sustainability

Article

Alternative Low-Cost Treatment for Real Acid Mine Drainage: Performance, Bioaccumulation, Translocation, Economic, Post-Harvest, and Bibliometric Analyses

Yudha Gusti Wibowo [1,*], Hana Safitri [2], Ida Bagus Ilham Malik [3], Sudibyo [4] and Sugeng Priyanto [5]

1 Department of Mining Engineering, Institut Teknologi Sumatera, Lampung Selatan 35365, Indonesia
2 Postgraduate Program of Chemical Science, IPB University, Bogor 16680, Indonesia
3 Department of Urban & Regional Planning, Institut Teknologi Sumatera, Lampung Selatan 35365, Indonesia
4 Research Centre for Mining Technology, National Research and Innovation Agency (BRIN), Jl. Ir. Sutami KM 15, Tanjung Bintang, South Lampung 35361, Indonesia
5 Department of Mechanical Engineering, State University of Jakarta, East Jakarta 13220, Indonesia
* Correspondence: yudha.wibowo@ta.itera.ac.id

Abstract: Environmental pollution due to industrial activities has been reported since 1760, dating back to the first industrial revolution. One industrial activity that has led to major environmental degradation is coal mining, which can pollute surface and underground water due to acid mine drainage (AMD). Phytoremediation is low-cost, applicable, environmental, and does not generate other waste materials. In this research, we analyze the utilization of *Eichhornia crassipes* and *Pistia stratiotes* for AMD treatment. The results indicated that the AMD initially contained Fe, Mn, Al, Ca, and Mg. *E. crassipes* successfully reduced these contents by up to 69%, while *P. stratiotes* removed up to 62%. A cost analysis for phytoremediation of AMD is designed in terms of two schemes, with 4298 USD for the first scheme and no cost in the second scheme. The post-harvest potential, future research directions, and bibliometric analysis are also discussed. Overall, the results of this study indicate that *P. stratiotes* and *E. crassipes* are plants with great potential for AMD phytoremediation.

Keywords: phytoremediation; *Eichhornia crassipes*; *Pistia stratiotes*; acid mine drainage; environmental pollution

check for updates

Citation: Wibowo, Y.G.; Safitri, H.; Malik, I.B.I.; Sudibyo; Priyanto, S. Alternative Low-Cost Treatment for Real Acid Mine Drainage: Performance, Bioaccumulation, Translocation, Economic, Post-Harvest, and Bibliometric Analyses. *Sustainability* **2022**, *14*, 15404. https://doi.org/10.3390/su142215404

Academic Editors: Naser Karimi, Zahra Souri and Muhammad Ansar Farooq

Received: 25 September 2022
Accepted: 15 November 2022
Published: 19 November 2022

1. Introduction

Environmental degradation has been significantly reported worldwide. Due to widespread industrialization, water pollution caused by various pollutant parameters (e.g., heavy metals, lightweight metals, and acidic conditions) has been increasing daily [1]. The mining industry adversely affects the environment, especially surface and underground water. According to this condition, water contamination due to heavy metal exposure has become a major concern worldwide. A recent study has also shown that water contaminated with heavy metals leads to effects including mutagenicity, genotoxicity, carcinogenicity, and immunotoxicity [2,3]. AMD is a surface water problem that impacts both the environment and human health [4,5]. Heavy metals contained in AMD are difficult to remove from the environment and the human body due to their non-biodegradability and lead to toxic effects [6,7].

Phytoremediation provides low-cost and applicable methods to resolve AMD. These methods can remediate heavy metals and other pollutant parameters in water contamination scenarios. Phytoremediation has received significant attention worldwide due to its applicability, acceptability, low cost, and ease of operation, as well as less harmful effects on the soil and water, unlike other chemical and physical remediation methods. In addition, a recent study has shown that phytoremediation could help to improve the quality of the environment (i.e., soil and water) in terms of chemical, physical, and biological aspects [8].

Other chemical and physical treatments also generate waste materials that can lead to other problems for the environment and human health; for example, the adsorption method and water treatment plants can generate sludge from the adsorbent, contaminated with heavy metals or presenting other toxic parameters [9,10]. Thus, this problem must be solved through a desorption method, requiring further treatment and high technological requirements [11]. Furthermore, chemical treatment (e.g., adding certain chemical reagents) may generate a new, unidentified chemical reaction [10]. Thus, phytoremediation provides a promising treatment model for wastewater, which will not generate an unidentified reaction or yield contaminated sludge that needs to be treated further.

Although phytoremediation has been widely reported, there has been no study regarding the use of this method to treat real AMD. Most phytoremediation methods have been aimed at treating domestic wastewater considering common pollutant parameters, such as total suspended solids, ammonia, chemical oxygen demand, electrical conductivity, phosphorous, nitrates, and nitrites [12,13]. To fill this gap in the literature, in this study, we investigate and analyze a phytoremediation method using *Eichhornia crassipes* and *Pistia stratiotes* to remove various components in a real AMD scenario. Although previous studies of AMD treatments using phytoremediation have been reported, holistic research, including statistical, cost, and bibliometric analyses for future recommendations, remain rare. For example, previous studies on phytoremediation for the treatment of acid mine drainage have not provided information on bioaccumulation, translocation, statistical analysis, cost analysis, and future research recommendations [14,15]. Thus, this study is important to fill such gaps, providing holistic information regarding the potential of *E. crassipes* and *P. stratiotes* for the treatment of acid mine drainage.

Therefore, in this study, we analyze and investigate the potential of *E. crassipes* and *P. stratiotes* as phytotechnology to remove pollutants from real AMD. The real AMD used in this study contained Fe, Mn, Al, Ca, and Mg. The reporting of pollutant parameters in this study is unique. Several studies have been limited to using artificial wastewater [16,17]. Thus, in this study, we evaluate and analyze the effect of phytoremediation using *E. crassipes* and *P. stratiotes* in terms of each parameter. Furthermore, we also provide a comparative cost analysis, as well as recommendations and future research directions considering phytoremediation for real AMD treatment through bibliometric analysis. To the best of our knowledge, this is the first study on the utilization of phytoremediation using *E. crassipes* and *P. stratiotes* for the treatment of AMD, with results reported in terms of various pollutant parameters.

2. Materials and Methods

2.1. Materials

Eichhornia crassipes and *Pistia stratiotes* were collected from Lampung, Indonesia, and 20 L of AMD was collected from a coal mining area in Jambi Province, Indonesia. The plants were acclimatized in glass boxes for a week before use. Acclimatization is an important step for the beneficial physiological adaptation of *E. crassipes* and *P. stratiotes*, helping the plants to adapt to the climatic, environmental, and/or surrounding conditions. This treatment can also be useful, such that the plants do not experience shock in response to their new environment. Most species of plants have been shown to require an acclimatization process to ensure that they survive and grow vigorously when transferred to a new environment [18].

Inductively Coupled Plasma-Optical Emission Spectrometry was used to measure the initial concentration of pollutant parameters in AMD (Fe, Mn, Al, Ca, and Mg), and the pH of the AMD was measured using a pH meter.

