water

MDPI

Article

Removal of Ag, Au, and As from Acid Mine Water Using *Lemna gibba* and *Lemna minor*—A Performance Analysis

Merve Sasmaz Kislioglu

School of Biological Earth and Environmental Sciences, University College Cork, North Mall, T23 TK30 Cork, Ireland; msasmazkislioglu@ucc.ie or msasmaz07051991@gmail.com

Abstract: Mining activities result in the accumulation of pollutants in aquatic environments. This study aimed to investigate the accumulation performances of Ag, Au, and As using *Lemna minor* and *Lemna gibba* in the acid mine waters of Maden copper deposit. *L. minor* and *L. gibba* are aquatic plants belonging to the duckweed family. They are small, fragile, and free-floating aquatic plants. *L. minor* and *L. gibba* were separately placed into two reactors. The plants and water from the reactors were collected daily for eight days. Additionally, the electric conductivity, temperature, and pH of the acid mine water were measured daily. *L. minor* and *L. gibba* samples were washed, dried, and burned at 300 °C in a drying oven for 24 h. The water and plant samples were analyzed for Ag, Au, and As content using ICP-MS (Inductively Coupled Plasma Mass Spectroscopy). The acid mine waters of Maden copper deposit contained 9.25 ± 0.4, 0.92 ± 0.02, and 193 ± 12 μg L^{-1}, Ag, Au, and As, respectively. In comparison to control samples, *L. gibba* and *L. minor* showed high and effective performances in removing Ag, Au and As from the acid mine waters of Maden copper deposit; 240 and 174 times for Ag; 336 and 394 times for Au; and 30 and 907 times for As, respectively. Overall, the results suggest that *L. gibba* and *L. minor* can effectively remove Ag, Au, and As from acid mine waters, highlighting their potential use in environmental remediation.

Keywords: accumulation; heavy metals; *Lemna minor*; *Lemna gibba*; acid mine waters; water treatment

check for updates

Citation: Sasmaz Kislioglu, M. Removal of Ag, Au, and As from Acid Mine Water Using *Lemna gibba* and *Lemna minor*—A Performance Analysis. *Water* **2023**, *15*, 1293. https://doi.org/10.3390/w15071293

Academic Editors: John Zhou and Laura Bulgariu

Received: 9 March 2023
Revised: 19 March 2023
Accepted: 23 March 2023
Published: 25 March 2023

Copyright: © 2023 by the author. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

Acid mine drainage (AMD) is commonly found around both active and abandoned mining areas, whether they are underground or open pit. Secondary sources of AMD include sludge ponds, pit lakes, quarries, haul roads, iron ore stockpiles, tailing dams, tailing dumps and mine waste dumps [1,2]. Due to its high concentration of heavy metals and pH levels, AMD can be difficult to treat and poses significant risks to human health and the environment. Discharging AMD without proper treatment can cause long-term environmental pollution and problems [3–5]. Acid mineral water is produced as a result of production and subsequent activities, particularly in sulfide mines. The concentration of heavy metal ions in this water can decrease from several hundred or even thousands of milligrams to just a few milligrams per liter. Heavy metals can lead to various diseases in humans and animals by polluting the air, soil, and water as well as through drinking water and contaminated food. Consequently, removing and reducing heavy metals from the air, soil, and water is a significant task and a scientific reality. Acid mine waters have been one of the most challenging problems of modern mining activities [6].

Heavy metals have a density five times greater than that of water and have high atomic weights [7], and Gergen and Harmanescu classified them into two groups [8]. According to Rai et al. [9] metals such as Ag, Au, As, Ni, Pb, Hg, Cd, and Cr have no beneficial role in plants and animals and cause widespread water, air, and soil contamination. While some metals such as Zn, Mn, Cu, Fe, and Co are essential for animals and plants, excessive concentrations of these metals can be toxic. As a result, heavy metal contamination remains one of the main problems affecting animals and plants in aquatic environments [10]. Certain

metals including Cd, Cr, Pb, Hg, Tl, and As are a particularly concerning for public health due to their high toxicity [7].

Phytoremediation is one of the most cost-effective and ecologically friendly methods for in situ removal or rehabilitation of heavy metals from soil and water, utilizing living green plants [11–17]. During the rhizofiltration stage, aquatic macrophytes accumulate contaminants and metals [18]. *Lemna* sp. is often preferred in phytoremediation studies by many scientists due to its easier harvest and faster growth [19–21]. It can grow quickly, floats on the water, and is the most effective plant among the aquatic macrophytes in terms of removing pesticides and metals [22–24]. Additionally, it is easy to transport, has fast reproduction rates, low cost, minimal biological and chemical sludge volume, and can grow under different climatic conditions, with a long storage capacity [21,24–26]. According to Khataee et al., the optimum temperature and pH ranges for the rapid growth of *Lemna* sp. [25] are 5–25 °C and 4–9, respectively.

High metal pollution from acid mine waters is one of the leading causes of water and soil degradation. Plants and organisms in the receiving environments where these waters are discharged can bioaccumulate heavy metals, making it necessary to improve the quality of the water before returning it to the natural environment. This study investigated the accumulation performances of Ag, Au, and As by using *L. gibba* and *L. minor* growing in the acid mine waters of the Maden copper deposit in low pH conditions. Changes in Ag, Au and As in both *L. gibba* and *L. minor* were measured daily to calculate the phytoremediation potential of both plants in the acid mine water. The study also measured the numbers of liters of acid mineral water removed from metals by these plants.

2. Material and Methods

The study was conducted in the natural environment of the Maden copper deposit. The climatic conditions during this experiment were: average global radiation of 480 ± 32 Wm^{-2}; an average of 13.8 ± 0.6 hours of sunny days; an average daily relative humidity of 28.6 ± 3.2%; and average daily temperature of 23.6 ± 7.2 °C (these data were collected by the Turkish State Meteorological Service).

