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Exploring Microalgae Diversity in Indonesia: Harnessing Potential for Lead Bioremediation

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Abstract

Background: Indonesia's biodiverse microalgae, numbering 2060 species, thrive in diverse environments, offering potential in pharmaceuticals, cosmetics, fuel, and heavy metal bioremediation. Lead pollution from mining poses risks, prompting stringent government contamination limits. Microalgae-based bioremediation, notably *Chlamydomonas reinhardtii* and *Chlorella vulgaris* removing up to 90% of lead, suggests further exploring Indonesia's microalgae diversity. **Methods**: Data sourcing (2013-2023) employed Google and Google Scholar using specific keyword combinations across Indonesian provinces. Seventy-eight sources underwent analysis and visualization via Microsoft Excel 2021. **Results:** Microalgae's potential as lead bioremediation was explored across classes like Chlorophyceae, Cyanophyceae, and Bacillariophyceae. Chlorophyceae, exemplified by *Chlorella* and *Scenedesmus*, exhibit varied cell sizes and complex cell walls, aiding metal ion binding. Cyanophyceae like *Cyanospira capsulata* and *N. commune* synthesize diverse EPS compositions, indicating their potential in lead remediation. **Conclusions**: Indonesia's microalgae diversity across habitats, especially in the Chlorophyceae and Cyanophyceae classes, suggests a significant role in lead bioremediation. Their adaptability and diverse compositions highlight their potential for sustainable practices in combatting environmental lead contamination.

Keywords: bioremediation; diversity; heavy metals; Indonesia; microalgae

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Introduction

Indonesia is a mega biodiversity hotspot, harboring an extensive array of microalgae species. According to Algabase.org (2023), Indonesia boasts 2.060 algae species, encompassing both microalgae and macroalgae. Microalgae, which span the spectrum of eukaryotic and prokaryotic organisms and measure between 2-50 µm, exhibit remarkable capabilities in photosynthesis (Sahoo & Baweja, 2015; Elisabeth et al., 2021). These organisms thrive in diverse habitats, ranging from freshwater, seawater, and brackish water to soil, waste, and various surfaces like trees, sediment, and rocks.

Presently, the focus of algae exploration in Indonesia predominantly revolves around macroalgae communities, commonly referred to as algae. As highlighted by the Food and Agriculture Organization (2019), the entire algae production of 9.962.900 tons in Indonesia originates from the macroalgae industry. However, Indonesia's wealth of microalgae diversity holds immense promise for multifaceted applications across pharmaceuticals, cosmetics, and fuel production industries. Moreover, their potential extends to serving as effective agents for bioremediation, especially in detoxifying heavy metals.

The surge in anthropogenic activities, particularly in sectors like mining, poses a significant risk by amplifying the generation of waste containing various heavy metals.

Wuana and Okieimen (2011) underscored lead as the foremost prevalent heavy metal originating from the mining industry. Beyond its primary association with mining activities, lead contamination is common in polluted soils and biosolid products. Furthermore, Zhou et al. (2020) highlighted lead as among the metal pollutants consistently surpassing permissible thresholds in numerous rivers and bodies of water worldwide between 1972 and 2017.

In Indonesia, lead emissions stem from the mining sector, diverse industries such as clay and ceramic manufacturing, and the batik industry. Miranda et al. (2018) observed elevated lead levels, registering at 12.96 mg/L in river sediment within the Bangka Regency, while Tawa et al. (2019) identified lead concentrations ranging between 0.2624 and 0.5713 mg/L in waters surrounding tin mining sites situated in the Bangka Belitung Province. Under Government Regulation No. 22 of 2021, the Indonesian government has established limits for lead contamination at 0.03-0.5 mg/L in river water and 0.008-0.05 mg/L in seawater to regulate these levels. Exceeding these thresholds poses significant risks to living organisms, as it heightens the probability of disabilities, cancer development, and even fatality. In humans, exposure to lead within the range of 0.36-2.43 μg/kg body weight can result in detrimental impacts like infertility, nervous disorders, and chronic kidney issues. Animals exposed to lead concentrations ≥ 0.3 mg/kg may experience compromised stress response, immune system suppression, nerve damage, and vascular problems. In contrast, plant exposure between 400-800 mg/kg can hinder photosynthesis, mineral absorption, root damage, and disrupt growth hormone balance (Ashkan, 2023).

According to Abadin et al. (2019), lead contamination at concentrations ranging from 0.05-0.5 ppm can significantly impair the nervous system function, affecting cognitive abilities and mood in children. Adolescents and adults exposed to lead levels within the range of $0.05 \leq Pb < 0.5$ ppm may encounter diverse health complications such as kidney failure, reduced hemoglobin levels, sperm abnormalities, gastrointestinal disorders, and potential fetal defects if consumed by pregnant women (Abadin et al., 2019).

Lead contamination poses dangers not only to human health but also to other organisms. In aquatic environments, lead pollution triggers DNA damage and mutations by activating and synthesizing reactive oxygen species (ROS) (Assi et al., 2016). Lead can be fatal to living organisms at elevated concentrations, emphasizing its hazardous nature across ecosystems.

