Biota
Biologi dan Pendidikan Biologi

http://biota.ac.id/index.php/jb
DOI: http://dx.doi.org/10.20414/jb.v18i1.531

Research Article

Evaluating the Efficiency of *Lemna perpussilla* in Removing Heavy Metals from River Wastewater in Yogyakarta

Fajar Riyadi[1], Selvianyi Br Hasibuan[1], Jeremia Gustian Nababan[1], Yovi Avianto[1]*

[1]Department of Agrotechnology, Institut Pertanian STIPER Yogyakarta, Sleman, Indonesia

** Corresponding author: yovi@instiperjogja.ac.id*

Abstract

Heavy metal pollution in Yogyakarta's rivers, caused by textile industries, sand mining, and domestic waste, poses significant environmental and health risks. While conventional water treatment methods face limitations, phytoremediation using Lemna offers a sustainable solution due to its ability to absorb heavy metals efficiently. This study assessed the impact of varying Lemna biomass (control, 20 g, 30 g, 40 g, 50 g per container) on reducing As, Cd, Cr, and Pb in textile, sand mining, and domestic wastewater over three weeks. Heavy metal concentrations were measured using an Atomic Absorption Spectrophotometer (AAS), and Lemna's growth rates were analyzed using ANOVA followed by Tukey's HSD. Results showed that *Lemna perpusilla* effectively adsorbs As, Cd, Cr, and Pb from domestic, sand mining, and batik textile wastewater, with higher biomass leading to improved removal efficiencies. Maximum heavy metal adsorption was observed in batik textile wastewater, achieving over 70% removal for all metals, while domestic and sand mining wastewater showed variable adsorption rates depending on the metal and Lemna biomass. Optimal biomass for growth and adsorption varied: 30 g for domestic, 50 g for sand mining, and 40 g for batik textile wastewater

Keywords: Bioconcentration factor, heavy metals. phytoremediation, sustainability, wastewater treatment

1. Introduction

Water pollution caused by industrial and domestic waste has become a pressing environmental issue in Indonesia. In 2018, reports indicated that 25 rivers were severely contaminated with heavy metals originating from industrial and household activities. By 2019, this number had increased to 38 rivers classified as heavily polluted (Basuki et al., 2024). A similar situation is observed in Yogyakarta, where major rivers such as Code, Gajah Wong, Winongo, and Bantul are heavily polluted due to industrial and domestic waste (Aminatun et al., 2024; Santoso et al., 2024). The heavy metal pollution in Yogyakarta's rivers is a significant environmental concern. Key sources of this contamination include the batik industry, household waste, and sand mining activities. The batik industry, which is closely associated with Yogyakarta's cultural heritage, contributes significantly to heavy metal pollution in local rivers (Handayani et al., 2018). In addition, improper disposal of domestic waste and sand mining further intensify the pollution problem (Suprayogi et al., 2019; Trisnaning et al., 2022).

Wastewater that is not properly treated often contains dangerous heavy metals such as chromium (Cr), cadmium (Cd), mercury (Hg), arsenic (As), zinc (Zn), copper (Cu), iron (Fe), aluminum (Al), barium (Ba), lead (Pb), manganese (Mn), silver (Ag), sodium (Na), and selenium (Se) (Amjad et al., 2020). When heavy metals in water exceed safe limits, they pose serious risks to human health and aquatic ecosystems. Contaminated water can lead to discoloration, unpleasant odors, and degraded water quality, thereby endangering organisms that depend on the water (Purba & Fitrihidajati, 2021).

Efforts to address heavy metal pollution in water have drawn attention from various stakeholders. Various approaches have been developed to remove heavy metal ions from wastewater. Each technique targets specific types of contamination. Adsorption relies on materials with high surface areas to trap metal ions. This method is widely used due to its cost-effectiveness and simplicity (Li et al., 2018). Membrane filtration separates pollutants using selective barriers according to (Xiang et al., 2022). It is effective in removing fine particles and dissolved metals from water. Chemical processes convert heavy metals into less harmful forms. These processes often involve precipitation or oxidation-reduction reactions (Wu et al., 2024). Electrochemical methods extract metals by applying electrical currents, while photocatalysis uses light energy to degrade or transform contaminants (Luo et al., 2019; Xu et al., 2019). It is considered an environmentally friendly option for breaking down complex pollutants.

Despite the advantages of these methods, they are not without drawbacks. Adsorption requires frequent replacement or regeneration of materials. Membrane filtration faces challenges such as high costs and fouling. Chemical processes often produce sludge that requires further treatment. Electrochemical methods demand significant energy input, making them less economical. Photocatalysis relies on expensive catalysts and specific light sources. These limitations highlight the need for more efficient and sustainable solutions in heavy metal wastewater treatment. As a result, alternative methods that are both cost-effective and eco-friendly are urgently needed. One promising approach is phytoremediation, which uses plants to absorb or degrade pollutants from water (Yadav et al., 2018). This technique involves plants improving the quality of contaminated water or soil by transferring, removing, stabilizing, or degrading harmful substances. Various aquatic plants, often considered weeds, have shown great potential as phytoremediation agents for heavy metal pollution (Aminatun et al., 2024).