2.1. The Study Area

The study was conducted in the Maden copper deposit in Elazig, Turkey (located at E39.671450° and N38.388434°) (Figure 1). The area has a long history of mining, with primitive activities dating back to 2000 BC. Modern copper production began in 1939 by Etibank, and between 1939 and 1968, 6.1 million tons of massive sulfide ore with an average of 6.5% Cu grade were extracted from Anayatak and its surrounding deposits. The Maden copper deposit is one of the largest copper-producing areas in Turkey and consists of several geographic sectors, such as Anayatak, Kısabekir, Mızırtepe, Weis, and Hacan. These deposits are believed to be related to black smoker obtained from hydrothermal rifts on the mid-ocean ridges, where basaltic volcanism is common on the seafloor [27,28]. These deposits also contain large reserves of Cu, Ag, Au, Ni and Co. Mining activities result in a common water effluent observed from the mine site throughout the year, which is discharged into the Maden River.

2.2. Water and Plant Samples

The chemical composition of the acid mine waters in the Maden copper deposit may vary due to the ore contents and wall rocks. These factors can impact the water's electric conductivity (EC), temperature (T °C), and pH levels. To measure pH, an Orion 4-Star pH meter with gel-filled pH electrodes was used. Anion and cation analyses (including fluoride, sulfate, nitrate, and carbonate) were conducted using an ICP-MS (A Perkin-Elmer Elan 9000). Additionally, an Orion conductivity electrode was used to record the pH, electrical conductivity, and temperature.

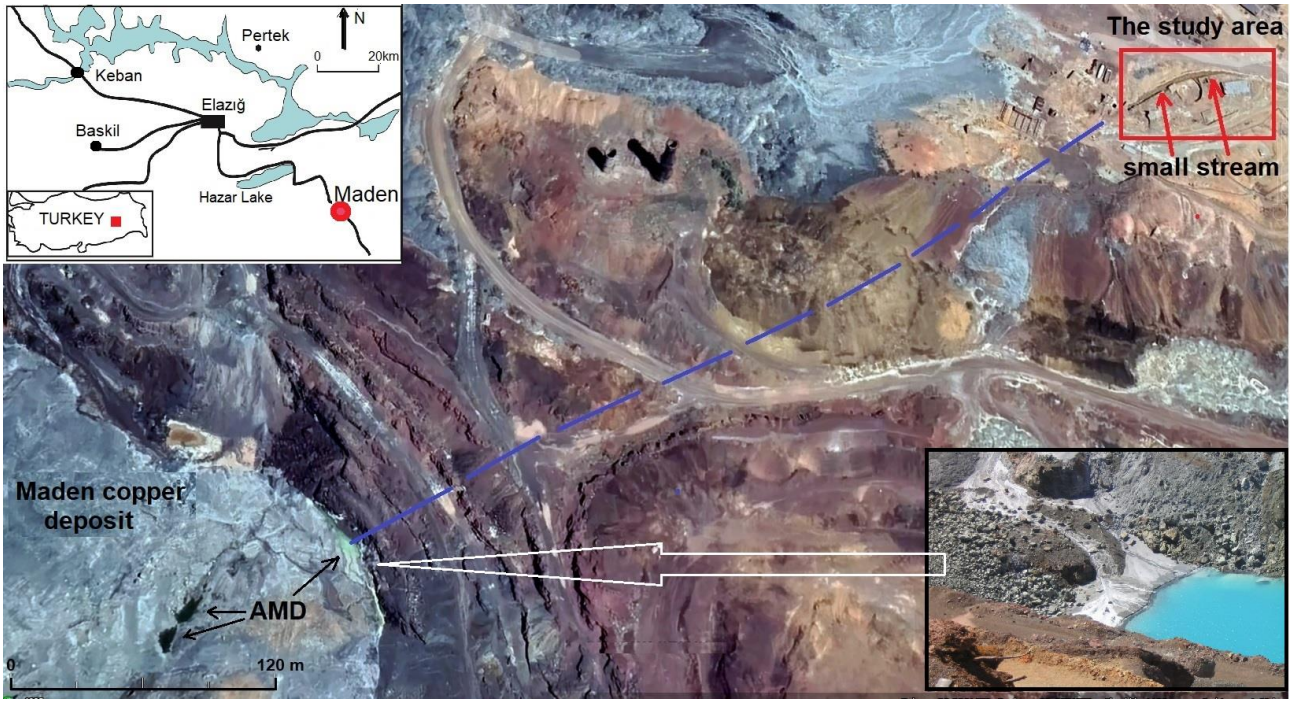
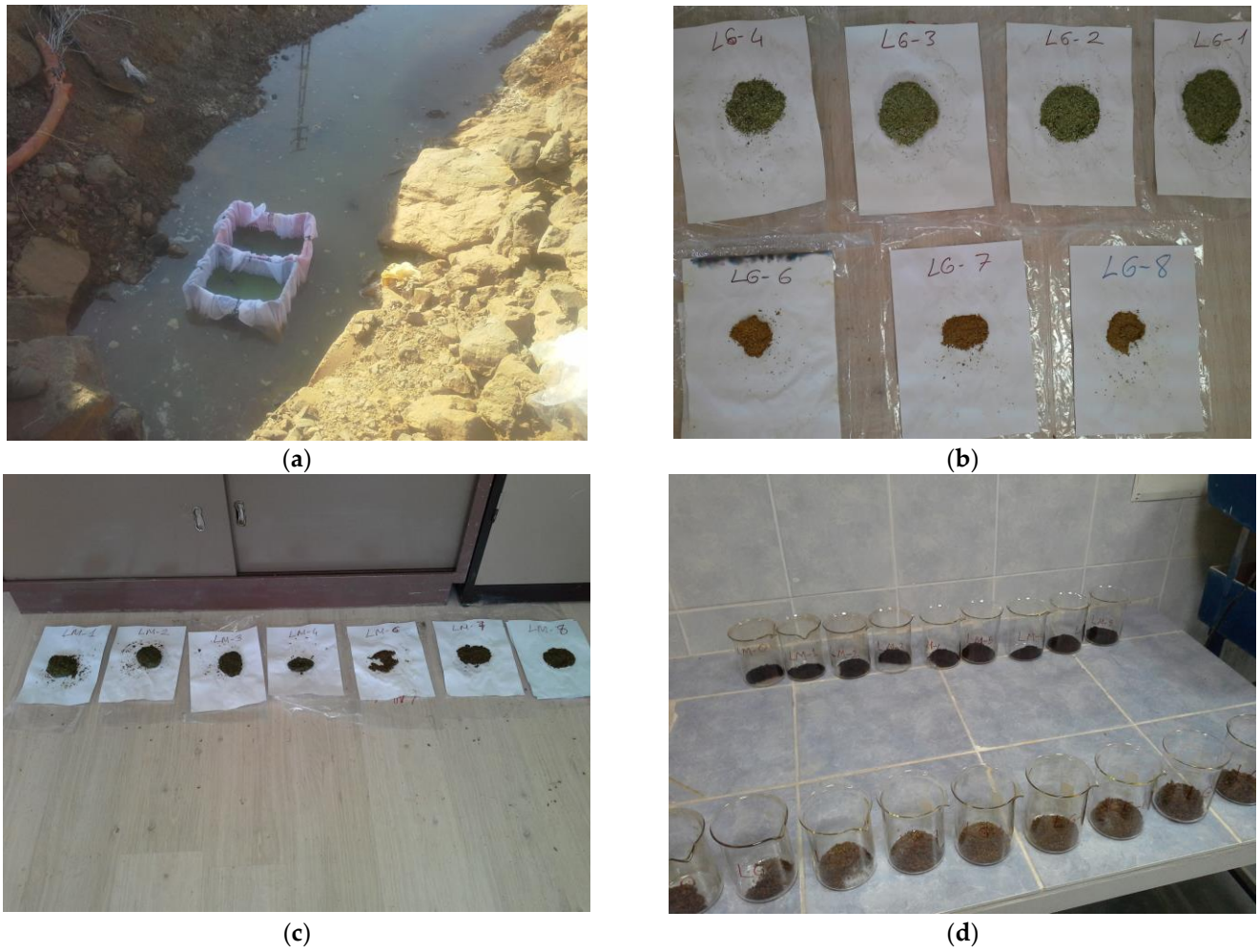