2.2. Determination of Plant Growth

Both plants were acclimated for a week using tap water in plastic buckets. After acclimation, the root length *E. crassipes* was 18 cm, while that of *P. stratiotes* were 10 cm. The shoot diameter for *E. crassipes* was around 8 cm, and the length of *P. stratiotes* leaves was 8 cm.

2.3. Plant Batch Studies

E. crassipes and *P. stratiotes* were added separately into glass boxes with 2 L of AMD. Two glass boxes with 5 L of AMD were used to analyze plant batch studies. Each plant was put into different glass boxes at room temperature (28 °C) for five weeks (40 days). The parameters of AMD were analyzed separately for each week (weeks 1, 2, 3, 4, and 5) in glass boxes with three plants each.

2.4. Experimental Setting and Quality Control of Samples

Both plants were handled carefully. We confirmed that no diseased plants were used, and all plants were fresh plants with good leaves and stems. The AMD sample used in this study was collected carefully using polyethylene bottles that had been cleaned twice using distilled water. The bottles were also checked to have not been contaminated by previous samples. Before sending to the laboratory, the AMD used was placed in a freezer (4 ± 2 °C) under acidic conditions (pH 2) in order to ensure that the sample was not damaged. All samples were brought and utilized under strict supervision, according to the National Indonesian Standard (SNI 6989.59:2008) [19].

2.5. Pollutants Removal

Removal percentage of pollutants from AMD was calculated by Equation (1):

$$\text{Removal percent} = \frac{(C_o - C_e)}{C_o} \times 100\%, \tag{1}$$

where C_o is the initial concentration of a pollutant parameter in AMD and C_e is the final concentration of the pollutant parameter in AMD. The unit of this variable is percentage.

2.6. Bioconcentration Factors

Bioconcentration is the ratio of substance in *E. crassipes* or *P. stratiotes* to the exposure concentration under equilibrium conditions. The bioconcentration factors of *E. crassipes* and *P. stratiotes* were calculated in their dry mass (Equation (2)):

$$\text{Bioconcentration factor} = \frac{P}{E}, \tag{2}$$

where P is the pollutant concentration in plant tissue (mg/kg) under dry weight conditions, and E is the pollutant concentration in AMD (mg/L).

2.7. Translocation Factor

The translocation factor indicates the translocation of heavy metals from the root of *E. crassipes* or *P. stratiotes* to the aerial parts. This parameter was calculated by Equation (3):

$$\text{Translocation factor} = \frac{C_{shoot}}{C_{root}}, \tag{3}$$

where C_{shoot} is the concentration of AMD pollutants in the shoots and C_{root} is the concentration of pollutants in the roots of *E. crassipes* or *P. stratiotes.*

2.8. Statistical Test

In this study, one-way analysis of variance (ANOVA) was conducted to determine the significant differences in contaminant removal under various periods of contact. ANOVA was carried out using the Microsoft Excel 2016 software (Microsoft Corporation, Redmond, WA, USA), considering a significance level of 0.05.

2.9. Cost Analysis

Cost analysis of AMD treatment using phytoremediation was analyzed using the investment method [20] (Equation (4)):

$$TC = TVC + TFC, \tag{4}$$

where *TC* is the total cost, *TVC* is the total fixed cost, and *TFC* is the total variable cost. The cost analysis was conducted in terms of USD. The costs calculated included those related to aeration, circulation, and the construction of wetland for phytoremediation. The depreciation analysis was conducted according to the straight-line method (Equation (5)) [20]:

$$D = \frac{P - s}{N} = \frac{0.9P}{N}. \tag{5}$$

2.10. Bibliometric Analysis

Bibliometric analysis was carried out to find studies focused on phytoremediation. This method provides a powerful means to discover recommendations and future research directions. To analyze the phytoremediation literature until 2022, the VOSviewer software was used. A total of 122 published papers and books (including book chapters) were found in the search engine (Google Scholar) with the range of study from 2012 to 2022. The published papers used for bibliometric analysis were limited to several publishers (Elsevier, Springer, Nature, and Hindawi). The keywords used to find the published papers were "phytoremediation", "phytoremediation for wastewater treatment", and "phytoremediation for acid mine drainage".

3. Results

3.1. AMD Characteristics

The used AMD had high concentrations of Fe, Mn, Al, Ca, and Mg (Table 1). In addition, the acid condition of AMD was also determined (pH 3.76). The acid condition of water may lead to the high mobility of metal ions, thus creating a high concentration of heavy metals in the AMD sample. According to Indonesian National Standard, the pH of AMD should be between 6 and 9, and the concentration of AMD must be less than 7 mg/L for Fe and less than 4 mg/L for Mn. All of the parameters in the AMD sample were higher than the levels stipulated in relevant standards and, so, can be considered dangerous to the environment.

Table 1. Characteristics of utilized AMD.

Parameters	Value/Concentration
Fe (mg/L)	9.21
Mn (mg/L)	8.35
Al (mg/L)	7.43
Ca (mg/L)	4.75
Mg (mg/L)	6.56
pH	3.76
Temperature (°C)	33

3.2. Effect of Contact Time

The effect of contact time between plants and AMD is depicted in Figure 1, from which it can be seen that a longer contact time had a positive impact on decreasing the content of heavy metals, that is, longer contact between the plants and the AMD led to a higher sorption effect for each pollutant parameter. *E. crassipes* showed a higher ability for Fe and Mn removal, while *P. stratiotes* showed a better ability for Al, Ca, and Mg removal.

