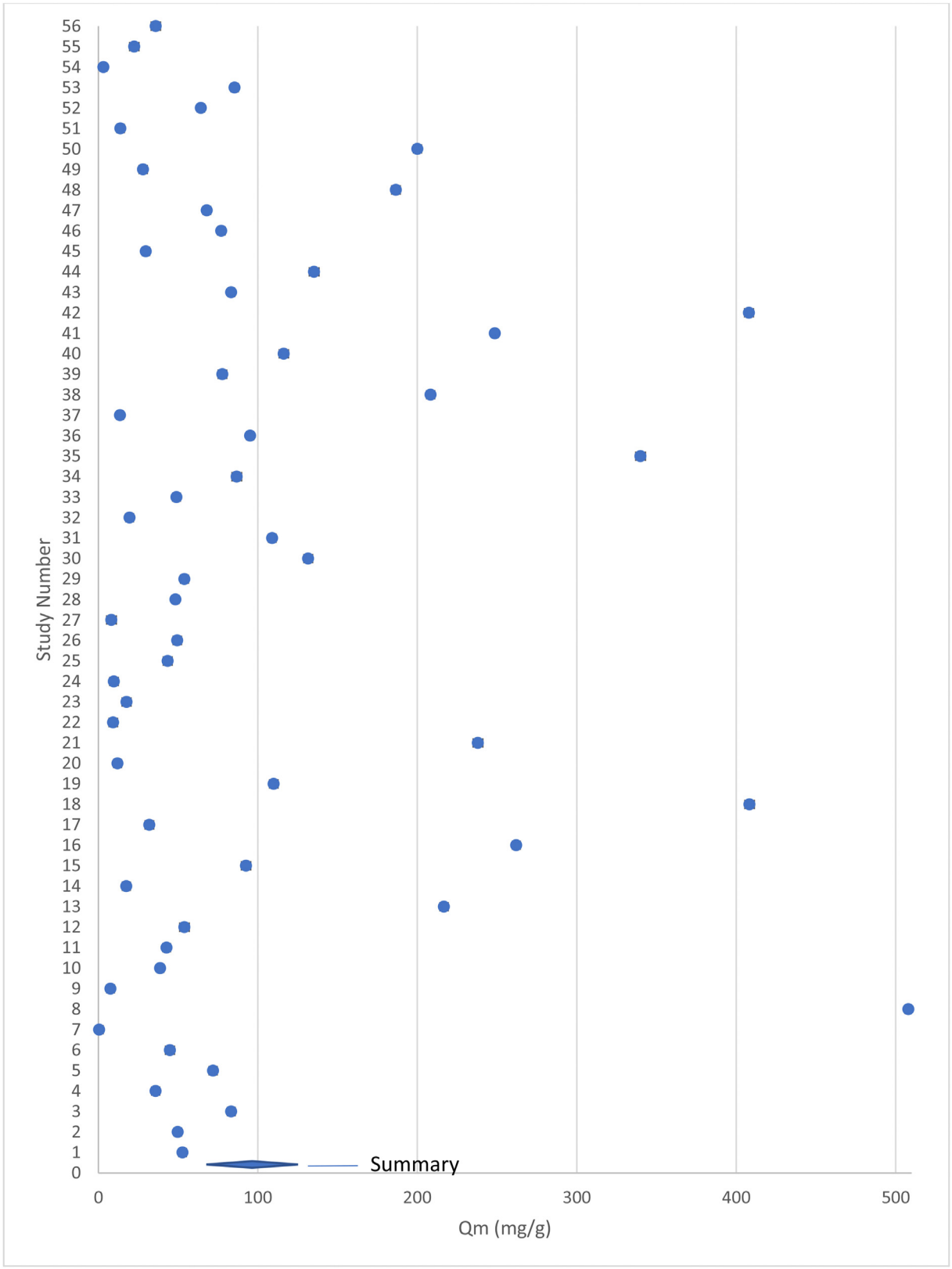

Fig. 6. Forest plots for biosorption capacities (mg g ^{1}) of the selected studies using the random effects model. Error bars are 95% CI.

3.4. Publication bias

The Egger's and Begg's test results for biosorption capacities, of the studies in this meta-analysis were t = 0.1562, P = 0.0627 and z = 0.7866, P = 0.4391, respectively, which were statistically not significant. This result revealed that there was no publication bias in the present study. Moreover, Fig. 7 displays the biosorption capacities of the selected studies and their standard errors, using a trim and fill method. The funnel plot of the biosorption capacities of the studies was semi asymmetrical, which indicated no risk of publication bias. No risk of publication bias was a result of a robust study selection and quality control protocol in this meta-analysis.

3.5. Research gaps

This survey of the studies in the last decade, revealed a research gap in the biosorption area. Few studies used a consortia or kingdoms of bacteria for biosorption of heavy metals and none of them carried out a thorough investigation of the biosorption process. More studies in this area are required to evaluate the efficiency of biosorption. Moreover, studies addressing the biosorption of heavy metals such as mercury (Hg), cobalt (Co) and arsenic (As) by bacterial biomass, are missing from the literature in the past decade. The majority of studies with high quality according to this meta-analysis used suspended bacterial cells for the biosorption process. Studies on biosorption capacities of bacterial strains supported by biofilms and on platforms, were not selected for this meta-analysis due to not having high quality or adequately reported experimental data which revealed the necessity for more detailed investigations in this area.

Significant evidence exists that mature, mixed community, in-situ biofilms would be capable of more effective biosorption than single strain, detached bacteria as included in the present study. It should be noted that the studies included in this meta-analysis are very far from what would be encountered in nature, where suspended bacteria are rare in comparison with those in a biofilm. For this reason, despite the complications that may inhibit effective analysis, there is a real need to determine the way that biofilms might influence the decontamination of metal polluted water.