Figure 1. Location map of the study area.

The plants in this study are identified systematically as *L. minor* and *L. gibba* according to *the East Aegean Islands and Flora of Turkey* [29]. *L. minor* and *L. gibba* are both members of the *Lemna* genus, commonly known as the duckweed family [30], represented by species of five genera (Lemna, Wolffia, Wolffiella, Landoltia and Spirodela). These floating aquatic plants reproduce asexually, with new plants growing from the parent plant without a seed stage [31]. *L. gibba* and *L. minor* were each placed in separate reactors, and both plants and water were collected daily for eight consecutive days. Sterile plastic bottles were used to collect the samples, and the pH, electric conductivity, and temperature of the acid mine water were measured each day. Once the plants were collected, they were washed, dried, and then burned at 300 °C in a drying oven for 24 h (Figure 1).

2.3. Analytical Method

L. minor and *L. gibba* plants were obtained from the Istanbul University Botanical Garden and grown separately in two natural pools before being transferred to individual reactors. As described by Tatar and Obek [16], each reactor, measuring 70 × 35 × 30 cm, contained 500 g of plants, with *L. minor* in one reactor and *L. gibba* in the other. The reactors supplied with constantly flowing acid mineral water at a rate of 1.28 L sec^{-1} (Figure 2), provided a fresh supply of water to the plants throughout the experiment. Approximately 50 g of plant material was collected daily from each reactor for a period of eight days. The collected samples were washed with tap water, rinsed with distilled water, and dried in a laboratory oven at 60 °C for 24 h. The dried plant materials were then burned at 300 °C for 24 h to create ash samples, which were subsequently digested in HNO_3 for one hour, followed by digestion in a mixture of HNO_3: H_2O: HCl (1:1:1) at 95 °C for one hour by taking 1 gram of the ash sample. Finally, all samples were analyzed for Ag, Au, and As using ICP-MS techniques.



(**a**) (**b**)

(**c**) (**d**)

Figure 2. (**a**) *L. minor* and *L. gibba* adapted in each reactors, (**b**,**c**) *L. gibba* and *L. minor* samples collected at the end of the experiment, (**d**) ash samples of *L. minor* and *L. gibba* burned in the oven at 300 °C.

3. Results and Discussion

3.1. Ag, Au, and As in Acid Mine Water

The physicochemical characteristics of the acid mine water, along with the major anion and cation results, are shown in Table 1. The pH of the acid mine waters ranged from 5.62 to 5.84 (mean: 5.76 ± 0.14); the temperature ranged from 18.6–24.8 °C (mean: 22.6 ± 1.2 °C); and the EC values ranged from 2.38 to 2.64 mS cm^{-1} (mean: 2.55 ± 0.08 mS cm^{-1}) (Table 1). Water samples were taken daily in the field during the eight-day experiment. As shown in Table 1, the average Ag, Au, and As contents were determined to be 9.25 ± 0.4, 0.92 ± 0.02, and 193 ± 12 μg L^{-1}, respectively, in the acid mine water ($p < 0.5$). The distance of the acid mineral water from the recharge area, long-term rock–water interaction, flow volume of acid mine water, and the residence time of the acid mineral water in the flow system significantly affect the chemistry of the acid mineral water. The measured results indicate that the waters coming from the ore area generally have similar chemistry and physicochemical parameters. Intense metal pollution in water and soil causes significant pollution along the Maden stream.

Table 1. Physicochemical characteristics of the acid mine water and their trace element, major anion and cation results.