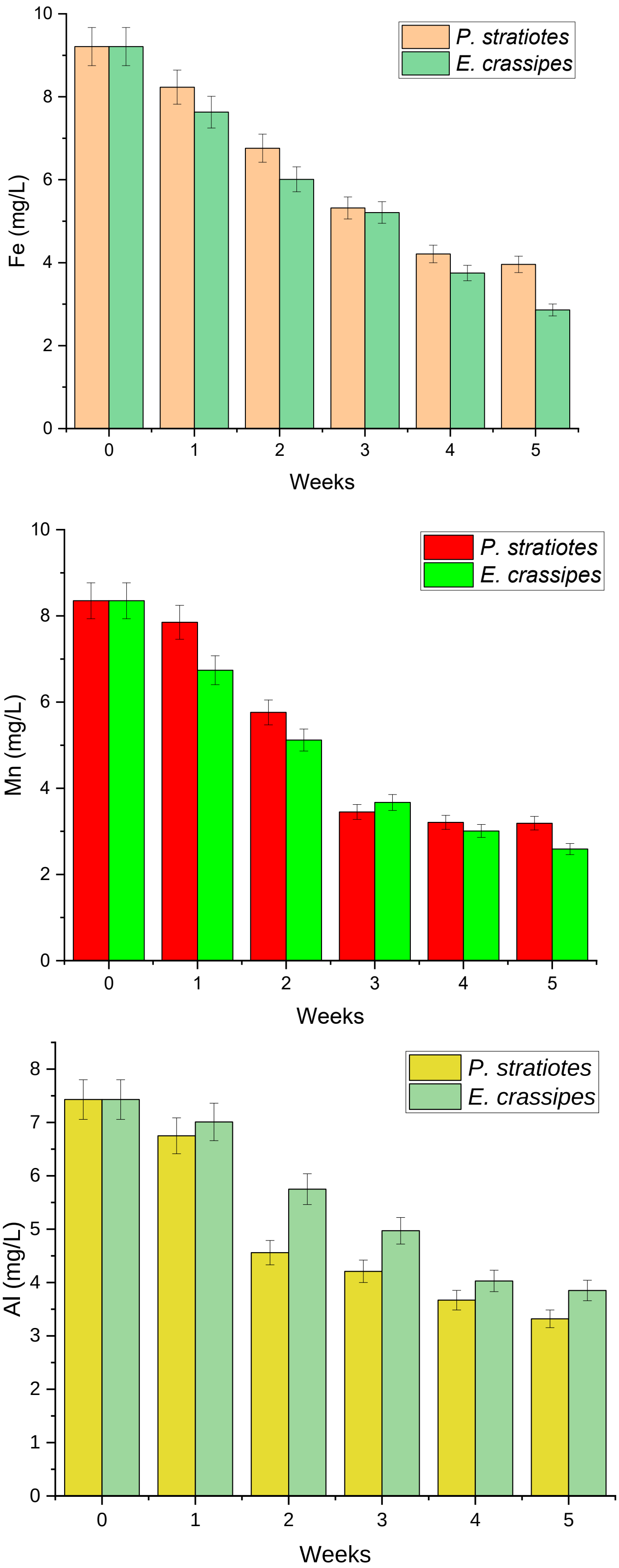

Figure 1. *Cont.*

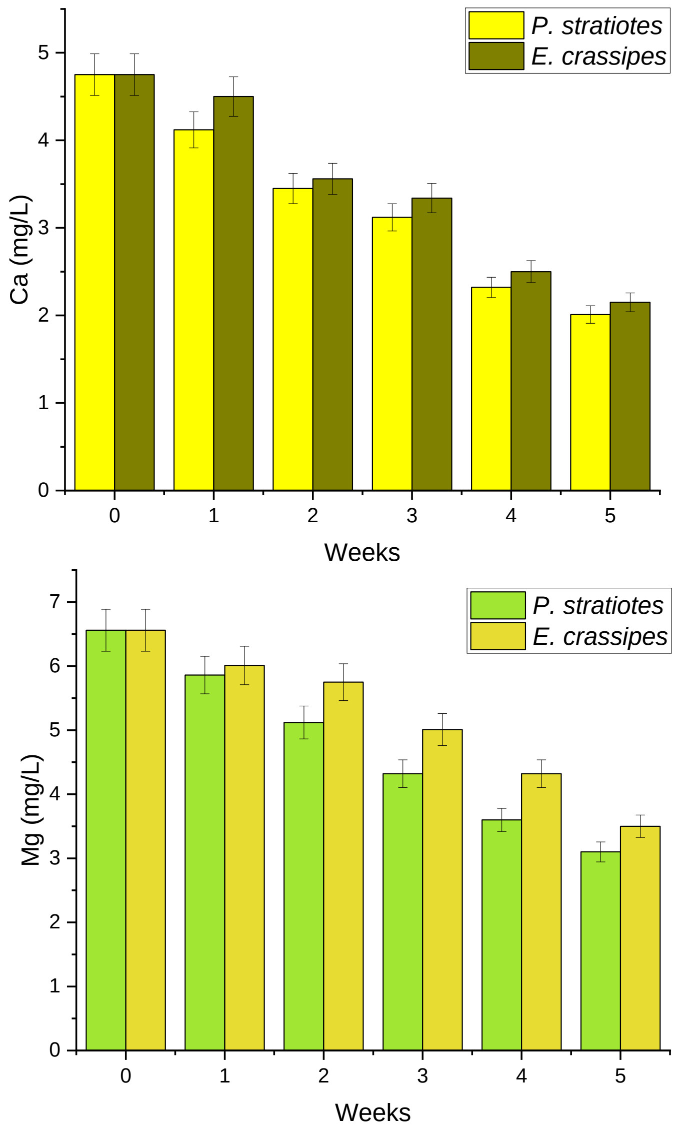

Figure 1. Effect of contact time between *P. stratiotes* or *E. crassipes* and AMD.

3.3. Removal Percentage

The removal percentage for each pollutant parameter is shown in Figure 2, indicating that contact time also had an impact on removal percentage. The best removal percentage of Fe was reached after five weeks for *E. crassipes* (>65%). The sorption of Mn plant roots showed the same result. After five weeks of contact, the best removal percentage of Mn was reached. In terms of Mn removal, *P. stratiotes* showed better removal ability compared with Fe. An opposite result was observed for Al, Ca, and Mg, for which *P. stratiotes* had higher percentage removal than *E. crassipes*. These results also confirmed that *E. crassipes* has better potential for heavy metal removal, while *P. stratiotes* is better for the removal of lightweight metals.

3.4. Bioaccumulation and Translocation Factor

The bioaccumulation and translocation factor results for both of the plants are shown in Figure 3. We observed that the bioaccumulation of pollutant parameters occurred in both shoots and roots, where most pollutants showed higher bioaccumulation in roots than in shoots. In addition, the translocation factor results indicated high results from Fe, Mn, Al, and Ca, confirming that *P. stratiotes* and *E. crassipes* are hyperaccumulator plants due to the translocation factor values being close to one.