Lemna, commonly known as duckweed, is one such plant with the ability to absorb heavy metals from polluted water. *Lemna*'s rapid growth, high adaptability, and minimal maintenance requirements make it an ideal candidate for large-scale applications in water pollution management (Liu et al., 2021). Research has highlighted several species of *Lemna*, including *Lemna minor*, *Lemna gibba*, and , as effective phytoremediators for heavy metals such as cadmium (Cd), lead (Pb), chromium (Cr), and arsenic (As) (Chrismadha et al., 2019; M. K. Daud et al., 2018; Sasmaz et al., 2015). According to (Nguyen et al., 2020), *Lemna* absorbs heavy metals through bioaccumulation, where heavy metal ions are taken up via the plant's roots and leaf surfaces. These ions are chemically bound within the plant tissues through interactions with proteins, enzymes, and cell wall polysaccharides. The efficiency of *Lemna* in removing heavy metals depends on the species, environmental conditions, and the concentration of heavy metals in the water. For instance, studies indicate that *Lemna minor* can reduce cadmium levels by 70–80% in a short period, while

Lemna gibba can remove over 90% of lead from synthetic wastewater (Ceschin et al., 2020; Sasmaz et al., 2015). Additionally, *Lemna*'s fast growth, resilience in various environments, and ease of harvesting further enhance its suitability for phytoremediation applications (Ali et al., 2020).

Although previous research has extensively studied *Lemna*'s ability to absorb heavy metals, there is limited information on the population density of *Lemna* required to achieve maximum removal efficiency. This study aims to examine the effect of *Lemna* population density on reducing heavy metal concentrations in polluted water. The research will use wastewater samples from domestic, industrial, and mining sources. The findings are expected to provide an alternative solution for managing heavy metal pollution and contribute to the advancement of environmentally friendly water treatment technologies.

2. Material and Method

Location, Time, and Materials

This study was conducted from October to November 2024 in Maguwoharjo, Depok District, Sleman Regency, Special Region of Yogyakarta. The primary material used was *Lemna perpusilla* Torr., which served as a plant for absorbing heavy metals present in wastewater. The wastewater used in the study consisted of three types. Textile wastewater originating from the production or dyeing process of batik fabrics in Wukirsari, Imogiri District, Bantul Regency, Special Region of Yogyakarta. Sand mining wastewater collected from sand mining activities in Propok Kulon, Sendangmulyo, Minggir District, Sleman Regency, Special Region of Yogyakarta. Domestic wastewater or household waste, obtained from leftovers of restaurant industries in Pugeran, Maguwoharjo, Depok District, Sleman Regency, Special Region of Yogyakarta.

Research Design

The study employed a completely randomized design (CRD) with five replications. Prior to treatment, the heavy metal content, including arsenic (As), cadmium (Cd), lead (Pb), and chromium (Cr), in each of the three wastewater samples was analyzed. *Lemna perpusilla* Torr. is taken from the propagation pond and placed into a plastic container filled with water to reduce stress levels. The plants are then selected and reproduced in an adaptation pond. During the reproduction and adaptation process, all aquatic plants other than *Lemna perpusilla* Torr. are removed. The plants are further selected based on the condition of having four leaves. The treatments involved varying biomass of *Lemna perpusilla* Torr., consisting of a control (no *Lemna*) and 20 grams, 30 grams, 40 grams, and 50 grams of *Lemna* per container. The containers used were plastic trays measuring 40 cm x 30 cm x 4 cm, with each filled with 1,500 mL of water (Figure 1). After observing the growth parameters of *Lemna* and the physical properties of the water, the heavy metal content in the wastewater was re-analyzed after three weeks of treatment.

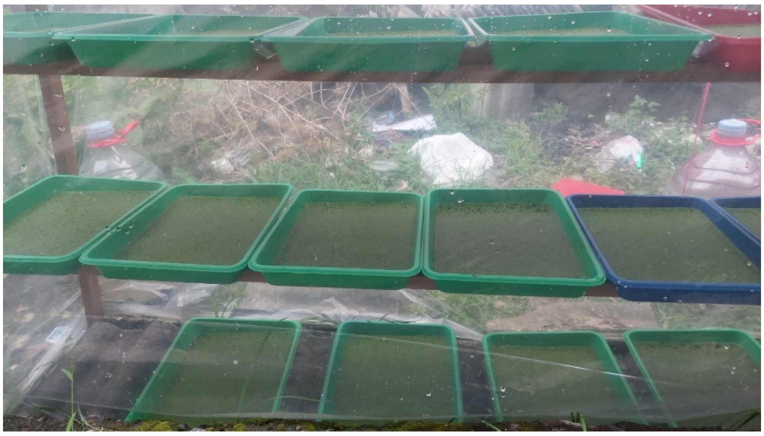

Figure 1. *Lemna perpusilla* research container

Analysis of Heavy Metal Contents

The heavy metal content in the water was analyzed using an Atomic Absorption Spectrophotometer (AAS). Total heavy metal elements were measured directly from clear water filtrates using the AAS, employing the Flame Method for concentrations in ppm and the Graphite Furnace Method for concentrations in ppb. The equipment used included pipettes, volumetric flasks, test tubes, and the AAS itself. Standard heavy metal solutions for Pb, Cd, As, and Cr were prepared from primary stock solutions (1,000 ppm) and diluted to specific concentrations as needed for analysis. Mixed standards were created by combining primary standard solutions, and a series of standard dilutions were prepared to achieve a specific range of concentrations.

The water filtrates were extracted until clear and then directly measured using the AAS. Heavy metal concentrations were determined based on a calibration curve, which was established by plotting the relationship between the standard concentration series and their readings. The heavy metal levels were calculated by multiplying the calibration curve results by the dilution factor. Subsequently, the heavy metal concentrations of As, Cd, Cr, and Pb were compared before and after the addition of *Lemna perpusilla* Torr. to determine whether the plant effectively reduced these heavy metals.