Parameter	T (°C)	pH	EC (mS cm^{-1})	HCO_3^- (mgL^{-1})	NO_3^- (mgL^{-1})	SO_4 (mgL^{-1})	F^- (mgL^{-1})	Ca (mgL^{-1})	Mg (mgL^{-1})	K (mgL^{-1})	Na (mgL^{-1})	Fe (mgL^{-1})
DL	-	-	-	-	-	-	-	0.05	0.05	0.05	0.05	10
Mining water	22.6 ± 1.6	5.76 ± 0.1	2.55 ± 0.2	282 ± 16	1.86 ± 0.06	128 ± 8	0.41 ± 0.1	482 ± 24	426 ± 18	5.80 ± 0.3	115± 6	118 ± 7
Parameter	**Mn (mg L^{-1})**	**S (mg L^{-1})**	**P (µg L^{-1})**	**B (µg L^{-1})**	**Zn (µg L^{-1})**	**Cr (µgL^{-1})**	**Ni (µg L^{-1})**	**Co (µg L^{-1})**	**Cu (µg L^{-1})**	**Ag (µg L^{-1})**	**Au (µg L^{-1})**	**As (µg L^{-1})**
DL	0.05	1	10	5	0.5	0.5	0.2	0.02	0.02	0.05	0.05	0.5
Mining water	6.4 ± 0.3	670 ± 28	236 ± 12	850 ± 45	2852 ± 84	202 ± 16	965 ± 58	1766 ± 72	15,535 ± 322	9.25 ± 0.4	0.92 ± 0.02	193 ± 12

As shown in Table 1, mean Ag, Au, and As contents in the acid mine waters were higher than the limit values of ATSDR [32] and US EPA [33]. Ag concentrations in the acid mine water of the study area varied from 8.86 to 9.45 µg L^{-1}). Silver contents in surface water and groundwater are usually below 2 µg L^{-1} [32]. The average As value in the study area exceeded the limit values (10 mg L^{-1}) established by the WHO [34] for drinking water (Table 1). Average Ag contents in these natural waters according to US EPA [33] have been reported as 0.2–0.3 µg/L. The only adverse health effect associated with chronic silver exposure in humans is argyria. Silver is deposited in various organs (liver, kidney, skin) after oral ingestion in its ionic form. Excessive silver in the body causes skin darkening, as seen in people with argyria [35]. Au is also toxic to plants, leading to wilting and necrosis by loss of swelling in leaves [36]. The water leaking from the mine pollutes both the soil and water in the environment. The treatments of these polluted water and soils are very difficult [37,38]. Ning et al. [39] showed that the heavy metal contents of water around the gold deposits were higher than WHO's [34] average values. Antimony and arsenic are the main contaminants in surface and groundwater in Slovakia's mining areas. The highest dissolved concentrations of arsenic were found to be 2.4 mg L^{-1} in Poproč and 1.35 mg L^{-1} in Čučma, Slovakia [40]. Due to the intense arsenic pollution observed in the deposits in and around the Zarshuran gold mine, it has caused quite a lot of pollution, especially in the surrounding water and soil [41]. Arsenic concentrations hundreds of times the allowable limit were found in most of the samples.

The acid mine waters in the study area were classified into hydro chemical groups based on the major anions and cations (Ca–Mg–HCO_3; Ca–Mg–Fe–SO_4; Na–F–NO_3). Using Piper's [42] triangular drawing technique, the water types in the aquifer were revealed. The predominant cations in the studied waters are Ca, Fe, Mg, S, Na, Mn and K, constituting more than 90% of the cations in the aquifer. Bicarbonate and sulfate were the predominant anion species in the study area's waters, accounting for 85–90 % of the total anions. The acid mine water in Maden copper deposit could be classified as Ca-Mg-Fe-Na-SO_4 HCO_3 water.

3.2. Lemna minor and Lemna gibba

Phytoremediation is a cheap, efficient, green and cost-effective method for cleaning and rehabilitating polluted environments. However, information about how heavy metals affect plant physiology should be obtained in order to optimize the system before designing a decontamination system [43]. Factors such as bioavailability of the metal, chemical features of the contaminant, plant species, environmental conditions, pH, phosphorus, and organic matter contents of the polluted environment can affect the uptake mechanism of Ag, Au, and As [44]. Several aquatic plants are noted as the pollution indicators for heavy metals and are successfully used for monitoring of contaminated environments [45]. Heavy metals such as Ag, Au, As, Hg, Pb, Cd, Zn, Cu, Co, and Tl are dangerous and toxic due to their capacity to accumulate in biological system [46].

Before the start of the experimental study, the Ag contents of *L. minor* (LM-0) and *L. gibba* (LG-0) were detected to be 47 and 23 µg kg^{-1}, respectively ($p < 0.05$) (Figure 3). These concentrations are considered control group values for these plants. On the first day of the experimental study *L. minor* and *L. gibba* accumulated 64 and 246 µg kg^{-1} of Ag, respectively. The amount of Ag absorbed from acid mineral water by both plants increased slightly or remained constant in the first 4 days of the experiment. However,

L. gibba accumulated 88 and 174 times more Ag than the control on the fifth and eighth days, and *L. minor* accumulated 13 and 240 times more Ag during the same period. Although *L. minor* had a higher Ag accumulation ability than *L. gibba*, both plants showed remarkable Ag accumulation abilities from day 5 to day 8.

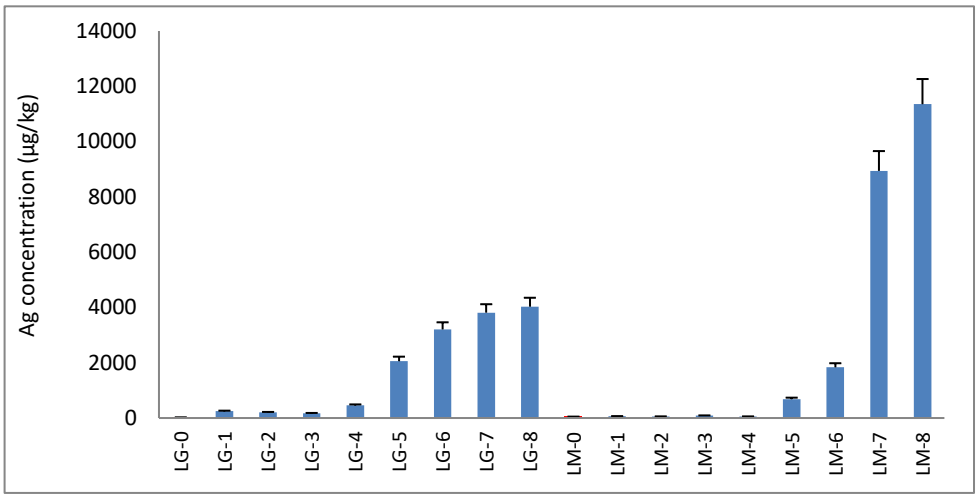


Figure 3. Ag accumulation ratios by *L. gibba* and *L. minor*.