Conventional waste processing methods often entail substantial costs, intricate technological setups, and the potential generation of by-products like sludge deposits. Alternatively, utilizing microalgae as a metal bioremediation agent presents a promising waste management solution with several advantages. Microalgae exhibit the ability to assimilate carbon (C), phosphorus (P), and nitrogen (N) into organic compounds, as demonstrated by studies (Chen et al., 2018; Abdelfattah et al., 2023), thereby mitigating the risk of sludge formation. Moreover, these microorganisms facilitate the carbon dioxide (CO_2) fixation process, effectively curbing CO_2 pollution in the environment, as supported by research (Chai et al., 2021; Abdelfattah et al., 2023). Unlike animals or plants, microalgae demand less space, making their cultivation notably efficient.

Several microalgae species, such as *Chlamydomonas reinhardtii* and *Chlorella vulgaris*, have shown promising potential for lead metal bioremediation. Research indicates that *C. reinhardtii* can eliminate up to 78% of lead contamination (Li et al., 2021), while *C. vulgaris* achieves an impressive 90% removal rate (Manzoor et al., 2019). However, due to limited exploration, Indonesia's precise count of microalgae species remains uncertain. Therefore, conducting a comprehensive review of microalgae exploration becomes crucial, serving as a valuable resource to catalog the diverse microalgae species within the country. Recent environmental shifts linked to global warming and increased human activities have posed threats to microalgae populations, heightening their risk of extinction. By examining microalgae records from the past decade (2013-2023), this research aims to elucidate their prevalence, distribution, and dominant communities in Indonesia. The primary objective involves exploring Indonesia's varied microalgae species to evaluate their potential efficacy as agents for lead metal bioremediation.

Methods

The research methodology was adapted from Geremia et al. (2021), which involves collecting data through a simple random sampling method from 2013 to 2023 using the search engines

Google and Google Scholar. Keywords used in searching for references include diversity, microalgae, Indonesia, and various province-specific queries. The selection criteria encompassed scientific articles, including journals, online books, university research reports, theses, and dissertations. These criteria ensured the inclusion of articles that explicitly discussed microalgae exploration in Indonesia, provided precise isolation locations in Indonesian or English, and granted open access with detailed species classifications matching accepted phycological references. Conversely, sources were excluded if they fell outside the specified search year range, lacked location specifics for species discovery, focused on species use without isolation details, or failed to classify the mentioned species as microalgae, requiring complete and free manuscript access. The subsequent processing of 78 data sources was managed using Microsoft Excel 2021. Subsequently, the species data was cross-referenced against scientific sources about the identified microalgae's potential as lead bioremediation agents. This quest for scientific evidence adhered to stringent criteria, including species-specific mentions, original or review articles with proper sourcing, and content focused on lead remediation.

Result and Discussion

Biodiversity of microalgae in Indonesia

The analysis of 78 data sources revealed a comprehensive inventory of 1058 species, 225 genera, 130 families, and 23 classes of microalgae across Indonesia (Figure 1). These findings encompassed data from 29 provinces within the country. Notably, certain provinces such as Central Sulawesi, North Sulawesi, West Sulawesi, North Maluku, East Kalimantan, Papua Mountains, South Papua, Southwest Papua, and Central Papua lacked microalgae data. Several reasons account for this absence: (1) insufficient available data sources, (2) absence of species names in the collected data originating from these provinces, (3) exclusion of relevant data falling outside the 2013-2023 timeframe, and (4) the recent establishment of new provinces in 2023, potentially leading to changes or additions to the existing provincial boundary.

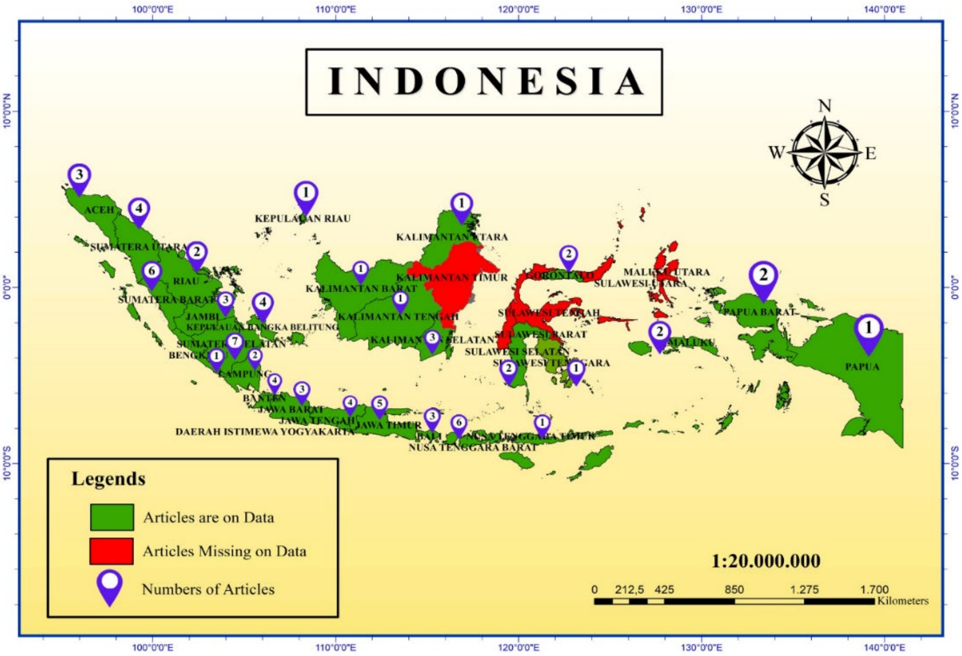

Figure 1. Geographical representation of microalgae biodiversity research across Indonesia

The microalgae come from various habitats such as river water, lakes, dams, reservoirs, seawater, coastlines, and bays. Apart from living in aquatic locations, microalgae are also found to be epiphytes such as *Aurantiochytrium* sp. collected from the mangrove forests of Raja Ampat Papua (Suhendra et al., 2022), *Biddulphia* sp. which is epiphytic in the seagrass *Thalassia hemprichii* and *Cymodocea rotundata* on Sintok Island, Karimunjawa National Park (Samosir et al., 2022), and *Grammatophora* sp. found in epiphytes on *Padina* sp. in the waters of Sepempang Village, Natuna Regency (Lestari et al., 2020).