Agronomical Variables

The agronomic variables observed were the fresh weight and dry weight of *Lemna perpusilla* Torr. These measurements were taken at the start of the experiment and again on day 21. Samples were collected, weighed, and then dried in an oven at 70°C for 48 hours. After drying, the samples were reweighed to calculate the percentage of dry weight. The fresh and dry weight values were also analyzed to determine their relationship, estimate the total dry weight in each container, and calculate the total biomass. The dry weight data were also used to calculate the relative growth rate (RGR) using the following formula:

$$RGR\ (g^{-1}g^{-1}day^{-1}) = \frac{\ln\ (W2 - W1)}{T2 - T1}$$

Where:
W1 : Dry weight of Lemna at the start
W2 : Dry weight of Lemna at the end
T1 : Initial time
T2 : Final time

Statistical Analysis

The data were analyzed using a 5% Analysis of Variance (ANOVA) after collection. Before performing ANOVA, normality and homogeneity tests were conducted. The Shapiro-Wilk test was used to assess error normality, while the Bartlett test was applied to check homogeneity. If significant differences were found among Lemna densities, further comparisons were made using Fisher's LSD test. If the assumptions of normality and homogeneity were not met, the non-parametric Kruskal-Wallis test was used instead.

3. Results and Discussion

3.1.Results

Heavy Metals Concentration in Wastewater

The analysis of heavy metal concentrations in wastewater reveals concerning pollution levels, particularly from the batik industry in Yogyakarta (Table 1). Arsenic, cadmium, and lead in this wastewater significantly exceed regulatory limits according to PP RI no 22 (2021). These contaminations highlighted the inadequate treatment of industrial effluents especially from the dyeing process. These metals are highly toxic and can accumulate in aquatic ecosystems, posing risks to both the environment and human health. Sand mine wastewater also shows elevated cadmium levels, although arsenic, chromium, and lead remain within acceptable limits. Mining activities often disrupt natural systems, and even metals within permissible levels can accumulate over time. Household wastewater, on the other hand, shows much lower concentrations of heavy metals, suggesting minimal contribution to pollution. However, growing chemical use in homes could present future challenges if not managed responsibly. These findings suggest the potential of as a phytoremediation agent to address heavy metal contamination in wastewater.

Table 1. Heavy Metals Concentration in Wastewater

Waste Types	As	Cd	Cr	Pb
Household	0,0008	0,0012	0,013	0,0011
Sand Mine	0,0162	0,021	0,0149	0,015
Batik Industry	0,312	0,34	0,0562	0,1175
Permissible Limit*	0,05	0,01	0,1	0,03

Note: *Standard Quality of Surface Water PP RI no 22 (2021)

Adsorption of Heavy Metals in Domestic Wastewater

The adsorption efficiency of *Lemna perpusilla* in removing heavy metals from domestic wastewater was evaluated across varying plant weights (Table 2, Figure 2). Statistical analysis indicates significant differences in the adsorption and residual concentrations of certain heavy metals, while others remain unaffected. For arsenic (As), the concentration in water decreased consistently as the weight increased. At 20 g, the concentration was 0.00061 ppm, significantly higher than that observed at 30 g, 40 g, and 50 g (0.00043, 0.00031, and 0.00026 ppm, respectively). The percentage of adsorption increased from 23.75% at 20 g to 67.50% at 50 g. These findings suggest that higher biomass enhances the adsorption of arsenic, with significant improvements noted between 20 g and higher weights. Cadmium (Cd) exhibited a similar trend, with its concentration in water reducing significantly from 0.00092 ppm at 20 g to 0.00032 ppm at 50 g. Adsorption percentages increased substantially, reaching 73.33% at 50 g, compared to 23.33% at 20 g. Statistical analysis revealed no significant difference between 20 g and 30 g in cadmium concentration, but the efficiency improved markedly at 40 g and above.

Table 2. Heavy Metals Concentration in Water and Its Adsorption Percentage by *Lemna perpusilla* in Domestic Wastewater

Heavy Metals	**Lemna Weight (g)**			
	20	**30**	**40**	**50**
Concentration (ppm)				
As	0,00061 b	0,00043 a	0,00031 a	0,00026 a
Cd	0,00092 b	0,00085 b	0,00041 a	0,00032 a
Cr	0,00550 a	0,00509 a	0,00532 a	0,00473 a
Pb	0,00080 a	0,00070 a	0,00072 a	0,00074 a
Adsorption (%)				
As	23,75 b	46,25 a	61,25 a	67,50 a
Cd	23,33 b	29,17 b	65,83 a	73,33 a
Cr	57,69 a	60,85 a	59,08 a	63,62 a
Pb	27,27 a	36,36 a	34,55 a	32,73 a

Note: Mean followed by the same notation shows no difference according to LSD Fisher (α=5%)

Chromium (Cr) concentrations did not show significant differences across the various weights of *Lemna*. The residual concentration ranged narrowly from 0.00550 ppm at 20 g to 0.00473 ppm at 50 g. Adsorption percentages also remained consistent, with values between 57.69% and 63.62%, suggesting that chromium removal efficiency is less influenced by plant weight under these conditions. Lead (Pb) concentrations similarly displayed no significant differences among all weights tested. The residual concentration ranged from 0.00080 ppm to 0.00074 ppm, with adsorption percentages varying between 27.27% and 36.36%. This indicates that *Lemna perpusilla* may exhibit a limited capacity for lead adsorption regardless of biomass.