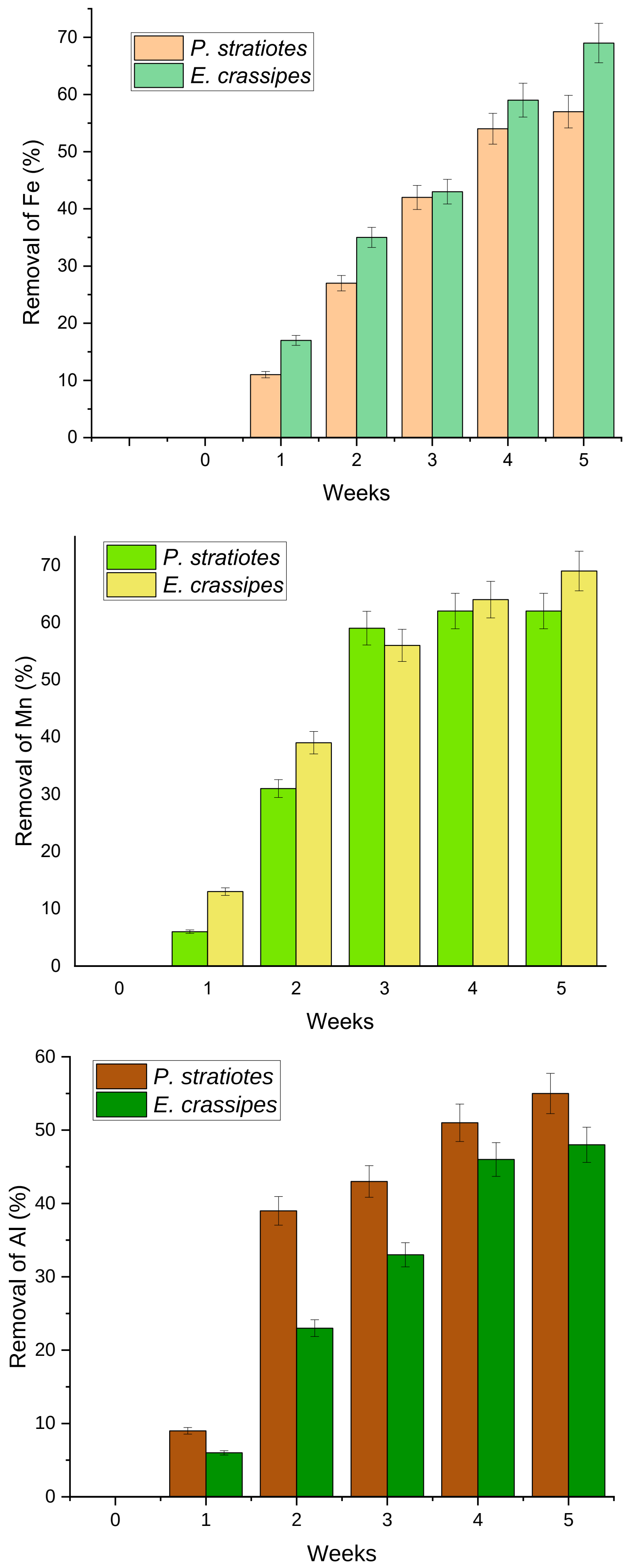

Figure 2. *Cont.*

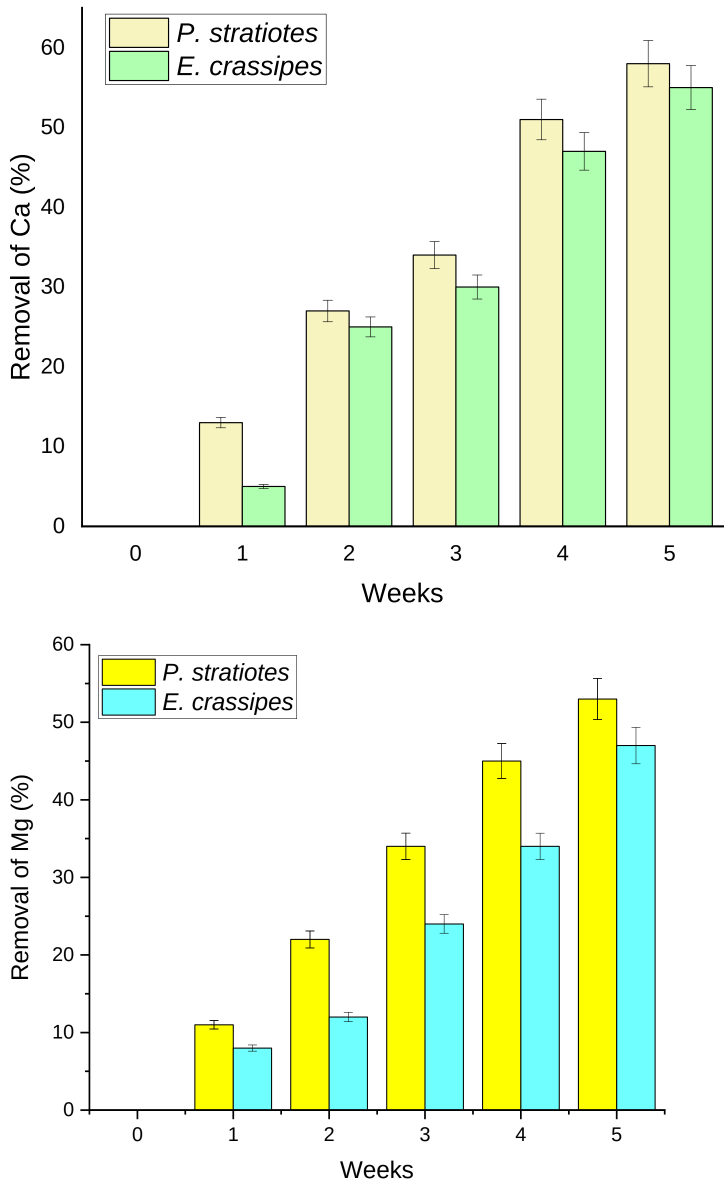

Figure 2. Removal percentage of pollutant parameters from AMD by *P. stratiotes* or *E. crassipes*.

3.5. Statistical Analysis

A statistical test—that is, one-way ANOVA—was conducted to assess the effect of contact time on heavy metal concentration. The results demonstrated that the P-value for *E. crassipes* was 0.209, while that for *P. stratiotes* was 0.099. Besides, the F-crit value was 2.758 for both *P. stratiotes* and *E. crassipes*. According to the statistical test, the *p*-value for both plants was higher than 0.05. Thus, the average pollutant removal effect when using *E. crassipes* and *P. stratiotes* was the same, with a significance level of 5%.

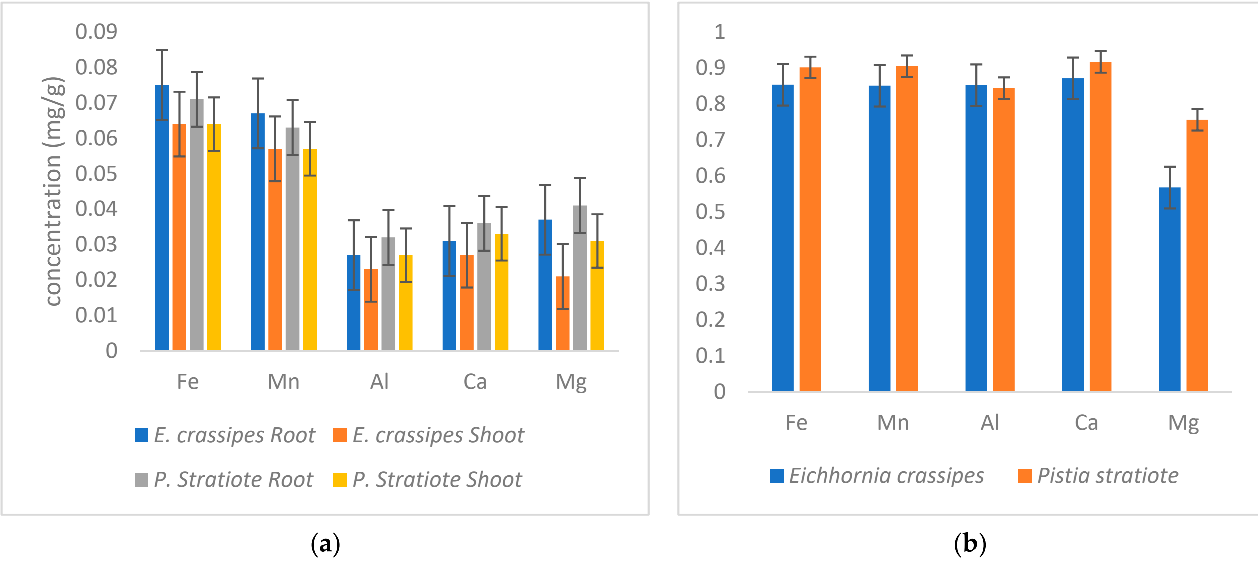

Figure 3. Bioconcentration (**a**) and translocation (**b**) of heavy metals in plants.