Various instances showcase the resilience and adaptability of microalgae in unconventional habitats, highlighting their presence in diverse waste materials. For example, *Spirulina* sp. was discovered thriving in fishery waste sourced from Pasar Cemara Medan (Yusni & Hartono, 2021), while *Kirchneriella* sp. was identified in temporary storage of nuclear waste in Serpong, South Tangerang (Sugoro et al., 2022). Additionally, microalgae have exhibited habitat versatility, colonizing soil and rocks in unexpected environments. Gunawan (2018) documented *Tetraselmis*, *Galdieria*, *Tribonema*, and *Nanochloropsis* species in reclaimed former coal mine lands of Cempaka, South Kalimantan. Purbani et al. (2020) discovered *Ankistrodesmus falcatus* and *Pseudendoclonium arthropyreniae* thriving in the rock biofilm surrounding the Borobudur Temple in Malang, Central Java.

The prevalent microalgae genera within the Bacillariophyceae family notably include *Chaetoceros*, *Nitzschia*, and *Navicula* (Figure 2), with each genus accounting for 62, 42, and 39 species, respectively. Diatoms, particularly those of the *Chaetoceros* genus, dominate the research data due to their adaptability to freshwater and seawater environments. This adaptability has resulted in numerous recorded instances of diatom species discovered across various research locations. Among the 62 *Chaetoceros* species identified, 30 were classified to the genus level, while 32 were identified with specific morphological and molecular characteristics. According to Algabase.org (2023), 583 *Chaetoceros* species are documented worldwide. Noteworthy *Chaetoceros* species frequently found in Indonesia encompass *C. affinis, C. atlanticus, C. capensis, C. didymus, C. diversus, C. laciniosus, and C. peruvianus.*

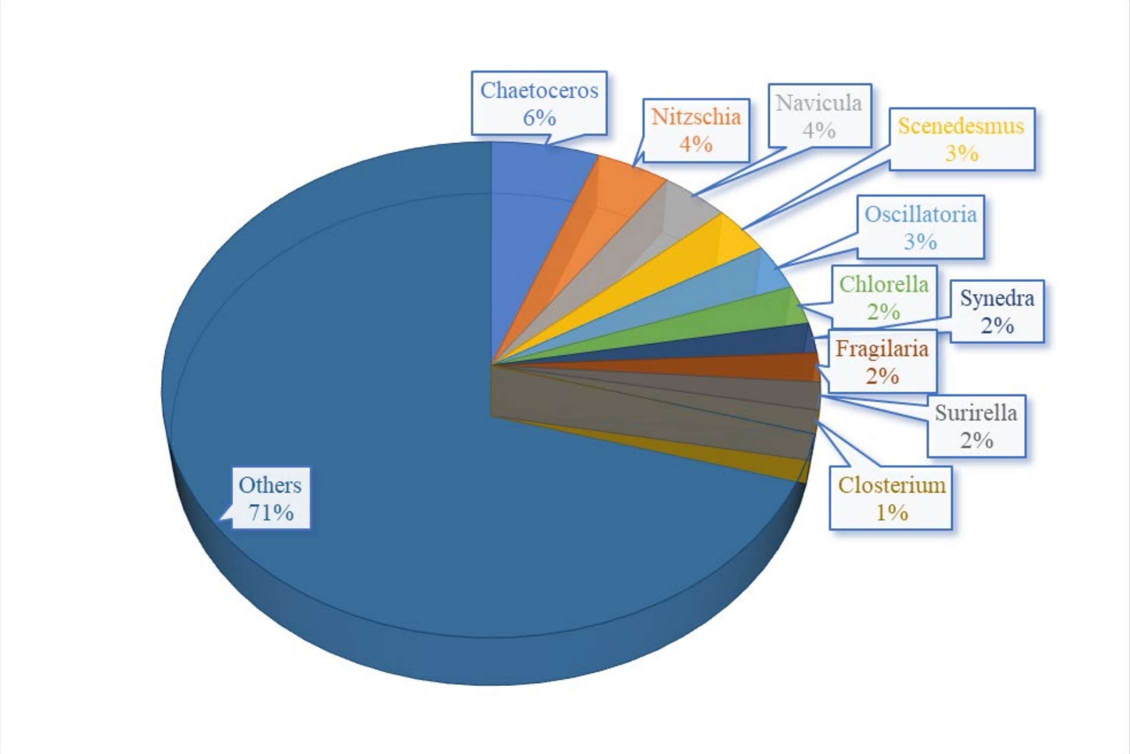

Figure 2. Genera distribution percentage among reviewed articles

Chaetoceros, a diatom species of the Bacillariophyceae, thrives predominantly in marine environments, although some variants also inhabit freshwater habitats. All *Chaetoceros* species identified within the data source were exclusively located in seawater habitats and culture collections or adhered to various substrates. The discovery sites for *Chaetoceros* encompass diverse coastal regions, including the shorelines of West Bangka Regency (Rachman et al., 2019), Sendang Biru Beach in Malang, East Java (Zakiyah & Mulyanto, 2020), Cemara Beach in West Lombok (Subagio, 2021), Sintok Island within the Karimun Java National Park (Samosir et al., 2022), Banda Sakti Lhokseumawe District beaches (Andika et al., 2022), Youtefa Bay and Yos Sudarso Bay in Jayapura (Sulistiowati et al., 2019), Attack Island in Bali (Sugiana et al., 2022), Bole