Adsorption of Heavy Metals in Sand Mining Wastewater

Lemna phytoremediation ability in sand mining wastewater had a different pattern compared to domestic wastewater as shown in Table 3 and Figure 3. For arsenic (As), the concentration decreased significantly at 50 g, reaching 0.01040 ppm. At this weight, the adsorption percentage was 35.80%, which was higher than the other weights. There was no significant difference in adsorption at 20 g, 30 g, or 40 g, showing limited effectiveness at lower biomass levels. Cadmium (Cd) removal also improved with increasing biomass. The concentration was reduced to 0.01000 ppm and 0.00990 ppm at 40 g and 50 g, respectively. These weights showed adsorption percentages of 52.38% and 52.85%. No significant difference was observed between 20 g and 30 g, where the adsorption remained below 41.43%. These results indicate that higher biomass is necessary for effective cadmium removal.

Chromium (Cr) concentrations were significantly reduced only at 50 g, with a remaining level of 0.00670 ppm. Adsorption at this weight reached 55.03%, which was much higher than at 20 g, 30 g, or 40 g. At lower biomass levels, the adsorption percentages ranged from 26.85% to 39.59%, showing limited chromium removal. Lead (Pb) concentrations also decreased significantly at 40 g and 50 g. The concentrations were 0.00641 ppm and 0.00530 ppm, respectively. The adsorption percentage at 50 g was 64.67%, the highest among all weights. Weights of 20 g and 30 g showed no significant difference with adsorption remaining around 28%.

Table 3. Heavy Metals Concentration in Water and Its Adsorption Percentage by *Lemna perpusilla* in Sand Mining Wastewater

Heavy Metals	**Lemna Weight (g)**			
	20	**30**	**40**	**50**
Concentration (ppm)				
As	0,01540 b	0,01430 b	0,01420 b	0,01040 a
Cd	0,01730 b	0,01230 ab	0,01000 a	0,00990 a
Cr	0,01090 b	0,00950 b	0,00900 b	0,00670 a
Pb	0,01080 b	0,01075 b	0,00641 a	0,0053 a
Adsorption (%)				
As	4,94 b	11,73 b	12,35 b	35,80 a
Cd	17,62 b	41,43 ab	52,38 a	52,85 a
Cr	26,85 b	36,24 b	39,59 b	55,03 a
Pb	28,00 b	28,33 b	57,27 a	64,67 a

Note: Mean followed by the same notation shows no difference according to LSD Fisher (α=5%)

Adsorption of Heavy Metals in Batik Textile Wastewater

The ability of *Lemna* to mitigate heavy metal contamination in batik textile wastewater displayed noticeable improvements with increasing biomass (Table 4, Figure 4). For arsenic (As), the most substantial reduction occurred at 40 g and 50 g, with residual concentrations of 0.06200 ppm and 0.06100 ppm. Adsorption rates at these weights were markedly high, reaching 80.13% and 80.44%, respectively. In contrast, at 20 g and 30 g, adsorption efficiency remained below 60%, indicating limited effectiveness at lower biomass levels. Cadmium (Cd) exhibited a similar trend, where concentrations dropped significantly at 40 g and 50 g to 0.11000 ppm and 0.10300 ppm. The corresponding adsorption rates were 67.65% and 69.70%, showcasing a notable improvement compared to 20 g and 30 g, which achieved adsorption rates below 41%. This pattern suggests a strong correlation between biomass and cadmium removal efficiency.

Chromium (Cr) removal was particularly striking at 50 g, where concentrations decreased to 0.01620 ppm, corresponding to an adsorption rate of 71.17%. While 40 g also demonstrated improvement with 57.11% adsorption, lower weights of 20 g and 30 g remained less effective, with adsorption percentages below 49%. These results highlight the superior capacity of higher biomass for chromium remediation. Lead (Pb) removal was significantly enhanced starting from 30 g, with residual concentrations of 0.05100 ppm at 30 g, 0.04030 ppm at 40 g, and 0.03500 ppm at 50 g. The highest adsorption was observed at 50 g, reaching 70.21%. At 20 g, however, lead adsorption was minimal at just 14.80%, underscoring the limited potential of lower biomass levels in removing lead.

Table 4. Heavy Metals Concentration in Water and Its Adsorption Percentage by *Lemna perpusilla* in Batik Textile Waste

Heavy Metals	Lemna Weight (g)			
	20	30	40	50
Concentration (ppm)				
As	0,12840 b	0,14500 b	0,06200 a	0,06100 a
Cd	0,20800 b	0,20100 b	0,11000 a	0,10300 a
Cr	0,03140 c	0,02890 c	0,02410 b	0,01620 a
Pb	0,10010 b	0,05100 a	0,04030 a	0,03500 a
Adsorption (%)				
As	58,84 b	53,52 b	80,13 a	80,44 a
Cd	38,82 b	40,88 b	67,65 a	69,70 a
Cr	44,13 c	48,57 c	57,11 b	71,17 a
Pb	14,80 b	56,59 a	65,70 a	70,21 a

Note: Mean followed by the same notation shows no difference according to LSD Fisher (α=5%)

Growth of *Lemna perpusilla*

The growth of *Lemna perpusilla* varied across waste types and initial biomass levels (Table 5). In domestic waste, the highest fresh weight gain was 9.1 g at 30 g *Lemna* weight. Dry weight gain at this level reached 2.49 g, with an RGR of 0.043 and a fresh weight gain percentage of 30.33%. Fresh weight gain decreased at 40 g and 50 g, with values of 5.4 g and 3.9 g, respectively. The RGR at these weights dropped to 0.011 and 0.014. These results indicate that 30 g biomass optimized growth in domestic wastewater. In sand mine wastewater, fresh weight gain reached a maximum of 8.1 g at 50 g *Lemna* weight. Dry weight gain at this level was 1.42 g, with an RGR of 0.016. The percentage of fresh weight gain was 16.20%, which was lower than at 20 g and 30 g. At these lower weights, fresh weight gain percentages were 29.20% and 22.67%. The data suggest that higher biomass accumulates more weight but reduces growth efficiency. In batik textile wastewater, 40 g *Lemna* weight showed the highest fresh weight gain at 6.9 g. Dry weight gain was 0.71 g, with a fresh weight gain percentage of 17.25%. The RGR at this weight was 0.136. Lower weights of 20 g and 30 g and higher weights of 50 g produced significantly lower fresh weight gains and RGR values.

