

# Unraveling the Physiological Mechanisms and Bioaccumulation Efficacy of *Lemna perpusilla* for Heavy Metal Phytoremediation in Yogyakarta River Wastewater

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**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.

## 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 intensifies 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 *Lemna perpusilla*, 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 <https://jurnal.fkip.unram.ac.id/index.php/JBT/article/view/10368> 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 ability and population of *Lemna* in specific wastewater, such as mining, textile industry, and domestic wastewater. 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.

## Materials and Methods

### 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.



**Figure 1.** Experimental setup showing different *Lemna* biomass treatments

### Research Design

The study employed a completely randomized design (CRD) with five replications. Before 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.

### 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 was prepared to achieve a specific range of concentrations.

The water filtrates were extracted until clear and then directly measured using 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. Next, the heavy metal concentrations of As, Cd, Cr, and Pb were compared before and after the addition of *Lemna perpusilla* Torr. to assess 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.

### Results and Discussion

The results presented in Tables 1–5 demonstrate variations in heavy metal concentrations and the adsorption efficiency of *Lemna perpusilla* across different wastewater types. These findings provide insights into the phytoremediation potential of *Lemna perpusilla* under diverse contamination conditions originating from domestic, sand mining, and batik textile sources. To better understand these results, the following discussion elaborates on the relationship between plant biomass, wastewater characteristics, and the efficiency of heavy metal removal, as well as the growth performance of *Lemna perpusilla* in each condition.

#### 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.

#### 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.

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.

**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)

**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        |
| <i>Concentration (ppm)</i> |                  |           |           |           |
| 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 |
| <i>Adsorption (%)</i>      |                  |           |           |           |
| 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:** Means followed by the same letter are not significantly different according to Fisher's LSD test at  $\alpha = 0.05$ .

**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        |
| <i>Concentration (ppm)</i> |                  |            |           |           |
| 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  |
| <i>Adsorption (%)</i>      |                  |            |           |           |
| 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:** Means followed by the same letter are not significantly different according to Fisher's LSD test at  $\alpha = 0.05$ .

### 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%.

### Adsorption of Heavy Metals in Batik Textile Water

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.

### Growth & Physiology 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 of *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 optimizes growth in domestic wastewater. In sand mine wastewater, fresh weight gain reached a maximum of 8.1 g at 50 g of *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 of *Lemna* 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.

**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        |
| <i>Concentration (ppm)</i> |                  |           |           |           |
| 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 |
| <i>Adsorption (%)</i>      |                  |           |           |           |
| 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:** Means followed by the same letter are not significantly different according to Fisher's LSD test at  $\alpha = 0.05$ .

**Table 5.** Agronomic and Growth Parameters of *Lemna perpusilla* in Several Types of Waste

| Lemna Weight (g)     | Fresh Weight Gain (g) | Dry Weight Gain (g) | % of Fresh Weight Gain | RGR     |
|----------------------|-----------------------|---------------------|------------------------|---------|
| <i>Domestic</i>      |                       |                     |                        |         |
| 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 |
| <i>Sand Mine</i>     |                       |                     |                        |         |
| 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 |
| <i>Batik Textile</i> |                       |                     |                        |         |
| 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:** Means followed by the same letter are not significantly different according to Fisher's LSD test at  $\alpha = 0.05$ .

## Discussion

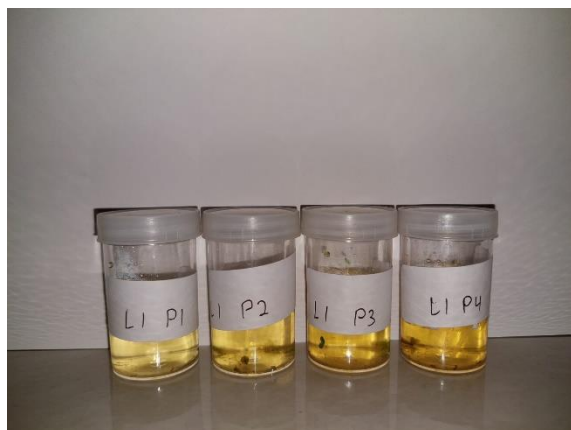
### Adsorption of Arsenic (As)

According to Tables 2, 3, and 4, arsenic (As) adsorption by *Lemna perpusilla* increased significantly with higher biomass across all wastewater types, although the degree of efficiency varied. In domestic wastewater, As concentration decreased from 0.00061 ppm at 20 g to 0.00026 ppm at 50 g, corresponding to a rise in adsorption efficiency from 23.75% to 67.50%. A similar trend occurred in sand mining wastewater, where the highest adsorption (35.80%) was achieved at 50 g. The most remarkable performance was observed in batik

textile wastewater, reaching 80.44% adsorption at 50 g biomass.