Despite the low concentrations of silver (9.25 µg L^{-1}) in the acid mineral water used in the study, *L. gibba* and *L. minor* were able to remove Ag from 433 L and 1222 L of acid mine water, respectively, by the end of the 8-day experiment.

During the first four days of the experiment, similar increases in Au accumulation were observed in both *L. gibba* and *L. minor*. From the fifth to the eighth day, both plants exhibited a linear and very high accumulation performance. According to the control samples, *L. gibba* accumulated 78 times (176 µg kg^{-1}) and 394 times more Au (884 µg kg^{-1}) from acid mine water on day 5 and day 8. Similarly, *L. minor* accumulated gold from acid mine water 31 times (16.2 µg kg^{-1}) and 336 times on the fifth and eighth days, respectively, (882 µg kg^{-1}) compared to the control sample (Figure 4).

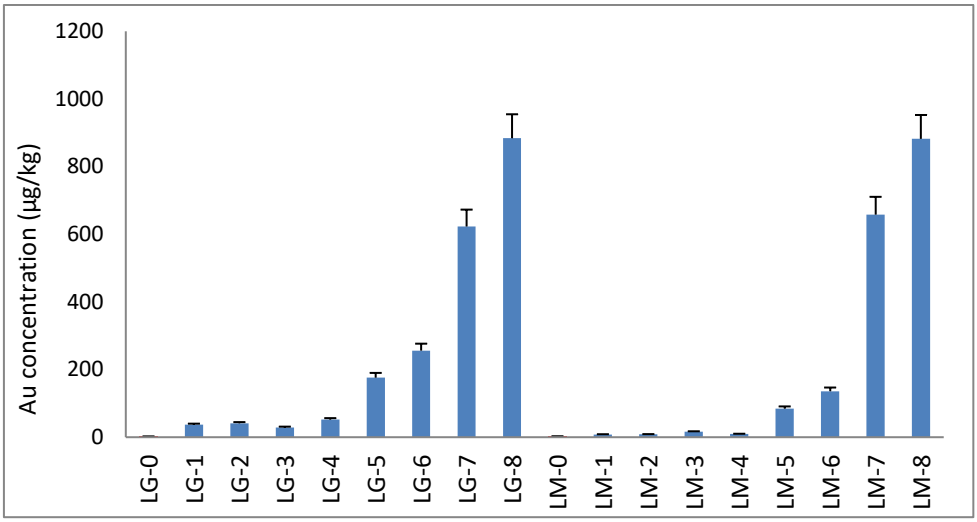


Figure 4. Au accumulation ratios by *L. gibba* and *L. minor*.

Despite the low concentration of gold in the acid mineral water used in the study (0.92 µg L^{-1}), *L. gibba* and *L. minor* removed Au from 958 L and 956 L of water, respectively, by the end of the 8-day experiment.

During the first four days of the experiment, both *L. gibba* and *L. minor* exhibited similar low increases in accumulations. However, from the fifth to the eighth day, both plants demonstrated a linear and significant increase in accumulation performance. According to the control samples, *L. gibba* accumulated 34.5 mg kg^{-1} (15 times) and 1255 mg kg^{-1} (30 times) of As from acid mine water on the fifth and eighth days, respectively. Likewise, *L. minor* accumulated 17.8 mg kg^{-1} (12 times) and 1255 mg kg^{-1} (922 times) of As from acid mine water on the fifth and eighth days, respectively, compared to the control sample (Figure 5).

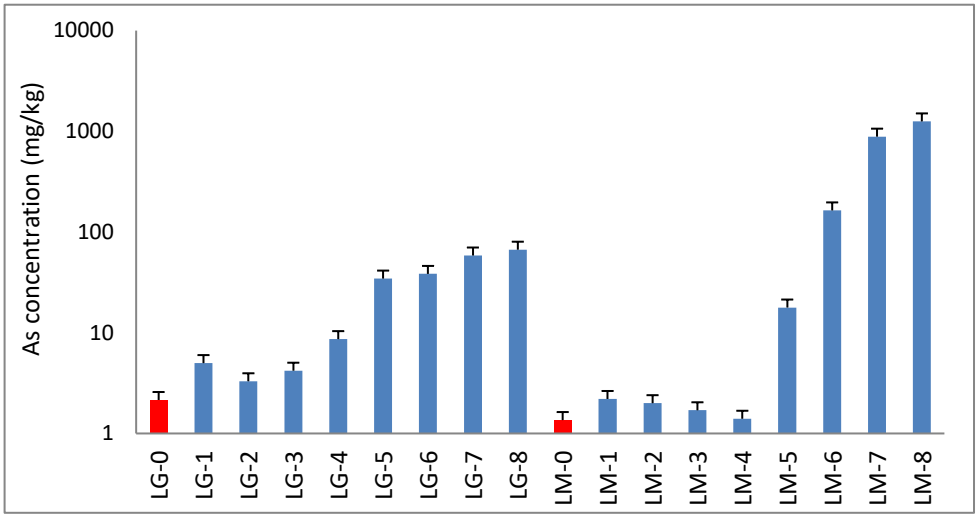


Figure 5. As accumulation ratios by *L. gibba* and *L. minor*.

Despite the high concentrations of arsenic (193 µg L^{-1}) in the acid mine water of the study area, *L. gibba* and *L. minor* removed As from 355 L and 6496 L of water, respectively, by the end of the 8-day experiment.