3.2. Discussion

According to Tables 2, 3, and 4, higher biomass consistently improves adsorption efficiency for certain heavy metals but has different patterns in each wastewater type. In domestic and sand mining wastewater, the adsorption efficiency for arsenic increases significantly with higher *Lemna* biomass. Earlier research (Rai & Nongtri, 2024) demonstrates the affinity of *Lemna* species for arsenic due to its root structure and surface interactions. In batik textile wastewater, arsenic removal reaches its highest efficiency due to the unique ionic composition of the wastewater (Zakaria et al., 2023).

Cadmium adsorption also improves with increasing *Lemna* biomass. In domestic wastewater, cadmium removal efficiency depends on plant biomass and the number of active adsorption sites available (Raza et al., 2020). In sand mining wastewater, cadmium adsorption efficiency increases at higher biomass levels after remaining moderate at lower weights. In batik textile wastewater, cadmium removal achieves its maximum potential with increased biomass. The composition of batik wastewater enhances the uptake efficiency of cadmium (Juliani et al., 2021).

Table 5. Agronomic and Growth Parameter of *Lemna perpussilla* in Several Types of Waste

***Lemna* Weight (g)**	**Fresh Weight Gain (g)**	**Dry Weight Gain (g)**	**% of Fresh Weight Gain**	**RGR**
Domestic				
20	3,2 b	1,41 b	16,00 b	0,016 b
30	9,1 a	2,49 a	30,33 a	0,043 a
40	5,4 b	1,26 b	13,50 b	0,011 b
50	3,9 b	1,35 b	7,80 b	0,014 b
Sand Mine				
20	5,9 a	1,27 a	29,20 a	0,011 a
30	6,8 a	1,31 a	22,67 a	0,013 a
40	4,7 b	1,09 a	11,75 b	0,004 b
50	8,1 a	1,42 a	16,20 b	0,016 a
Batik Textile				
20	1,7 b	0,59 b	8,50 b	0,102 b
30	1,8 b	0,48 b	6,00 b	0,085 b

40	6,9 a	0,71 a	17,25 a	0,136 a
50	2,2 b	0,49 b	4,40 b	0,070 b

Note: Mean followed by the same notation shows no difference according to LSD Fisher (α=5%)

Chromium removal shows minimal improvement with increased biomass in domestic wastewater. In sand mining wastewater, higher biomass weights lead to enhanced chromium removal. In batik textile wastewater, the most significant chromium removal occurs at higher biomass levels. The properties of the wastewater influence the bioavailability and uptake of chromium by *Lemna perpusilla*. Lead adsorption by *Lemna* remains lower than for other metals regardless of biomass weight. In domestic wastewater, lead removal efficiency shows limited variation with increased biomass. In sand mining wastewater, moderate lead removal occurs only at higher biomass weights. In batik textile wastewater, lead adsorption efficiency improves substantially at higher biomass levels. The complex ionic and organic composition of batik wastewater enhances interactions between lead and *Lemna* biomass. Adsorption efficiency varies across wastewater types. Batik textile wastewater achieves higher adsorption rates for chromium and cadmium compared to the other wastewater types. Metal concentrations, competing ions, and the physicochemical properties of the wastewater play a role in determining adsorption efficiency.