4. Discussion

4.1. AMD Characteristics

High levels of heavy metals were found in the used AMD, associated with its low pH conditions. In acidic conditions, metal ions will move faster, leading to negative impacts such as increased heavy metal concentration. Not only was Fe present, but the AMD also presented a high Mn concentration, which is dangerous for both the environment and human health [21]. High concentrations of Fe and Mn can lead to long-term negative impacts on aquatic ecosystems [22] and plants [23]. High concentrations of Fe and Mn have also been reported to have impacts through biochemical reactions, sediment deposition, dissolved or particulate forms, and volatilization [24]. In terms of human health effects, long-term contamination of Fe and Mn has been reported to result in non-carcinogenic diseases [21].

AMD has different characteristics, according to geological and environmental conditions. For example, AMD may have different pollutant parameters in the same Province but at different locations. A recent study has stated particular AMD as having Al, Ca, and Mg in high concentrations but no Fe or Mn [5]. The characteristics of the AMD used in this study were similar to those reported in a recent study on AMD in India [25]. High concentrations of Fe and Mg were reported due to finely disseminated pyrite crystals, pyrite oxidation, and hydrated sulfate complexes [25]. High long-term contamination of Fe and Mn has been reported to have effects on several diseases, such as inflammatory bowel disease [26], or Parkinson's and Alzheimer's diseases [27].

4.2. Effect of Contact Time

We found that a longer contact time between plants and AMD led to better capturing of pollutants from AMD. As shown in Figure 1, *E. crassipes* showed a better ability to decrease Fe and Mn, while *P. stratiotes* had a better effect on decreasing Al, Ca, and Mg. The different abilities of these plants are due to competitive sorption in the roots and shoots of plants. Assessment at all contact times showed that there was no release of heavy metals from the plants into water. The best decrease of Fe was observed with *E stratiotes*, successfully reducing Fe from 9 to 2 mg/L. Thus, this plant could remove more than half of the Fe content from AMD.

The concentration of Mn in AMD was also reduced from 8 to 3 for *P. stratiotes* and from 8 to 2 for *E. crassipes*. These results confirmed that *E. crassipes* has a higher ability than *P. stratiotes* in terms of the removal of heavy metals from water. The phytoremediation batch study demonstrated better removal efficiency than phytoremediation in Batch-Fed

Free Water Flow Constructed Wetlands, which can only remove 26% of Fe [28]. Although phytoremediation generally has lower performance than other methods, such as adsorption, this method is more sustainable than adsorption. Furthermore, due to the limited studies of phytoremediation utilization in AMD treatment in the literature, this research only details one of the conditions for AMD treatment through phytoremediation.

4.3. Percentage Removal

E. crassipes showed the best removal percentages for Fe (>60%) and Mn (>50%). Although the values were high, this study showed low removal percentage when compared with that in an artificial metal solution [29]. This phenomenon is due to a lack of competitive sorption in the plant roots. Thus, the root can optimally adsorb a single heavy metal. Both plants also successfully removed more than 50% and 60% of all metals. A significant difference was observed in the removal percentage of Al, Ca, and Mg between the plants. These pollutant parameters were more strongly decreased by *P. stratiotes*. No study has reported the same remediation effects of *E. crassipes* and *P. stratiotes* in acid mine drainage or other wastewater with similar pollutant parameters.

A study in Brazil has reported that phytoremediation using *P. stratiotes* successfully decreased Zn [30], another important pollutant parameter in AMD [31]. Thus, this method provides a powerful means to resolve the environmental and human health impacts of AMD. AMD typically contains 36 pollutant parameters, including Al, As, B, Cr, Cu, Fe, Mn, Na, Ni, and Pb [32]. Besides providing a cheap and easy method, phytoremediation using *E. crassipes* and *P. stratiotes* is a sustainable way to reduce pollutant parameters in AMD. *E. crassipes* and *P. stratiotes* are easy to grow and develop, as evidenced by the ease with which these plants can be found in swamps without needing to be planted.

4.4. Bioconcentration and Translocation Factor

The abilities of *E. crassipes* and *P. stratiotes* in absorbing heavy metals are detailed in Figure 3a, indicating that most heavy metal accumulation occurred in the roots of these plants. This result showed that both plants had not yet finished transferring heavy metals from root to shoot, in agreement with a recent study in Nigeria, which stated that the bioconcentration in roots was higher than in shoots for Zn and Cd [33]. The high concentration in roots and shoots indicated that the sorption of pollutant parameters (i.e., heavy metals) occurred faster than the catabolism process in both plants.

Figure 3b depicts the abilities of the plants in terms of heavy metal translocation. We found that both plants had high translocation abilities for Fe, Mn, Al, and Ca (between 0.8–0.9) and good translocation ability for Mg (0.6 for *E. crassipes* and 0.7 for *P. stratiotes*). The best translocation value was 0.9 for Ca and Mg for *P. stratiotes*. This research also indicated that the values of the translocation factors were all close to 1, demonstrating that both plants may potentially be categorized as hyperaccumulator plants.

4.5. Cost Analysis

The cost analysis for several AMD treatment methods is provided in Table 2. The first scheme for investment to create a constructed wetland in the mining area requires 4298 USD for 20 years. The second scheme involves creating a non-permanent location for the acclimatization pool, aeration, and constructed wetlands and has zero costs. The acclimatization pool can be created with unused buckets or drums. The constructed wetlands for phytoremediation can be the natural wetland around the mining area. In addition, phytoremediation can simply be implemented in the settling pond of the coal mining area. Thus, the second scheme reduces the costs associated with AMD treatment. A study has reported the economic feasibility of phytoremediation, which stated that 51 companies worldwide offer environmental management services using the phytoremediation method [34]. Phytoremediation feasibility studies require site-specific information, such as landscaping information, site conditions, and species of plants for phytoremediation technologies associated with certain industries, authorities, or farmers [35].

The comparison of several methods for wastewater treatment showed in Table 2, with the cost analysis shown. Here, there is no means for direct comparison, as every method has certain strengths and weaknesses. For example, phytoremediation has advantages in terms of service life (can reach decades) but is relatively slower in reducing heavy metal levels; in contrast, an adsorption method may be able to significantly reduce heavy metal content within minutes [36]. However, adsorption methods have drawbacks, such as being difficult to apply in the field and yielding a by-product in the form of an adsorbent that is contaminated with heavy metals.

Table 2. Comparison and cost analysis.

Method	Materials/Plants	Pollutants	Cost (USD)	Reference
Phytoremediation (First scheme)	*P. Stratiotes* *E. crassipes*	Fe, Al, Ca, Mg	4298	This study
Phytoremediation (Second scheme)	*P. Stratiotes* *E. crassipes*	Fe, Al, Ca, Mg	-	This study
Adsorption	Porous metal oxide	Phosphate	100–200	[37]
Phytoremediation	*Thlaspi caerulescens*	Heavy metals in agricultural land	14,600 for 20 years	[38]
WWTP (No information)	N/A	N/A	$0.12/m^3$	[39]

(Note) *P. Stratiotes* and *E. crassipes* in this study collected from swamp.