Sasmaz and Obek [20] demonstrated the capability of *L. gibba* to remove As, U, and B from secondary-treated municipal wastewater over a period of eight days. Notably, *L. gibba* exhibited the highest removal efficiencies for As, U, and B, with removal rates of 133%, 122%, and 40%, respectively, during the initial two days of the experiment. These findings suggest that *L. gibba* has potential as a natural approach to mitigating the presence of these contaminants in wastewater. Goswami and Majumder [12] discovered that *L. minor* exhibits greater capability for accumulating lower concentrations of Cr and Ni. Additionally, Sasmaz and Obek [47] investigated the uptakes of Ag and Au by *L. gibba* from secondary-treated municipal wastewater. The study revealed that both Au and Ag were rapidly accumulated within six days of the experiment. However, following day six, the accumulation levels of Au and Ag became variable, likely due to the saturation of the plant. The maximum accumulations were recorded as 2303% for Ag and 247% for Au on the fifth and sixth days of the experiment, respectively. Uysal [48] studied the Cr sorption potential of *Lemna* at different pH and concentrations and observed that although the plants were exposed to toxic effects, they continued to take up Cr from the water. Abdallah [49] observed that *L. gibba* performed extremely well, accumulating more than 84% of the chromium in the solution during the 12-day experiment. Ucuncu et al. [50] stated that *L. minor* is able to quickly and effectively accumulate Pb and Cr, making it a promising candidate for rehabilitating ecosystems polluted with these metals. Sasmaz et al. [15] investigated the potential of both *L. minor* and *L. gibba* for phytoremediation of As, Zn, Pb and Cu in acid mine water. The study tracked the daily changes in metal abundances in both plants and identified the optimal harvesting time. According to obtained results, *L. gibba* and *L. minor* accumulated 4316 times and 3941 times more As, 2888 times and 3708 times more Pb, 1146 times and 1156 times more Zn and 108 times and 147 times more Cu than in the gallery water, respectively. Goswami et al. [12] reported that *L. minor* was effective in

remediating low-concentration As-contaminated waters. Sasmaz et al. [51] determined the performance of *L. gibba* and *L. minor* in removing Y, La, and Ce from polluted gallery water. The results showed that *L gibba* removed more of these metals than *L. minor* when compared with the control samples. De Souza et al. [52] showed that *L. valdiviana* As significantly optimized the phytoremediation process. Furthermore, if a suitable mixture of pH, nitrate and phosphate concentration in the solution was handled, 1190 mg kg^{-1} As was accumulated as dry weight. Leblebici et al. [53] studied the biological responses and phytoremediation capability of two aquatic macropyhtes: *Salvinia natans* and *L. minor*. They found that *S. natans* was a more effective Pb and Ni accumulator than *L. minor*, while *L. minor* was a more effective Cd accumulator than *S. natans*. Amare et al. [54] revealed that *L. minor* was a high phytoaccumulator for Fe, Mn, Zn, and Co but only moderate for Cd, Cu, Ni, and Cr. Tatar et al. [55] showed that *L. gibba* has a high accumulation performance for S, Na, Ca, Mg, Cu, Mo, and Se, while *L. minor* has a high accumulation capacity for P, Sb, Ba, Co, Fe, Pb, Mn, Hg, Ag, and Zn.

4. Conclusions

L. gibba accumulated 88 and 174 times, while Ag and *L. minor* accumulated 13 and 240 times the amount of Ag on the fifth and eighth days, according to the values of the control samples (LG-0 and LM-0) from acid mineral water. The results indicate that *L. minor* has a greater Ag accumulation ability than *L. gibba*. Both plants demonstrated remarkable Ag accumulation abilities between day 5 and day 8, and they removed Ag from 433 L and 1222 L acid mine water, respectively, at the end of the 8-day experiment. *L. gibba* accumulated 78 times (176 μg kg^{-1}) and 394 times Au (884 μg kg^{-1}) from acid mine water on day 5 and day 8, while *L. minor* accumulated 31 times (16.2 μg kg^{-1}) and 336 times Au (882 μg kg^{-1}) on the fifth and eighth days, respectively, compared to the control sample. *L. gibba* and *L. minor* also removed Au, respectively, from 958 L and 956 L acid mine water at the end of the 8-day experiment. *L. gibba* accumulated 15 times (34.5 mg kg^{-1}) and 30 times As (66.8 mg kg^{-1}) from acid mine water on day 5 and day 8, while *L. minor* accumulated, 12 times (17.8 mg kg^{-1}) and 922 times As (1255 mg kg^{-1}) on the fifth and eighth days compared to the control sample. *L. gibba* and *L. minor* removed As, respectively, from 355 L and 6496 L acid mine water at the end of the 8-day experiment. Overall, *L. gibba* and *L. minor* are ecologically safe, cost effective, and efficient in treating the acid mine water contaminated with Ag, Au, and As. However, it is important to note *L. gibba* and *L. minor* grown in acid mine water contain high levels of heavy metals when harvested, and the harvested biomass must be carefully protected to prevent harm to the environment. These metals can be recovered by washing the biomass with strong acids immediately after harvest, thereby contributing to the country's economy. This method should be adopted in all mining enterprises using acid mineral water and suitable pools should be created to ensure widespread metal recovery processes and a supply of cleaner water to nature.

Funding: This research received no external funding.

Data Availability Statement: Data for this study can be found within the article.

Conflicts of Interest: The author declares no conflict of interest.

References

1. Wiessner, A.; Müller, J.A.; Kuschk, P. Environmental pollution by wastewater from brown coal processing—A remediation case study in Germany. *J. Environ. Eng. Landsc. Manag.* **2010**, *22*, 71–83. [CrossRef]
2. Cesar Minga, J.; Elorza, F.J.; Rodriguez, R.; Iglesias, A.; Esenarro, D. Assessment of Water Resources Pollution Associated with Mining Activities in the Parac Subbasin of the Rimac River. *Water* **2023**, *15*, 965. [CrossRef]
3. Tong, L.; Fan, R.; Yang, S.; Li, C. Development and status of the treatment technology for acid mine drainage. *Min. Metall. Explor.* **2021**, *38*, 315–327. [CrossRef]
4. Lü, J.; An, Y. Hydrochemical Characteristics and Risk Assessment of Tongzi River, Guizhou Province, Southwest China. *Water* **2023**, *15*, 802. [CrossRef]