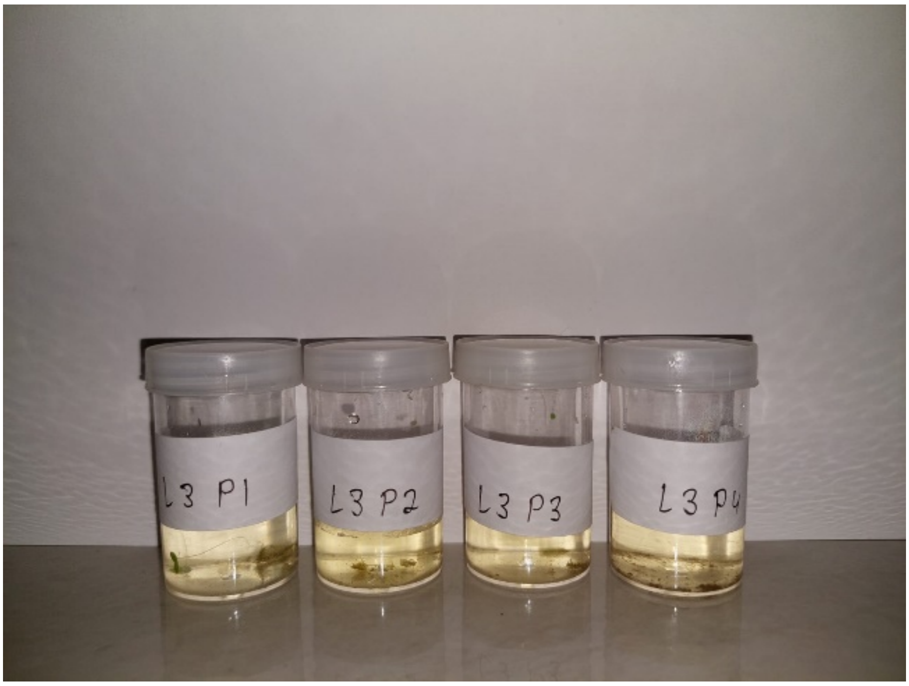

Figure 2. Domestic wastewater after phytoremediation

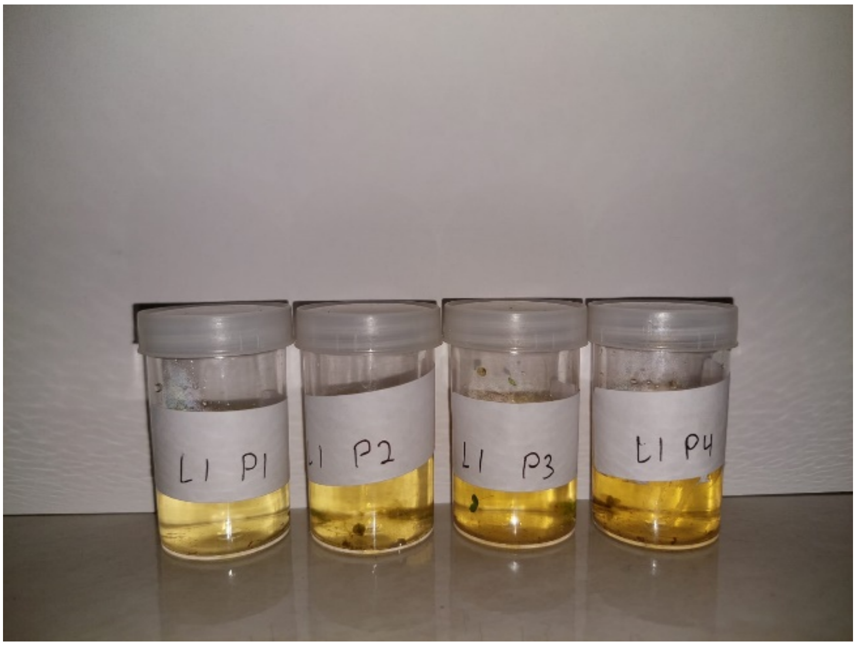

Figure 3. Sand mining wastewater after phytoremediation

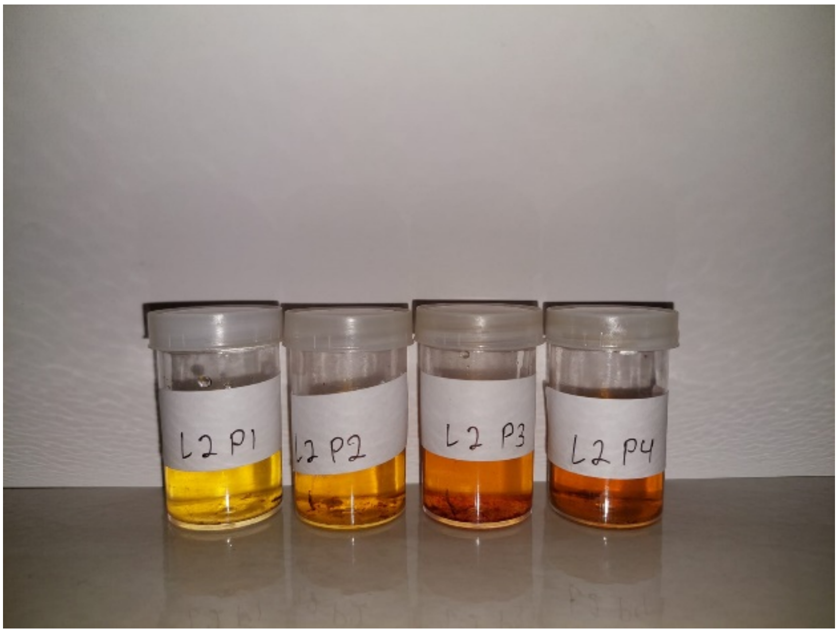

Figure 4. Batik textile wastewater after phytoremediation

The growth of *Lemna perpusilla* across different wastewater types and biomass levels highlights the influence of wastewater composition and nutrient availability. In domestic wastewater, the highest fresh and dry weight gains observed at 30 g biomass align with previous studies that show optimal growth at moderate plant densities (Coughlan et al., 2022; Walsh et al., 2021a). Excessive biomass, as seen at 40 g and 50 g, can create competition for nutrients and light, reducing growth rates. This is consistent with research by Walsh et al. (2021b), indicating that overcrowding limits the photosynthetic capacity of aquatic plants, thereby affecting relative growth rates (RGR). In sand mine wastewater, the maximum fresh weight gain at 50 g biomass suggests higher nutrient uptake at greater plant densities. However, the reduced growth efficiency, as shown by lower RGR values, reflects the diminishing returns often observed in nutrient-rich environments. Previous studies have demonstrated that increased biomass can lead to nutrient depletion in localized areas (DalCorso et al., 2019). The lower fresh weight gain percentages at higher biomass levels further support findings that nutrient distribution becomes less efficient as plant density increases. In batik textile wastewater, the highest fresh weight and RGR observed at 40 g biomass suggest a balance between nutrient availability and plant density. Prior research indicates that wastewater with complex compositions, such as batik effluent, may provide specific nutrients or compounds that enhance growth at intermediate biomass levels (Daud et al., 2022). The significantly lower growth rates at 50 g biomass could result from nutrient competition or the accumulation of inhibitory substances.