Bolengo in Gorontalo (Kadir & Arsad, 2016), and the Pangkep District coast in South Sulawesi (Tambaru et al., 2021).

Among the commonly found *Nitzschia* spp. are *N. amphibia*, *N. longissima*, *N. palea*, and *N. sigma*, exhibiting a habitat preference for benthic environments in freshwater and saltwater. Observations reveal the presence of *Nitzschia* species in various freshwater locations, such as *N. microcephala* and *N. linearis* identified within the Selagan River and Tes Lake in Bengkulu (Selviana et al., 2022), along with *N. amphibia* and *N. angustata* inhabiting the waters of the Jangkok River in Mataram, Nusa West Southeast (Purwati et al., 2022). Conversely, certain *Nitzschia* species, like *N. longissima*, are exclusive to seawater habitats, notably in Yotefa Bay in Jayapura (Sulistiowati et al., 2016).

Navicula, another benthic diatom species, exhibits a dual habitat preference, thriving in freshwater and seawater environments. Among the frequently encountered *Navicula* spp. in Indonesia are *N. elegans*, *N. gregaria*, and *N. salinarum*. Notably, *Navicula* species inhabit diverse aquatic settings, with *N. distans* identified in coastal waters off Lhokseumawe, Aceh (Andika et al., 2022), and the coastal region of West Nusa Tenggara (Suripto & Japa, 2019). In freshwater habitats, species like *N. elegans* were recorded in the waters of the Bonan-Dolok River in Samosir, North Sumatra (Satya et al., 2020).

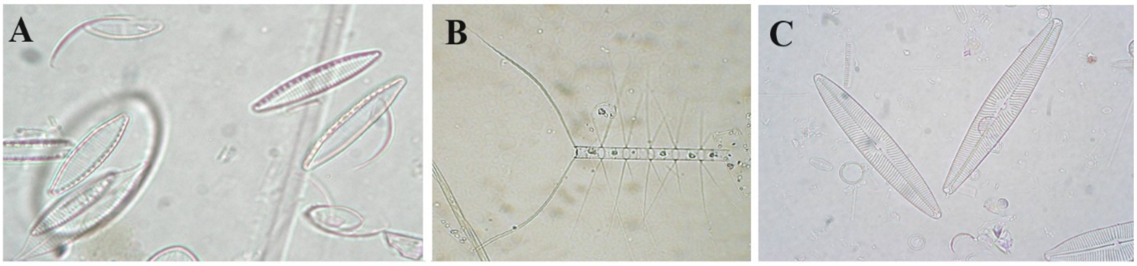

Figure 3. Predominant research articles of microalgae identified in Indonesian: [A]. *Nitzschia,* [B.] *Chaetoceros,* dan [C.] *Navicula.* (Wikipedia Creative Common Licensed)

Beyond the genera within the Bacillariophyceae family, several other prominent families encompass Desmidiaceae, Chlorellaceae, Fragillariaceae, Scenedesmaceae, and Selenastraceae (Figure 4). The Desmidiaceae family, comprising 12 genera—*Cosmarium*, *Desmidium*, *Euastrum*, *Hyalotheca*, *Micrasterias*, Pleurotaenium, *Roya*, *Spondylosium*, *Staurastrum*, *Tetmemorus*, *Triploceras*, and *Xanthidium*—stands out notably. The most prevalent classes observed overall are Bacillariophyceae, Chlorophyceae, and Cyanophyceae (Figure 5).

Among the commonly encountered Chlorophyceae, *Scenedesmus* stands out, comprising species such as *S. acuminatus*, *S. amatus*, *S. dimorphus*, *S. obliquus*, and *S. quadricauda*. This non-motile green algae species typically forms colonies and primarily inhabits freshwater environments (Schubert & Gartner, 2015). Recorded data highlights the presence of *Scenedesmus* species, specifically *Scenedesmus* sp., in various freshwater locations like the Kati River in South Sumatra (Harmoko & Sepriyaningsih, 2017) and the Barumun River in North Sumatra (Pane & Harahap, 2020). Certain *Scenedesmus* species are also found in marine environments despite their freshwater predominance. For instance, *S. bijugatus* was identified on Simuele Island in Aceh, and *S. vacuolatus* was discovered in the Tambarauw Sea, West Papua (Purbani et al., 2019).