4.6. Potential of Eichhornia crassipes and Pistia stratiotes for Post-Harvest

Several studies have reported the potential of phytoremediation using *E. crassipes* and *P. stratiotes*. In this study, we also confirmed that both of these plants have high abilities to reduce metal species in AMD. Furthermore, *E. crassipes* and *P. stratiotes* are plants with several benefits in terms of further utilization. A study in India has reported that *P. stratiotes* may have pharmaceutical potential, indicating that this plant could be used due to its anti-inflammatory activities [40]. This plant has been used in Ghana for curing ophthalmic disease and iritis. Furthermore, the plant also can be used as an anti-inflammatory through the inhibition of histamine, serotonin, prostaglandin, and bradykinin [41]. *P. stratiotes* also has other benefits, including antifungal, anti-microbial, and diuretic activities. An extract from the leaves of this plant can be used to treat uric acid formation and inhibit the enzyme xanthine oxidase. Hence, it may be used for the treatment of gout [42].

E. crassipes is also a plant that offers many benefits post-harvest (Figure 4). A study has reported that this plant can be used to make paper, organic fertilizer, and handicrafts. *E. crassipes* has also been shown to have pharmaceutical potential: A study has shown that the leaves of *E. crassipes* could be successfully converted into an in vitro anti-bacterial [43]. Another study has reported that *E. crassipes* has potential use as a compost additive, having a positive impact on soil quality [44]. This plant has been reported to have better N, P_2O_5, K_2O, and C:N contents, being four times richer than farmyard manure [44]. Fertilizer generated from *E. crassipes* could improve soil properties, bulk density, soil cation exchange capacity, pH, soil aggregation, and soil mineral nutrients [44].

E. crassipes not only has a positive impact on the environment, but this plant has also had a good economic impact in Madagascar. *E. crassipes* can be converted into hats, sandals, handbags, mats, and shopping bags, which are deemed acceptable by consumers [45].

As a liquid fertilizer, *E. crassipes* was reported as a potential plant having a positive impact on water and soil quality. A recent study has shown that a liquid fertilizer from *E. crassipes* facilitates potential nitrogen recovery from water and increased C/N ratio in soil [46]. This plant has also been shown to have low cost, promote a faster increase in fermentation temperature, and have lower nitrous oxide emissions [47].

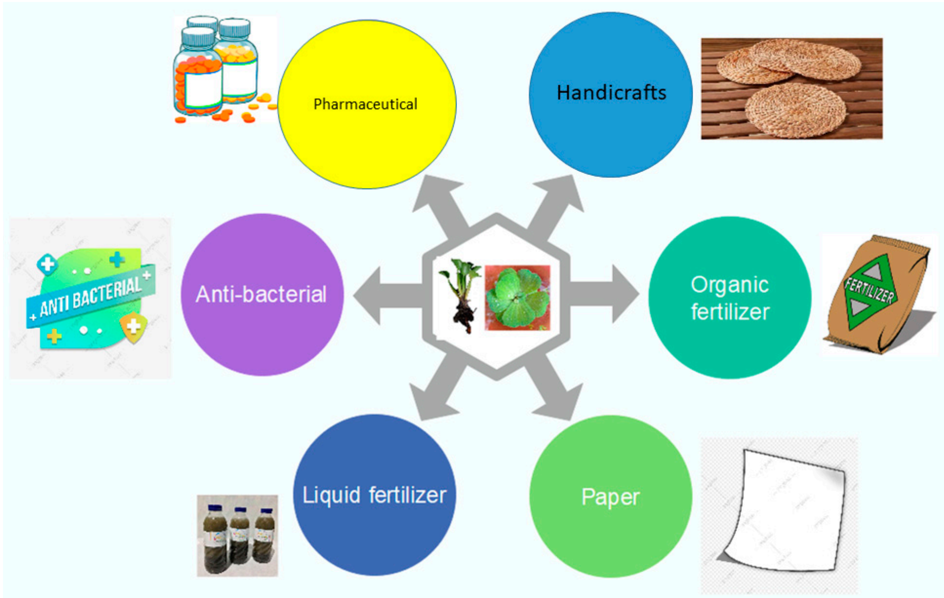

Figure 4. Potential utilization of *E. crassipes* and *P. stratiotes* post-harvest.

4.7. Bibliometric Analysis and Recommendations for Future Research

The results of the bibliometric analysis regarding wastewater remediation are shown in Figure 5. According to the bibliometric analysis, heavy metals and wastewater treatment were the two keywords most associated with phytoremediation, which was confirmed based on recent studies that have associated phytoremediation with wastewater treatment and heavy metals [48–50]. Furthermore, some plants also appeared in the bibliometric analysis, such as *E. crassipes* used in this study. The bigger balloon in the bibliometric analysis indicates that many studies have considered this plant. Several keywords were found in the analysis, including phytoremediation, heavy metal, biochemical composition, lead, detoxification, aquaculture, wastewater, fouling, plants, pollutants removal, etc.

In Figure 5, a small balloon is shown for AMD. Thus, the study of AMD in phytoremediation is rare. Although many papers have been published regarding wastewater treatment through phytoremediation, not many studies have reported on the utilization of phytoremediation in real AMD. The utilization of phytoremediation for treating AMD requires further development, including research to find the optimal plants that are acceptable and applicable and which can survive in mining areas. Mining areas have different characteristics compared with domestic wastewater. To date, most published papers on phytoremediation have been limited to domestic wastewater [51]. In addition, the utilization of phytoremediation in AMD is a new challenge. If the optimal plants can be added to a sump, they will be powerful in allowing for a reduction in the utilization of CaO (as a conventional method for treating AMD).

Further research should also focus on local plants that are obtainable in rural areas (i.e., mining areas) and should also work towards creating a sustainable and circular economy for treating AMD using phytoremediation. There are no waste materials that can be created in this process. Knowing that *E. crassipes* and *P. stratiotes* only reduce the pollutant parameters by half, a combination of methods needs to be developed. In this line, there has only been one study on the combination of phytoremediation and passive biopiling for the treatment of contaminated soil [52]. Thus, studies focused on a combination of two or more methods are rare. Therefore, the combination of bioremediation and phytoremediation needs to be further developed. Additionally, the combination of adsorption and phytoremediation needs to be explored. Although a study on the combination of phytoremediation and adsorption has been reported [53], the results only reported the 77.5% removal of COD and 54.3% for phosphate. New materials and combinations of two or three methods can potentially address the AMD problem. Finally, easy, acceptable, and low-cost combination materials and methods need to be found as soon as possible (Figure 6).