Conclusion

The study shows that *Lemna perpusilla* effectively adsorbs arsenic, cadmium, chromium, and lead from polluted water, with varying efficiencies across waste types and plant weights. In domestic wastewater, arsenic and cadmium adsorption increased with higher biomass, reaching maximum removal rates of 67.50% and 73.33%, respectively, while chromium and lead showed limited adsorption changes. In sand mining wastewater, cadmium and lead removal were highest at 52.85% and 64.67%, respectively, with arsenic and chromium adsorption showing moderate improvement at higher weights. For batik textile wastewater, arsenic, cadmium, chromium, and lead showed significant removal efficiencies at 80.44%, 69.70%, 71.17%, and 70.21%, respectively, at higher *Lemna* biomass. Growth variables, including fresh weight gain, relative growth rate (RGR), and dry weight gain, varied across wastewater types and initial *Lemna* weights, with optimal growth achieved at 30 g in domestic wastewater, 50 g in sand mining wastewater, and 40 g in batik textile wastewater. These results indicate that higher *Lemna* biomass improves heavy metal adsorption efficiency and growth performance, highlighting its potential for phytoremediation of diverse wastewater types.

References

Ali, S., Abbas, Z., Rizwan, M., Zaheer, I., Yavaş, İ., Ünay, A., Abdel-DAIM, M., Bin-Jumah, M., Hasanuzzaman, M., & Kalderis, D. (2020). Application of Floating Aquatic Plants in Phytoremediation of Heavy Metals Polluted Water: A Review. *Sustainability*, *12*(5), 1927. https://doi.org/10.3390/su12051927

Aminatun, T., Rakhmawati, A., Budiasih, K. S., Marfuatun, M., Rijal, B. S., Amin, A. N., Arifin, D. M. N., & Putri, A. S. (2024). Identifikasi Logam Berat Kromium di Tiga Sungai yang Melintasi Kota Yogyakarta dan Potensi Fitoremediasinya. *Jurnal Ilmu Lingkungan*, *22*(3), 620–631. https://doi.org/10.14710/jil.22.3.620-631

Amjad, M., Hussain, S., Javed, K., Rehman Khan, A., & Shahjahan, M. (2020). The Sources, Toxicity, Determination of Heavy Metals and Their Removal Techniques from Drinking Water. *World Journal of Applied Chemistry*, *5*(2), 34. https://doi.org/10.11648/j.wjac.20200502.14

Basuki, T. M., Indrawati, D. R., Nugroho, H. Y. S. H., Pramono, I. B., Setiawan, O., Nugroho, N. P., Nada, F. M. H., Nandini, R., Savitri, E., Adi, R. N., Purwanto, P., & Sartohadi, J. (2024). Water Pollution of Some Major Riversin Indonesia: The Status, Institution, Regulation,and Recommendation for Its Mitigation. *Polish Journal of Environmental Studies*, *33*(4), 3515–3530. https://doi.org/10.15244/pjoes/178532

Ceschin, S., Crescenzi, M., & Iannelli, M. A. (2020). Phytoremediation potential of the duckweeds Lemna minuta and Lemna minor to remove nutrients from treated waters. *Environmental Science and Pollution Research*, *27*(13), 15806–15814. https://doi.org/10.1007/s11356-020-08045-3

Chrismadha, T., Suryono, T., Magfiroh, M., Mardiati, Y., & Mulyana, E. (2019). Phytoremediation of Maninjau Lake water using Minute Duckweed (Lemna perpusilla Torr.). *IOP Conference Series: Earth and Environmental Science*, *308*(1), 012021. https://doi.org/10.1088/1755-1315/308/1/012021

Coughlan, N. E., Walsh, É., Ahern, R., Burnell, G., O'Mahoney, R., Kuehnhold, H., & Jansen, M. A. K. (2022). Flow Rate and Water Depth Alters Biomass Production and Phytoremediation Capacity of Lemna minor. *Plants*, *11*(16), 2170. https://doi.org/10.3390/plants11162170

DalCorso, G., Fasani, E., Manara, A., Visioli, G., & Furini, A. (2019). Heavy Metal Pollutions: State of the Art and Innovation in Phytoremediation. *International Journal of Molecular Sciences*, *20*(14), 3412. https://doi.org/10.3390/ijms20143412

Daud, M. K., Ali, S., Abbas, Z., Zaheer, I. E., Riaz, M. A., Malik, A., Hussain, A., Rizwan, M., Zia-ur-Rehman, M., & Zhu, S. J. (2018). Potential of Duckweed (*Lemna minor*) for the Phytoremediation of Landfill Leachate. *Journal of Chemistry*, *2018*, 1–9. https://doi.org/10.1155/2018/3951540

Daud, N. M., Abdullah, S. R. S., Hasan, H. A., Ismail, N. 'Izzati, & Dhokhikah, Y. (2022). Integrated physical-biological treatment system for batik industry wastewater: A review on process selection. *Science of The Total Environment*, *819*, 152931. https://doi.org/10.1016/j.scitotenv.2022.152931

Handayani, W., Kristijanto, A. I., & Hunga, A. I. R. (2018). Are natural dyes eco-friendly? A case study on water usage and wastewater characteristics of batik production by natural dyes application. *Sustainable Water Resources Management*, *4*(4), 1011–1021. https://doi.org/10.1007/s40899-018-0217-9

Juliani, A., Rahmawati, S., & Yoneda, M. (2021). Heavy metal characteristics of wastewater from batik industry in Yogyakarta area, Indonesia. *International Journal of GEOMATE*, *20*(80), 59–67. https://doi.org/10.21660/2021.80.6271

Li, J., Wang, X., Zhao, G., Chen, C., Chai, Z., Alsaedi, A., Hayat, T., & Wang, X. (2018). Metal–organic framework-based materials: Superior adsorbents for the capture of toxic and radioactive metal ions. *Chemical Society Reviews*, *47*(7), 2322–2356. https://doi.org/10.1039/C7CS00543A