The Oscillatoria species such *as O. limnetica, O. limosa, O. brevis, and O. rubescens* are commonly observed within Cyanophyceae. *Oscillatoria* exhibits a filamentous morphology devoid of akinetic or heterocysts (Waditee-Sirisattha & Kageyama, 2022). This versatile species thrives in various habitats, including freshwater, seawater, bark, rocks, soil, and rice fields (Kant et al., 2021). Data analysis indicates the presence of *Oscillatoria* species exclusively in freshwater environments, such as the Sando Waterfall in Lubuklinggau City (Harmoko et al., 2019) and Barata Dam in Rawas (Rawas, 2021).

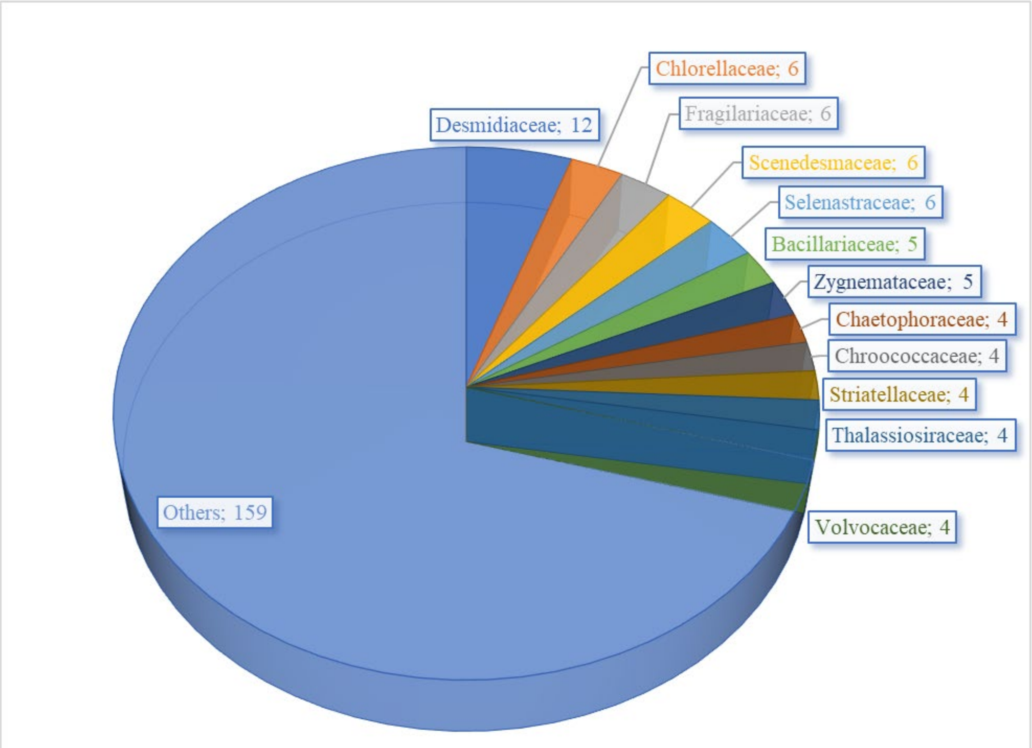

Figure 4. Family Distribution Percentage among Reviewed Articles.