5. Pan, Y.; Chen, M.; Wang, X.; Chen, Y.; Dong, K. Ecological Risk Assessment and Source Analysis of Heavy Metals in the Soils of a Lead-Zinc Mining Watershed Area. *Water* **2023**, *15*, 113. [CrossRef]
6. He, X.W.; Li, F.Q. New technology and development tendency of mine water treatment. *Coal Sci. Technol.* **2010**, *11*, 17–22.
7. Tchounwou, P.B.; Yedjou, C.G.; Patlolla, A.K.; Sutton, D.J. Heavy metals toxicity and the environment. In *Molecular, Clinical and Environmental Toxicology*; Springer: Basel, Switzerland, 2012; Volume 101, pp. 133–164.
8. Gergen, I.; Harmanescu, M. Application of principal component analysis in the pollution assessment with heavy metals of vegetable food chain in the oldmining areas. *Chem. Cent. J.* **2012**, *6*, 56. [CrossRef] [PubMed]
9. Rai, S.; Gupta, S.; Mittal, P.C. Dietary Intakes and Health Risk of Toxic and Essential Heavy Metals through the Food Chain in Agricultural, Industrial, and Coal Mining Areas of Northern India. *Hum. Ecol. Risk Assess. Int. J.* **2015**, *21*, 913–933. [CrossRef]
10. Duffus, J.H. "Heavy Metals" A meaningless term? IUPAC (International Union of Pure Applied Chemistry). *Pure Appl. Chem.* **2002**, *74*, 793–807. [CrossRef]
11. Goswami, C.; Majumder, A.; Misra, A.K.; Bandyopadhyay, K. Arsenic uptake by *Lemna minor* in hydroponic system. *Int. J. Phytoremediation* **2014**, *16*, 1221–1227. [CrossRef]
12. Goswami, C.; Majumder, A. Potential of *Lemna minor* in Ni and Cr removal from aqueous solution. *Pollution* **2015**, *1*, 373–385.
13. Abdel-Gawad, F.K.; Khalil, W.K.B.; Bassem, S.M.; Kumar, V.; Parisi, C.; Inglese, S.; Temraz, T.A.; Nassar, H.F.; Guerriero, G. The Duckweed, *Lemna minor* Modulates Heavy Metal-Induced Oxidative Stress in the Nile Tilapia, *Oreochromis niloticus*. *Water* **2020**, *12*, 2983. [CrossRef]
14. Haffner, O.; Kučera, E.; Drahoš, P.; Cigánek, J.; Kozáková, A.; Urminská, B. *Lemna minor* Bioassay Evaluation Using Computer Image Analysis. *Water* **2020**, *12*, 2207. [CrossRef]
15. Sasmaz, M.; Topal, E.I.A.; Obek, E.; Sasmaz, A. 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. *J. Environ. Manag.* **2015**, *163*, 246–253. [CrossRef]
16. Tatar, S.Y.; Obek, E. Potential of *Lemna gibba* L. and *Lemna minor* L. for accumulation of Boron from secondary effluents. *Ecol. Eng.* **2014**, *70*, 332–336. [CrossRef]
17. Sood, A.; Uniyal, P.L.; Prasanna, R.; Ahluwalia, A.S. Phytoremediation potential of aquatic macrophyte, *Azolla*. *Ambio* **2012**, *41*, 122–137. [CrossRef]
18. Chaudhuri, D.; Majumder, A.; Misra, A.M.; Bandyopadhyay, K. Cadmium removal by *Lemna minör* and *Spirodela polyrhiza*. *Int. J. Phytorem.* **2014**, *16*, 1119–1132. [CrossRef] [PubMed]
19. Obek, E. Bioaccumulation of heavy metals from the secondary treated municipal waste water by *Lemna gibba*. *Fres. Environ. Bull.* **2009**, *18*, 2159–2164.
20. Sasmaz, A.; Obek, E. The accumulation of arsenic, uranium, and boron in *Lemna gibba* L. exposed to secondary effluents. *Ecol. Eng.* **2009**, *35*, 1564–1567. [CrossRef]
21. Gerardo, R.; de Lima, I.P. Monitoring Duckweeds (*Lemna minor*) in Small Rivers Using Sentinel-2 Satellite Imagery: Application of Vegetation and Water Indices to the Lis River (Portugal). *Water* **2022**, *14*, 2284. [CrossRef]
22. Li, S.X.; Feng-Ying, F.; Yang, H.; Jian-Cong, N. Thorough removal of inorganic and organic mercury from aqueous solutions by adsorption on *Lemna minor* powder. *J. Hazard. Mater.* **2011**, *186*, 423–429. [CrossRef]
23. Dirilgen, N. Mercury and lead: Assessing the toxic effects on growth and metal accumulation by *Lemna minor*. *Ecotoxicol. Environ. Saf.* **2011**, *74*, 48–54. [CrossRef]
24. Lobotková, M.; Hybská, H.; Samešová, D.; Turˇcániová, E.; Barnová, J.; Rétfalvi, T.; Krakovský, A.; Bad'o, F. Study of the Applicability of the Root Wastewater Treatment Plants with the Possibility of the Water Recirculation in Terms of the Surfactant Content. *Water* **2022**, *14*, 2817. [CrossRef]
25. Khataee, A.; Movafeghi, A.; Torbati, S.; Salehi Lisar, S.; Zarei, M. Phytoremediation potential of duckweed (*Lemna minor* L.) in degradation of CI Acid Blue 92: Artificial neural network modeling. *Ecotoxicol. Environ. Saf.* **2012**, *80*, 291–298. [CrossRef]
26. Materazzi, S.; Canepari, S.; Aquili, S. Monitoring heavy metal pollution by aquatic plants. *Environ. Sci. Poll. Res.* **2012**, *19*, 3292–3298. [CrossRef]
27. Erler, A. The Hydrothermal Alteration around Madenköy-Siirt Massive Sulphide Deposit. Ph.D. Thesis, Middle East Technical University (METU), Ankara, Turkey, 1982; p. 131, Unpublished.
28. Sasmaz, A.; Gumus, G.; Sagiroglu, A. A typical example of allochtonous Cyprus type copper mineralizations: Derdere mineralizations. *Geol. Bull. Turkey* **1999**, *42*, 105–117.
29. Davis, P.H. *Flora of Turkey and The East Aegean Island*; Edinburgh University Press: Edinburgh, UK, 1984.
30. Cabrera, L.I.; Salazar, G.A.; Chase, M.W.; Mayo, S.J.; Bogner, J.; Davila, P. Phylogenetic relationships of aroids and duckweeds (Araceae) inferred from coding and noncoding plastid DNA. *Am. J. Bot.* **2008**, *95*, 1153–1165. [CrossRef]
31. Turck, D.; Bohn, T.; Castenmiller, J.; De Henauw, S.; Hirsch-Ernst, K.I.; Maciuk, A.; Mangelsdorf, I.; McArdle, H.J.; Knutsen, H.K.; EEFSA Panel on Nutrition, Novel Foods and Food Allergens (NDA); et al. Scientific Opinion on the safety of Lemna minorandLemna gibbawhole plant material as a novel food pursuant to Regulation (EU) 2015/2283. *EFSA J.* **2022**, *20*, 07598.
32. Agency for Toxic Substances and Disease Registry (ATSDR). *Toxicological Profile for Silver*; ATSDR: Atlanta, Georgia, 1990.
33. United States Environmental Protection Agency (US EPA). *Ambient Water Quality Criteria for Silver*; US EPA: Washington, DC, USA, 1980.
34. World Health Organization (WHO). *Guidelines for Drinking-Water Quality*; World Health Organization: Geneva, Switzerland, 2006; p. 553.