Liu, Y., Xu, H., Yu, C., & Zhou, G. (2021). Multifaceted roles of duckweed in aquatic phytoremediation and bioproducts synthesis. *GCB Bioenergy*, *13*(1), 70–82. https://doi.org/10.1111/gcbb.12747

Luo, J., Zhang, S., Sun, M., Yang, L., Luo, S., & Crittenden, J. C. (2019). A Critical Review on Energy Conversion and Environmental Remediation of Photocatalysts with Remodeling Crystal Lattice, Surface, and Interface. *ACS Nano*, *13*(9), 9811–9840. https://doi.org/10.1021/acsnano.9b03649

Nguyen, T. Q., Sesin, V., Kisiala, A., & Emery, R. J. N. (2020). Phytohormonal Roles in Plant Responses to Heavy Metal Stress: Implications for Using Macrophytes in Phytoremediation of Aquatic Ecosystems. *Environmental Toxicology and Chemistry*, *40*(1), 7–22. https://doi.org/10.1002/etc.4909

Purba, N. C., & Fitrihidajati, H. (2021). Kualitas Perairan Sungai Sadar Berdasarkan Indeks Keanekaragaman Makrozoobentos dan Kadar Logam Berat (Pb) di Kabupaten Mojokerto. *LenteraBio : Berkala Ilmiah Biologi*, *10*(3), 292–301. https://doi.org/10.26740/lenterabio.v10n3.p292-301

Rai, P. K., & Nongtri, E. S. (2024). Heavy metals/-metalloids (As) phytoremediation with Landoltia punctata and Lemna sp. (duckweeds): Coupling with biorefinery prospects for sustainable phytotechnologies. *Environmental Science and Pollution Research*, *31*(11), 16216–16240. https://doi.org/10.1007/s11356-024-32177-5

Raza, A., Habib, M., Kakavand, S. N., Zahid, Z., Zahra, N., Sharif, R., & Hasanuzzaman, M. (2020). Phytoremediation of Cadmium: Physiological, Biochemical, and Molecular Mechanisms. *Biology*, *9*(7), 177. https://doi.org/10.3390/biology9070177

Santoso, D. H., Usama, I. S. I., & Adventia, M. N. (2024). *Environmental degradation valuation in Daerah Istimewa Yogyakarta*. 020003. https://doi.org/10.1063/5.0226477

Sasmaz, M., Arslan Topal, E. I., Obek, E., & Sasmaz, A. (2015). The potential of Lemna gibba L. and Lemna minor L. to remove Cu, Pb, Zn, and As in gallery water in a mining area in Keban, Turkey. *Journal of Environmental Management*, *163*, 246–253. https://doi.org/10.1016/j.jenvman.2015.08.029

Suprayogi, S., Marfai, M. A., Cahyadi, A., Latifah, R., & Fatchurohman, H. (2019). Analyzing the Characteristics of Domestic Wastes in Belik River, the Special Region of

Yogyakarta, Indonesia. *ASEAN Journal on Science and Technology for Development*, *36*(3). https://doi.org/10.29037/ajstd.591

Trisnaning, P. T., Zamroni, A., Sugarbo, O., Prasetya, H. N. E., Sagala, S. T., & Hardiansyah, M. Y. (2022). Quality of surface water due to sand mining activity: A case study from the Progo River, Daerah Istimewa Yogyakarta Province, Indonesia. *IOP Conference Series: Earth and Environmental Science*, *1098*(1), 012031. https://doi.org/10.1088/1755-1315/1098/1/012031

Walsh, É., Coughlan, N. E., O'Brien, S., Jansen, M. A. K., & Kuehnhold, H. (2021). Density Dependence Influences the Efficacy of Wastewater Remediation by Lemna minor. *Plants*, *10*(7), 1366. https://doi.org/10.3390/plants10071366

Walsh, É., Kuehnhold, H., O'Brien, S., Coughlan, N. E., & Jansen, M. A. K. (2021). Light intensity alters the phytoremediation potential of Lemna minor. *Environmental Science and Pollution Research*, *28*(13), 16394–16407. https://doi.org/10.1007/s11356-020-11792-y

Wu, L., Garg, S., & Waite, T. D. (2024). Progress and challenges in the use of electrochemical oxidation and reduction processes for heavy metals removal and recovery from wastewaters. *Journal of Hazardous Materials*, *479*, 135581. https://doi.org/10.1016/j.jhazmat.2024.135581

Xiang, H., Min, X., Tang, C.-J., Sillanpää, M., & Zhao, F. (2022). Recent advances in membrane filtration for heavy metal removal from wastewater: A mini review. *Journal of Water Process Engineering*, *49*, 103023. https://doi.org/10.1016/j.jwpe.2022.103023

Xu, J., Liu, C., Hsu, P.-C., Zhao, J., Wu, T., Tang, J., Liu, K., & Cui, Y. (2019). Remediation of heavy metal contaminated soil by asymmetrical alternating current electrochemistry. *Nature Communications*, *10*(1), 2440. https://doi.org/10.1038/s41467-019-10472-x

Yadav, K. K., Gupta, N., Kumar, A., Reece, L. M., Singh, N., Rezania, S., & Ahmad Khan, S. (2018). Mechanistic understanding and holistic approach of phytoremediation: A review on application and future prospects. *Ecological Engineering*, *120*, 274–298. https://doi.org/10.1016/j.ecoleng.2018.05.039

Zakaria, N., Rohani, R., Wan Mohtar, W. H. M., Purwadi, R., Sumampouw, G. A., & Indarto, A. (2023). Batik Effluent Treatment and Decolorization—A Review. *Water*, *15*(7), 1339. https://doi.org/10.3390/w15071339