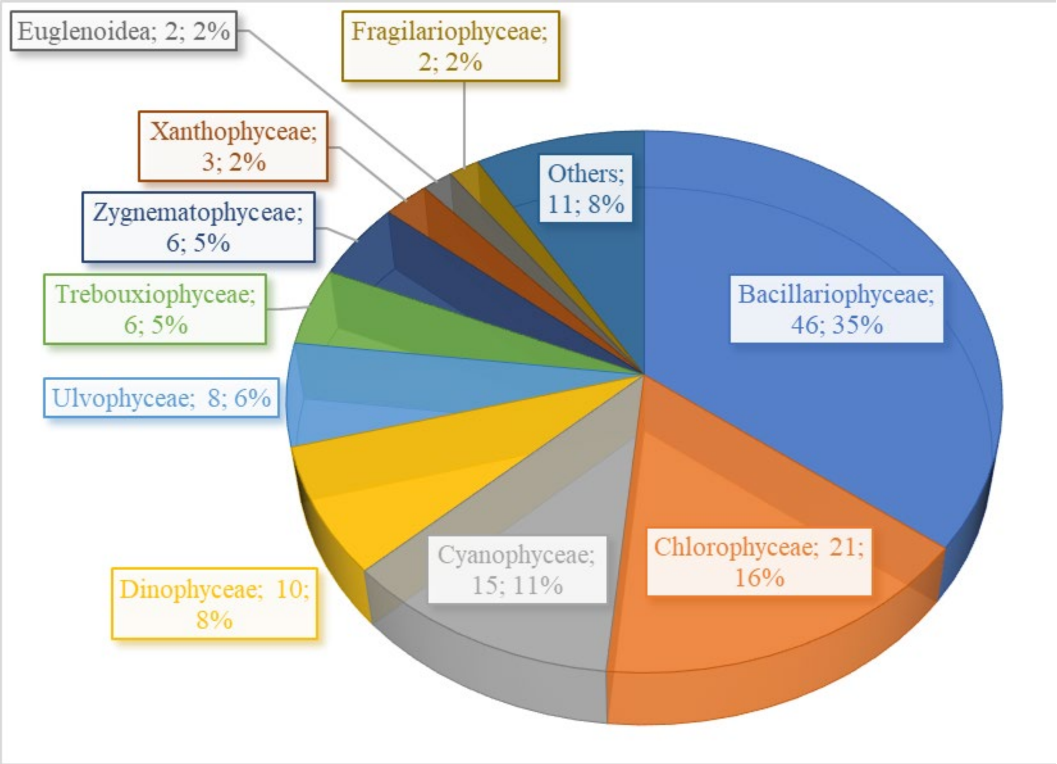

Figure 5. Class distribution percentage among reviewed articles

Additionally, numerous microalgae have been investigated for their diverse benefits across several fields. Some of these microalgae explored for pharmacological purposes include *Chlorella* sp., *C. vulgaris*, *Porphyridium cruentum*, and *Nannochloris* sp., valued for their antioxidant, antibacterial, and antihyperglycemic properties (Rafaelina, 2015; Nugroho et al., 2019; Handra et al., 2019; Indrasari, 2020; Tasman et al., 2020). Another species, *Aurantiochytrium* sp., has been studied as a raw material for vaccine adjuvants (Suhendra et al., 2022).

Metabolite exploration focusing on lipid and fatty acid content has been conducted in *Navicula salinicola* species. Studies reveal that *N. salinicola* contains palmatic acid, myristic acid, pentadecanoic acid, and eicosapentaenoic acid (Ramdanawanti et al., 2018). Additionally, species like *Chlamydomonas applanata* and *C. moewusii* contained 39% fatty acids within their biomass (Susanti et al., 2021).

Microalgae commonly employed as aquatic bioindicators primarily stem from Cyanophyceae, including *Microcystis aeruginosa*, *M. incerta* (Hairunnadawiah et al., 2022), *Oscillatoria tenuis*, and *Tolypothrix distorta* (Rahayu & Susilo, 2021). The preference for Cyanophyta as aquatic indicators lies in their broader tolerance for various environmental conditions compared to other microalgae divisions like Chlorophyta, as Pal & Choudhury (2014) highlighted.

Unveiling the Potential of Microalgae as Lead (Pb) Bioremediation Agents

Lead remediation is a complex process influenced by both external and internal factors. External factors, such as initial biomass quantity, contact time, metal concentration, temperature, pH, growth medium, biomass type, and light exposure, along with internal factors like cell size, presence of carboxyl and hydroxyl groups in the cell wall, metabolite compounds, gene expression, and metabolism (Sibi, 2019; Iqbal et al., 2021; Nyika & Dinka, 2023), collectively shape the efficacy of lead remediation efforts.

The effectiveness of lead remediation strategies is highly dependent on the research design employed. Each microalgae species and strain shows unique characteristics in responding to lead contamination. For instance, in the study conducted by Molazadeh et al. (2015), *Chlorella* sp. exhibited varying lead uptake rates based on different treatment variables such as pH, temperature, culture duration, initial biomass amount, and total lead concentration. Notably, maximum lead uptake occurred at specific conditions, including a pH of 6, a temperature of 25°C, a culture duration of 180 minutes, an initial biomass amount of 1.5 mg/L, and a maximum lead concentration of 20 mg/L.

External factors act as stimuli for microalgae to synthesize metabolites, enzymes, and hormones in response to environmental stressors, aiming to establish equilibrium. Specific genes, enzymes, and hormones related to heavy metal binding exhibit activity under distinct conditions. As proven by Zheng et al. (2020), increasing lead concentrations causes an increase in antioxidant enzymes that are important in increasing stress, such as superoxide dismutase (SOD), peroxidase (POD), and catalase (CAT). In addition to antioxidant enzymes, Zhang et al. (2020) highlighted the influence of lead concentration on the overexpression of the ATP-binding catalase (ABC) transporter gene. This gene plays a significant role in metal binding within vacuoles and augments hormone signals that upregulate proteins involved in the metal chelation process. These intricate mechanisms elucidate the varying absorption levels observed in the same species, shaped by the fluctuations in external variables that ultimately impact the internal conditions of the microalgae.

Bacilariophyceae

Table 1 displays the Bacillariophyceae species identified for their efficacy in removing lead (Pb) contamination. Diatoms belonging to Bacillariophyceae exhibit diverse mechanisms for metal remediation, encompassing biotransformation, biomineralization, bioaccumulation, and biosorption (Marella et al., 2020). Compared to other algae species, diatoms offer several advantages as potent metal bioremediation agents due to their larger vacuoles, faster cell division rate, and remarkable adaptability to low-light conditions (Furnas, 1990; Wagner et al., 2006; Raven & Beardal, 2016; Marella et al., 2020).

Research by Christos et al. (2021) emphasizes that diatoms display a higher affinity for Pb ions than Cd, Hg, As, Ba, and Cr metal ions. The ability to sequester Pb ions is attributed to the presence of the highly sensitive calmodulin (CaM) protein, which serves as a sensor for Pb^{2+} ions (Kursula & Mujava, 2007). Furthermore, various enzymes, including oxidoreductase, transferase, hydrolase, lysase, isomerase, ligase, and translocase, aid in the binding process of metal ions within diatoms (Christos et al., 2021).

Chlorophyceae

Among various classes, Chlorophyceae stands out as the most utilized class in lead bioremediation processes (Table 1). The advantages attributed to Chlorophyceae as metal bioremediation encompass their ability to thrive in diverse habitats under various environmental conditions and the presence of diverse cell sizes that influence the efficacy of metal uptake.