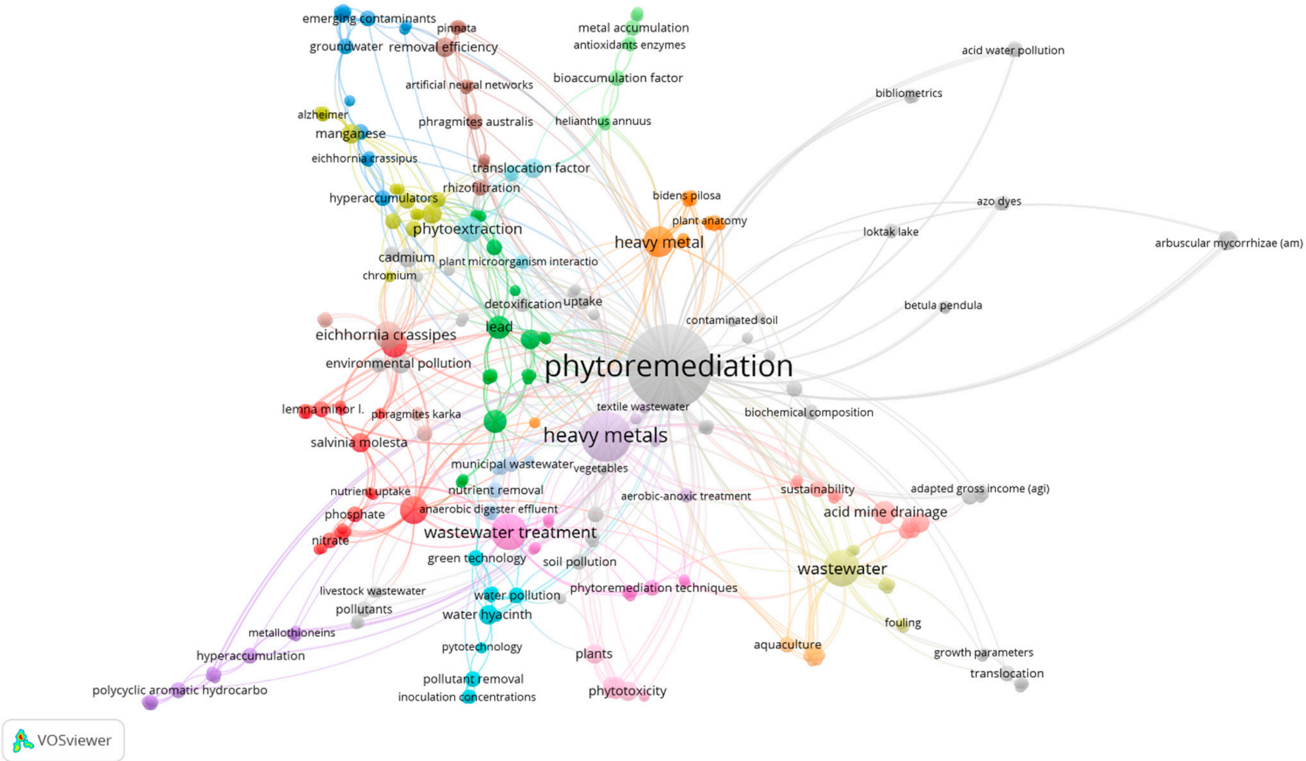

Figure 5. Bibliometric analysis of phytoremediation-related literature.

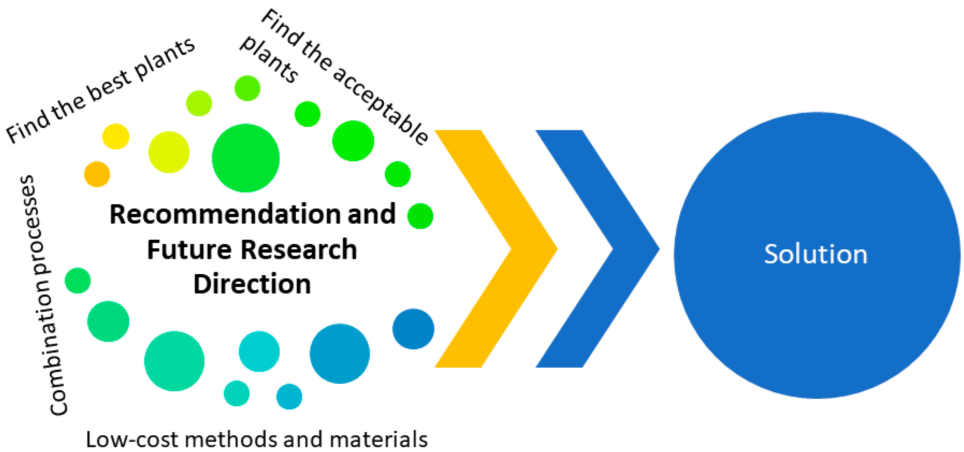

Figure 6. Recommendations for future research directions.

5. Conclusions

Research on phytoremediation strategies using *Eichhornia crassipes* and *Pistia stratiotes* for real AMD treatment to date is rare and limited. In this study, we aimed to analyze and investigate the potential of *E. crassipes* and *P. stratiotes* as phytotechnology to remove pollutants from real AMD. The results of this study demonstrated that the removal of pollutant parameters, such as Fe, Mn, Al, Ca, and Mg, by these plants was high: *E. crassipes* could remove up to 69%, 69%, 48%, 55%, and 47%, respectively, while *P. stratiotes* removed up to 57%, 62%, 55%, 58%, and 53%, respectively. Bioconcentration analysis of both plants showed that the heavy metal concentrations in roots were higher than in shoots for each plant. Translocation factor analysis also showed that the translocation value for both plants was between 0.8–0.9 for Fe, Mn, Al, and Ca and between 0.5–0.7 for Mg. Statistical analysis also returned p-values of 0.099935139 for *E. crassipes* and 0.209948549 for *P. stratiotes*. These results indicate that *E. crassipes* and *P. stratiotes* have great potential for the removal of various pollutant parameters from AMD. The cost analysis of phytoremediation for treating AMD was described in terms of two schemes, either costing 4298 USD or at no cost. Post-harvest analysis for *E. crassipes* and *P. stratiotes* indicated that both plants have good potential, for example, as materials for organic fertilizer, liquid fertilizer, paper, handicrafts, and pharmaceutical and anti-bacterial agents. Bibliometric analysis was also conducted in order to determine recommendations for future research directions relating to phytoremediation in treating AMD. In this aspect, the combination of phytoremediation with other methods should be investigated.