35. World Health Organization (WHO). *Silver in Drinking-Water*; World Health Organization: Geneva, Switzerland, 2021; p. 25.
36. Kabata-Pendias, A. *Trace Elements in Soils and Plants*; CRC Press: Washington, DC, USA, 2011; p. 412.
37. Dong, D.; Li, H.; Zhang, J.; Sun, L. Removal of heavy metals from mine water by cyanobacterial calcification. *Min. Sci. Technol.* **2010**, *20*, 566–570. [CrossRef]
38. Caussy, D.; Gochfeld, M.; Gurzau, E. Lessons from case studies of metals: Investigating exposure bioavailability and risk. *Ecotoxicol. Environ. Saf.* **2003**, *56*, 45–51. [CrossRef] [PubMed]
39. Ning, N.; Liyuan, Y.; Jirui, D.; Xugui, P. Heavy Metal Pollution in Surface Water of Linglong Gold Mining Area, China. *Proc. Environ. Sci.* **2011**, *10*, 914–917. [CrossRef]
40. Flakova, R.; Ženisova, Z.; Krcmar, D.; Ondrelkova, I.; Sracek, O. Occurrence of antimony and arsenic at mining sites in slovakia: Implications for theır mobility. *Carpathian J. Earth Environ. Sci.* **2017**, *12*, 41–48.
41. Bakhshinezhad, H.; Bakhtavar, E.; Afghan, A. Assessment of arsenic concentration along a surface water fow path from Zarshuran gold mine to the downstream residential area. *Environ. Earth Sci.* **2019**, *78*, 668. [CrossRef]
42. Piper, A.M. A graphic procedure in the geochemical interpretation of water analyses. *Eos Trans. Am. Geophys. Union* **1944**, *25*, 914–923. [CrossRef]
43. Pilon-Smits, E.A. Phytoremediation. *Ann. Rev. Plant Biol.* **2005**, *56*, 15–39. [CrossRef] [PubMed]
44. Tangahu, B.V.; Abdullah, S.R.S.; Basri, H.; Idris, M.; Anuar, N.; Mukhlisin, M. A review on heavy metals (As, Pb, and Hg) uptake by plants through phytoremediation. *Int. J. Chem. Eng.* **2011**, 939161. [CrossRef]
45. Cenci, R.M. The use of aquatic moss (*Fontinalis antipyretica*) as monitor of contamination in standing and running waters: Limits and advantages. *J. Limnol.* **2000**, *60*, 53–61. [CrossRef]
46. Baby, J.; Raj, J.; Biby, E.T.; Sankarganesh, P.; Jeevitha, M.V.; Ajisha, S.U.; Rajan, S.S. Toxic effect of heavy metals on aquatic environment. *Int. J. Biol. Chem. Sci.* **2010**, *4*, 939–952. [CrossRef]
47. Sasmaz, A.; Obek, E. The accumulation of silver and gold in *Lemna gibba* exposed to secondary effluents. *Chemie der Erde* **2012**, *72*, 149–152. [CrossRef]
48. Uysal, Y. Removal of chromium ions from wastewater by duckweed, *Lemna minor* L. by using a pilot system with continuous flow. *J. Hazard. Mater* **2013**, *263*, 486–492. [CrossRef]
49. Abdallah, M.A. Phytoremediation of heavy metals from aqueous solutions by two aquatic macrophytes, *Ceratophyllum demersum* and *Lemna gibba*. *Environ. Tech.* **2012**, *33*, 1609–1614. [CrossRef] [PubMed]
50. Ucuncu, E.; Tunca, E.; Fikirdeşici, S.; Özkan, A.D.; Altindag, A. Phytoremediation of Cu, Cr and Pb mixtures by *Lemna minor*. *Bull. Environ. Contam. Toxicol.* **2013**, *91*, 600–604. [CrossRef]
51. Sasmaz, M.; Obek, E.; Sasmaz, A. The accumulation of La, Ce and Y by *Lemna minor* and *Lemna gibba* in the Keban gallery water, Elazig Turkey. *Water Environ. J.* **2018**, *32*, 75–83. [CrossRef]
52. De Souza, T.D.; Borges, A.C.; Braga, A.F.; Veloso, R.W.; De Matos, A.T. Phytoremediation of arsenic-contaminated water by *Lemna Valdiviana*: An optimization study. *Chemosphere* **2019**, *234*, 402–408. [CrossRef]
53. Leblebici, Z.; Kar, M.; Yalcin, V. Comparative study of Cd, Pb, andNi removal potential bySalvinia natans(L.) All. andLemna minorL.: Interactions with growth parameters. *Rom. Biotech Lett.* **2018**, *23*, 13235–13248.
54. Amare, E.; Kebede, F.; Berihu, T.; Mulat, W. Field-based investigation on phytoremediation potentials of *Lemna minor* and *Azolla* filiculoidesin tropical, semiarid regions: Case of Ethiopia. *Int. J. Phytoremediation* **2018**, *20*, 965–972. [CrossRef] [PubMed]
55. Tatar, S.; Obek, E.; Arslan Topal, E.I.; Topal, M. Uptake of some elements with aquatic plants exposed to the effluent of wastewater treatment plant. *Pollution* **2019**, *5*, 377–386.

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.