The species predominantly employed in lead bioremediation are *Chlorella* and *Scenedesmus*. Chlorophyceae exhibit complex cell walls enriched with carboxyl and amine groups that enable the binding of metal ions, leading to their accumulation within the cell (Spain et al., 2021). Several microalgae species have reported significant lead reduction rates exceeding 90%, exemplified by *Dunaliela salina* and *Cladophora*, demonstrating absorption capacities ranging from 90% to 97%. Beyond their carboxyl and amine groups, Chlorophyceae synthesize phytochelatin proteins containing sulfhydryl (-SH), aiding in metal binding and accumulation within the vacuole (Dewi & Nuravivah, 2018). The efficiency of microalgae in conducting remediation is heavily reliant on experimental conditions. Thus, determining effectiveness solely based on one factor, such as species, proves inadequate. Nevertheless, the microalgae genera *Chlorella* and *Scenedesmus* from the green microalgae category have been extensively utilized in lead uptake experiments due to their widespread presence across various habitats (Spain et al., 2021).

Cyanophyceae

Cyanophyceae can synthesize orthophosphate compounds (PO_4^{3-}), facilitating the breakdown of metals (Danouche et al., 2021). Various species of cyanobacteria manifest diverse extracellular polymer compounds (EPS) to assist in metal binding. For instance, *Cyanospira capsulata* and *N. commune* exhibit distinct compositions of EPS groups based on pH levels: carboxyl groups prevail at pH 2–5, a combination of carboxyl and phosphate groups at pH 5–9, and carboxyl, phosphate, and hydroxyl (or amine) groups at pH 9–12 (Amin et al., 2021).

Leong & Chang (2020) outlined multiple challenges encountered in using microalgae as a bioremediation agent, including the need for (1) an efficient biomass harvesting process, (2) a pure culture devoid of other microorganisms, (3) identifying suitable growth media and conditions, (4) mitigating the risk of biomass reduction due to increased Total Suspended Solids (TSS) in muddy waste, and (5) managing the waste generated from the remediation process.

The application of microalgae in bioremediation requires further development, particularly in technological advancements and the selection of stable strains. Nevertheless, various studies indicate that microalgae exhibiting lead reduction capabilities often possess high lipid levels. This occurrence stems from lead-induced cell wall damage, prompting microalgae to synthesize neutral lipids for self-protection (Dao & Beardall, 2017). The high lipid content holds potential for exploration as biofuel.

Table 1. Comprehensive list of species demonstrating lead remediation abilities

Species	Remediation percentage (%)	Remediation Timeframe	Main References	Locations of Microalgae Discovery and Research Conducted in Indonesia	Relevant References Discovered in Indonesia
Bacillariophyceae					
Navicula salinicola	56,96	14 days	Elleuch et al., (2021)	Laboratory of Biochemistry Institut Teknologi Bandung	Ramdanawati et al., (2018)
Chaetoceros calcitrans	92	14 days	Soeprobowati & Hariyati, (2014)	Culture collection at the Research Center of Marine and Fisheries Lampung	Hartati et al., (2013)
Skletonema costatum	80	1 day	Soedarti et al., (2016)	Estuary water of Youtefa, Jayapura	Sulistiowati et al. (2016)
Nitzschia palea	>70	10 days	Al-Quraishy & Abbas, (2019)	Selagan river and Tes lake Bengkulu	Silviani et al., (2022)
Chaetoceros sp.	78	3 hours	Molazadeh et al., (2015)	water around Bangka Barat, Sendang Biru beach Malang	Rachman et al., (2019); Zakiyah & Mulyanto, 2020
Cholorophyceae					
Chlamydomonas sp.	30	10 days	Inthorn et al., (2002)	The coastal area of Suak Ribe Aceh, Gandoriah Beach west Sumatera, and Lengkuas Island Bangka Belitung	Pane et al. (2022)
Chlorella pyrenoidosa	32	96 hours	Purushanahalli et al., (2021)	Mesat river Lubuk Linggau	Sepriyaningsih et al., (2023)
Chlorella sp.	60	3 hours	Molazadeh et al., (2015)	A research center of Biotechnology (LIPI) Cibinong-west Jawa, Brantas River east Jawa	Indrasari, (2020); Arsad et al., (2021)
Chlorella vulgaris	>84	10 days	Inthorn et al., (2002)	Kincir Kamba Tigo river Kecamatan Rambatan, Tanah Datar – west Sumatera, Sungai Selagan river and Tes lake Bengkulu, Sai river, Riau	Tasman et al., (2020); Silviani et al., (2020), Yusnianda et al., (2022)
Chlorococcum sp.	71	10 days		Mesat river Lubuk Linggau, Ampenan island water Lombok west Nusa Tenggara	Sepriyaningsih et al., (2023); Putri et al., (2019)
Cladophora sp.	97	10 days	Cao et al. (2015)	Mandikapau Banjar Baru village, coast of Pasuruan and Sidoarjo	Indiryani & Destiara (2022); Mahmudi et al., (2023)
Dunaliela salina	80, 90	50 hours, 14 days	Imani et al., (2011); Elleuch et al., (2021)	Sediment of seagrass and Mangrove ecosystem, Jakarta	Hutari et al., (2022)
Kirchneriella sp.	81	10 days	Inthorn et al., (2002)	Universitas Terbuka lake, south Tanggerang, temporary storage of Serpong nuclear waste	Prasetyo (2013); Sugoro et al., (2022),
Monoraphidium sp.	65	72 hours	Lakmali et al., (2022)	Gintung lake and Pamulang lake south Tanggerang and Muara Peniti estuaries West Kalimantan	Pikoli et al., (2019); Apriansyah et al., (2021)
Nanochloropsis oculata	55	7 days	Waluyo et al., (2020)	coast and freshwater west Nusa Tenggara	Suripto et al., (2019)