4. Conclusions

The present met-analysis was conducted on papers published in last decade to identify the most appropriate bacterial phyla, bacterial state, experimental and process conditions to achieve the optimum biosorption efficiencies for different heavy metals in contaminated water and wastewater. The statistical analysis results of the present paper will be helpful to future researchers, environmentalists and industries in selecting the appropriate bacterial phyla and biosorption process conditions. The main findings of the present study are as follows:

- According to the pooled data, bacterial strains had an effect on the biosorption efficiency for different heavy metals. The order of bacterial biomass efficiencies for heavy metal removal from aqueous solutions was Cd(II) > Cr(III) > Pb(II) > Zn(II) > Cu(II) > Ni(II) > Mn(II).
- Bacterial phyla had important role in the efficiency of the biosorption process where firmicutes showed the highest overall (living and dead) biosorption efficiency for heavy metals.
- The bacterial state (living or non-living) had no significant influence on the biosorption efficiencies of firmicutes phyla. However, dead strains of Proteobacteria showed a significantly lower biosorption efficiency than living strains.
- Statistical analysis showed that a slightly acidic condition resulted in a higher heavy metal removal efficiency by bacterial

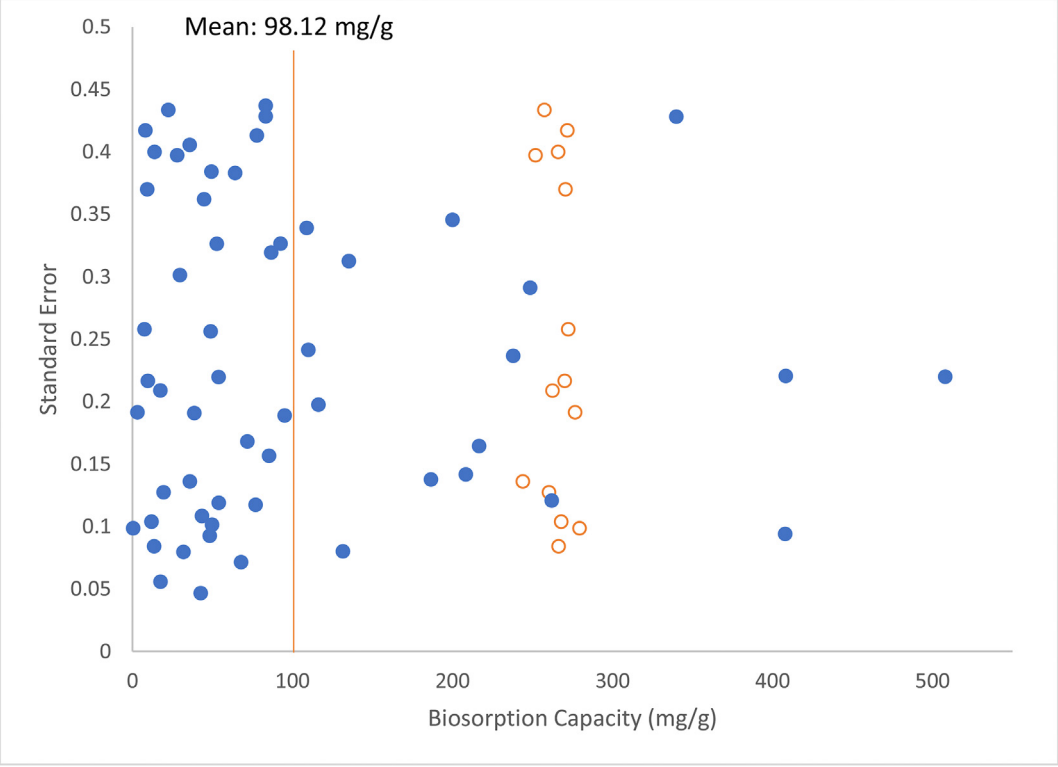

Fig. 7. Funnel plot for biosorption capacities (mg g ^{1}) of the selected studies based on standard errors using the trim-and-fill method.

strains from all phyla. Higher temperatures (>35 C) reduced the removal efficiencies for essential heavy metals (Cu(II) and Zn(II)) and increased the efficiencies for non-essential heavy metals (e.g. Cd(II) and Cr(III)).
- The maximum biosorption efficiency of non-essential heavy metals occurred at short contact times (2 h), however, essential metals such as Zn(II) and Cu(II) were more efficiently removed at long biosorption durations (>24 h).
- By increasing the initial concentrations of metal ions, the biosorption efficiencies were generally reduced. The pooled data revealed that increasing the biomass dosage led to a higher biosorption efficiency to a specific concentration, after which, the removal efficiency reduced.
- The mean biosorption capacity of bacterial biomass (71–125 mg g ^{1}) indicated the efficiency of suspended bacteria in heavy metal removal from contaminated water and wastewater.

Systematic review of the literature showed that there is a lack of comprehensive study on using a consortia or kingdoms of bacteria for biosorption of heavy metals. Moreover, no high quality (based on the present study criteria) papers were available on biosorption of mercury (Hg), cobalt (Co) and arsenic (As) by bacterial biomass.

Credit author statement

Alireza Fathollahi, Conceptualization, Methodology, Validation, Formal analysis, Investigation, Resources, Writing – original draft, Writing – review & editing. Nazanin Khasteganan, Conceptualization, Methodology, Validation, Writing – original draft, Investigation. Stephen J Coupe, Conceptualization, Methodology, Validation, Investigation, Resources, Writing – original draft, Writing – review & editing, Supervision, Project administration. Alan P Newman, Conceptualization, Methodology, Validation, Writing – original draft, Writing – review, Supervision.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

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