**Figure 2.** Domestic wastewater after phytoremediation



**Figure 3.** Sand mining wastewater after phytoremediation



**Figure 4.** Batik textile wastewater after phytoremediation

These results are consistent with findings by Rai & Nongtri (2024), who reported that *Lemna* species exhibit high affinity for arsenic due to extensive root surface area and functional groups facilitating ion exchange. Zakaria et al. (2023) also noted that wastewater with high ionic content, such as textile effluents, enhances arsenic solubility and uptake by aquatic plants. The higher removal efficiency observed in batik wastewater supports this, as its complex ionic and organic composition likely enhances metal bioavailability.

#### Adsorption of Cadmium (Cd)

Cadmium adsorption also showed a positive correlation with increasing *Lemna* biomass in all wastewater types. In domestic wastewater, Cd concentration decreased from 0.00092 ppm at 20 g to 0.00032 ppm at 50 g, with adsorption efficiency increasing from 23.33% to 73.33%. Similar improvements were observed in

sand mining and batik textile wastewater, where the highest adsorption percentages (52.85% and 69.70%, respectively) were obtained at 50 g biomass. These results align with Raza et al. (2020), who highlighted that the availability of active adsorption sites on *Lemna* biomass directly influences Cd uptake capacity. Juliani et al. (2021) further found that textile wastewater rich in organic ligands facilitates cadmium complexation, enhancing its removal by aquatic plants. The strong adsorption observed in batik wastewater in this study confirms this interaction.

#### Adsorption of Chromium (Cr)

Chromium removal exhibited varied responses depending on wastewater type. In domestic wastewater, Cr adsorption was relatively stable, ranging between 57.69–63.62%, showing minimal biomass influence. However, in sand mining wastewater, adsorption improved significantly at 50 g biomass (55.03%), and in batik wastewater, adsorption reached 71.17% at the same biomass level. These observations are consistent with previous research by Aslanzadeh et al. (2024), who reported that chromium uptake by *Lemna* minor depends on both plant density and metal speciation. Chromium (VI) tends to be more mobile and more easily absorbed compared to chromium (III). The higher adsorption observed in batik wastewater suggests that the effluent's chemical environment may promote the reduction of Cr(VI) to Cr(III), enhancing metal binding to plant tissues.

#### Adsorption of Lead (Pb)

Lead adsorption by *Lemna* remains lower than for other metals, regardless of biomass weight. In domestic wastewater, the adsorption efficiency remained between 27.27% and 36.36%. In sand mining wastewater, Pb removal improved slightly at 40–50 g biomass (up to 64.67%), while in batik wastewater, the efficiency reached 70.21% at 50 g biomass. The complex ionic and organic composition of batik wastewater enhances interactions between lead and *Lemna* biomass. Metal concentrations, competing ions, and the physicochemical properties of the wastewater play a role in determining adsorption efficiency. These results corroborate findings by Mousavi et al. (2022),

who reported that lead has lower bioavailability in aquatic environments due to its strong complexation with organic matter. However, the higher adsorption observed in batik wastewater suggests that the presence of surfactants and organic dyes may increase Pb solubility, facilitating uptake by *Lemna* (Ni et al., 2024).

### Growth and Physiology of *Lemna perpusilla*

The growth performance of *Lemna perpusilla* varied significantly among wastewater types and biomass levels (Table 5). In domestic wastewater, optimal growth was achieved at 30 g biomass, with a relative growth rate (RGR) of 0.043 and the highest fresh and dry weight gains. Excessive biomass (40 g and 50 g) led to competition for light and nutrients, reducing RGR values. This pattern agrees with Coughlan et al. (2022) and Walsh et al. (2021a), who noted that overcrowding in aquatic plants decreases photosynthetic efficiency and growth potential. 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 were observed at 40 g biomass, suggesting a balance between nutrient availability and plant density. Prior research indicates that sewage 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.

### Implications and Limitations

These findings reinforce the potential of *Lemna perpusilla* as a low-cost, sustainable phytoremediation agent for diverse wastewater sources with contamination of As, Cr, Cd, and Pb. Future applications could integrate *Lemna*-based systems in modular floating wetlands or combined phytoreactor systems for continuous treatment (Ahmed & Kareem, 2025). However, this study was limited to short-term batch experiments and focused on biomass level variation. Further studies should include longer operational periods, monitoring of physiological stress indicators, and post-harvest heavy metal recovery to evaluate the long-term sustainability of the system.

### Conclusion

The study found that *Lemna perpusilla* effectively removed arsenic, cadmium, chromium, and lead from different wastewater types, with efficiency depending on plant biomass and water source. In domestic wastewater, arsenic and cadmium removal increased with higher biomass, reaching 67.50% and 73.33%, while chromium and lead changed little. In sand mining wastewater, cadmium and lead removal were highest at 52.85% and 64.67%. In batik textile wastewater, all four metals showed high removal efficiencies—80.44% for arsenic, 69.70% for cadmium, 71.17% for chromium, and 70.21% for lead—at higher biomass levels. Growth performance also varied: optimal growth occurred at 30 g biomass in domestic wastewater, 50 g in sand mining wastewater, and 40 g in batik wastewater. Overall, greater biomass improved both metal removal and plant growth, showing that *Lemna perpusilla* is promising for phytoremediation of various wastewater sources.

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