Oedogonium sp.	70	5 hours	Gupta & Rastogi, (2008)	Kati River, south Sumatera, Sando waterfall Lubuk Linggau, river in West Bangka, and Barumun river	Harmoko & Sepriyaningsih, (2017); Harmoko et al., (2019); Pane & Harahap, (2023)
Scenedesmus obliquus	80	8 days	Ghafar et al., (2014)	Jangkok river, Mataram	Purwati et al., (2022)
Scenedesmus sp.	70	7 days	Pham et al. (2020)	Kati River, south Sumatera, Selagan River and Tes Lake Bengkulu	Harmoko & Sepriyaningsih, 2017, Silviani et al., 2020
Scenedesmus vacuolatus	85	10 days	Inthorn et al., (2002)	Tambarauw sea, Papua	Purbani et al., (2009)
Spirogyra sp.	70	5 hours	Gupta & Rastogi, (2008)	Tempe lake (Central Sulawesi), Kati river (South Sumatera), Barumun river (North Sumatera), Cibanten lake Ciomas (Banten)	Harmoko & Sepriyaningsih (2017); Nofidanto & Tanjung (2019); Rahayu & Susilo, (2021); Pane & Harahap (2023)
Cyanophyceae					
Nostoc sp.	46	5 hours	Gupta & Rastogi, (2008)	Tempe Lake, Central Sulawesi	Harmoko & Krisnawati, (2018); Nofdianto & Tanjung, (2019); Dimenta et al., (2020)
Nostoc commune	96	10 hours	Inthorn et al., (2002)	Jangkok river, Mataram, Aur lake South Sumatera, Bilah river Labuhan Batu North Sumatera	Purwati et al., (2022)
Calothrix sp.	86	10 days		Bonan-Dolok river, Samosir-North Sumatera	Satya et al. (2020)
Rivularia sp.	86	10 days		Tempe Lake, Central Sulawesi	Nofdianto & Tanjung, (2019)
Gleocapsa sp.	99	20 min	Raungsomboon et al., (2008)	Aur lake South Sumatera	Harmoko & Krisnawati, (2018)
Oscillatoria sp.	89	25 min	Kumar et al., (2011)	Lok Ulo River, Kebumen, Central Jawa, Kerinci Lake, Jambi, Gesek reservoir, Bintan island, Kepulauan Riau	Prakoso & Wahyuni, (2019); Hernandi et al., (2019); Melani et al., 2020
Phormidium sp.	77	30 min		Peniti estuary, West Kalimantan, coast of Pasuruan and Sidoarjo	Apriansyah et al., (2021), Mahmudi et al., (2023)
Microcyistis aeruginosa	86	8 days	Cheraghpour et al., (2009)	Selagan river dan Tes lake Bengkulu	Silvani et al., (2022)
Euglenoidea					
Euglena gracilis	<15	8 days	Mendoza-Cozati et al., (2006)	Selagan river and Tes lake Bengkulu	Silviani et al., (2022)
Phacus sp.	79,17	14 days	Ahmad et al. (2020)	Sipin Lake, Jambi	Anggraini et al., (2017)
Trebouxiophyceae					
Stichococcus sp.	86-93	7 days	Oyebamiji et al., (2021)	Simuele Island, Aceh	Purbani et al., (2020)
Prymnesiophyceae					
Isochrysis galbana	>70	7 days	Kumar et al. (2013)	epiphyte on Padina and Caulerpa at Lampung	Hartati et al., (2013)

Conclusions

The diverse range of microalgae classes in Indonesia, including Chlorophyceae, Cyanophyceae, and Bacillariophyceae, presents an excellent resource for lead bioremediation. Chlorophyceae, particularly *Chlorella* and *Scenedesmus*, possess diverse cell sizes and intricate cell wall compositions that facilitate effective binding and accumulation of metal ions. Additionally, Chlorophyceae synthesize phytochelatin proteins containing essential sulfhydryl (-SH) groups, aiding metal binding within vacuoles. Meanwhile, Cyanophyceae, like *Cyanospira capsulata* and *N. commune*, exhibit proficiency in synthesizing orthophosphate compounds and diverse extracellular polymer compounds (EPS) with varied compositions across different pH levels. Microalgae further exhibit potential in producing enzymes and proteins that assist in metal sequestration. The diversity of microalgae across Indonesia provides a wide array of species suitable for lead bioremediation across various habitats, including freshwater and marine environments. However, the application of microalgae in bioremediation demands further development. Especially in technological advancements and strain selection. Notably, studies indicate that microalgae with lead reduction capabilities often exhibit high lipid levels due to lead-induced cell wall damage, offering potential avenues for biofuel exploration. In summary, the multifaceted attributes of microalgae, evident in their diverse compositions, enzyme production, and adaptable responses to environmental conditions, highlight their promising role as effective agents for lead bioremediation in Indonesia. The region's extensive spectrum of microalgae species fosters opportunities for comprehensive research and implementing environmentally sustainable practices to combat lead pollution.

Declaration statement

The authors reported no potential conflict of interest

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