Author Contributions: Y.G.W.: Conceptualization, supervision, writing—original draft; H.S.: Methodology, formal analysis, writing—review and editing; I.B.I.M.: Software, investigation, data curation, and writing—review and editing; S.: Project administration, investigation, funding acquisition, resources, validation; S.P.: Project administration, investigation, funding acquisition, resources, validation. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Shah, V.; Daverey, A. Effects of sophorolipids augmentation on the plant growth and phytoremediation of heavy metal contaminated soil. *J. Clean. Prod.* **2021**, *280*, 124406. [CrossRef]
2. Jin, Z.; Deng, S.; Wen, Y.; Jin, Y.; Pan, L.; Zhang, Y.; Black, T.; Jones, K.C.; Zhang, H.; Zhang, D. Application of *Simplicillium chinense* for Cd and Pb biosorption and enhancing heavy metal phytoremediation of soils. *Sci. Total Environ.* **2019**, *697*, 134148. [CrossRef]
3. Sun, L.; Cao, X.; Li, M.; Zhang, X.; Li, X.; Cui, Z. Enhanced bioremediation of lead-contaminated soil by *Solanum nigrum* L. with Mucor circinelloides. *Environ. Sci. Pollut. Res.* **2017**, *24*, 9681–9689. [CrossRef]
4. Wibowo, Y.G.; Safitri, H.; Ramadan, B.S.; Sudibyo. Adsorption test using ultra-fine materials on heavy metals removal. *Bioresour. Technol. Rep.* **2022**, *19*, 154166. [CrossRef]
5. Wibowo, Y.G.; Sudibyo; Naswir, M.; Ramadan, B.S. Performance of a novel biochar-clamshell composite for real acid mine drainage treatment. *Bioresour. Technol. Rep.* **2022**, *17*, 118159. [CrossRef]
6. Alaboudi, K.A.; Ahmed, B.; Brodie, G. Phytoremediation of Pb and Cd contaminated soils by using sunflower (*Helianthus annuus*) plant. *Ann. Agric. Sci.* **2018**, *63*, 123–127. [CrossRef]
7. Etesami, H. Bacterial mediated alleviation of heavy metal stress and decreased accumulation of metals in plant tissues: Mechanisms and future prospects. *Ecotoxicol. Environ. Saf.* **2018**, *147*, 175–191. [CrossRef]
8. Deng, Q.; Deng, Q.; Wang, Y.; Li, L.; Long, X.; Ren, S.; Fan, Y.; Lin, L.; Xia, H.; Liang, D.; et al. Effects of intercropping with Bidens species plants on the growth and cadmium accumulation of Ziziphus acidojujuba seedlings. *Environ. Monit. Assess.* **2019**, *191*, 342. [CrossRef] [PubMed]
9. Boiteux, V.; Dauchy, X.; Bach, C.; Colin, A.; Hemard, J.; Sagres, V.; Rosin, C.; Munoz, J.F. Concentrations and patterns of perfluoroalkyl and polyfluoroalkyl substances in a river and three drinking water treatment plants near and far from a major production source. *Sci. Total Environ.* **2017**, *583*, 393–400. [CrossRef]
10. Dauchy, X.; Boiteux, V.; Bach, C.; Colin, A.; Hemard, J.; Rosin, C.; Munoz, J.F. Mass flows and fate of per- and polyfluoroalkyl substances (PFASs) in the wastewater treatment plant of a fluorochemical manufacturing facility. *Sci. Total Environ.* **2017**, *576*, 549–558. [CrossRef] [PubMed]
11. Kegl, T.; Košak, A.; Lobnik, A.; Novak, Z.; Kralj, A.K.; Ban, I. Adsorption of rare earth metals from wastewater by nanomaterials: A review. *J. Hazard. Mater.* **2020**, *386*, 121632. [CrossRef] [PubMed]
12. Aziz, N.I.H.A.; Hanafiah, M.M.; Halim, N.H.; Fidri, P.A.S. Phytoremediation of TSS, NH3-N and COD from sewage wastewater by *Lemna minor* L., *Salvinia minima*, *Ipomea aquatica* and *Centella asiatica*. *Appl. Sci.* **2020**, *10*, 5397. [CrossRef]
13. Mustafa, H.M.; Hayder, G. Recent studies on applications of aquatic weed plants in phytoremediation of wastewater: A review article. *Ain Shams Eng. J.* **2021**, *12*, 355–365. [CrossRef]
14. Palihakkara, C.R.; Dassanayake, S.; Jayawardena, C.; Senanayake, I.P. Floating wetland treatment of acid mine drainage using *Eichhornia crassipes* (water hyacinth). *J. Health Pollut.* **2018**, *8*, 14–19. [CrossRef] [PubMed]
15. Cruz, M.B.; Aguiar, R.; De Mello, J.W.V. Phytoremediation of acid mine drainage by aquatic floating macrophytes. *Sci. Technol.* **2010**, 1–3. Available online: https://www.academia.edu/20831963/Phytoremediation_of_acid_mine_drainage_by_aquatic_floating_macrophytes (accessed on 24 September 2022).
16. Park, J.-S.; Sung-Su, H.; Yoon, D.-J.; Shin, J.-D. Phytoremediation Technology with Using Water Celery (Oenanthe stolonifer DC.) to Clean up Heavy Metals in the Contaminated Wastewater. *Korea J. Environ. Agric.* **2002**, *21*, 122–129. [CrossRef]

17. Nugroho, A.P.; Butar, E.S.B.; Priantoro, E.A.; Sriwuryandari, L.; Pratiwi, Z.B.; Sembiring, T. Phytoremediation of electroplating wastewater by vetiver grass (*Chrysopogon zizanoides* L.). *Sci. Rep.* **2021**, *11*, 14482. [CrossRef] [PubMed]
18. Hazarika, B.N. Acclimatization of tissue-cultured plants. *Curr. Sci.* **2003**, *85*, 1704–1712. [CrossRef]
19. *SNI 6989.59:2008*; Metoda Pengambilan Contoh Air Permukaan. Badan Standardisasi Nasional: Jakarta, Indonesia, 2008.
20. Novita, E.; Wahyuningsih, S.; Adinda, C. Studi Kelayakan Teknik Dan Biaya Terhadap Alternatif Fitoremidiasi Pada Air Limbah Pengolahan Kopi. *Agrointek* **2021**, *15*, 513–520. [CrossRef]
21. Tepanosyan, G.; Sahakyan, L.; Belyaeva, O.; Asmaryan, S.; Saghatelyan, A. Continuous impact of mining activities on soil heavy metals levels and human health. *Sci. Total Environ.* **2018**, *639*, 900–909. [CrossRef]
22. Catsiki, V.A.; Florou, H. Study on the behavior of the heavy metals Cu, Cr, Ni, Zn, Fe, Mn and 137Cs in an estuarine ecosystem using Mytilus galloprovincialis as a bioindicator species: The case of Thermaikos gulf, Greece. *J. Environ. Radioact.* **2006**, *86*, 31–44. [CrossRef]
23. Sabina, R.O.; Santos, E.S.; Abreu, M.M. Accumulation of Mn and Fe in aromatic plant species from the abandoned Rosalgar Mine and their potential risk to human health. *Appl. Geochem.* **2019**, *104*, 42–50. [CrossRef]
24. Gheorghe, S. Metals Toxic Effects in Aquatic Ecosystems: Modulators of Water Quality. In *Water Quality*; Stoica, C., Ed.; IntechOpen: Rijeka, Croatia, 2017; pp. 60–89, Charter 4; ISBN 978-953-51-2882-3.
25. Equeenuddin, S.M.; Tripathy, S.; Sahoo, P.K.; Panigrahi, M.K. Hydrogeochemical characteristics of acid mine drainage and water pollution at Makum Coalfield, India. *J. Geochem. Explor.* **2010**, *105*, 75–82. [CrossRef]
26. Fraga, C.G. Relevance, essentiality and toxicity of trace elements in human health. *Mol. Asp. Med.* **2005**, *26*, 235–244. [CrossRef] [PubMed]
27. Martins, A.C., Jr.; Morcillo, P.; Ijomone, O.M.; Venkataramani, V.; Harrison, F.E.; Lee, E.; Bowman, A.B.; Aschner, M. New insights on therole of manganese in Alzheimer's Disease and Parkinson's Disease. *Int. J. Environ. Res. Public Health* **2019**, *16*, 3546.
28. Kodituwakku, K.A.R.K.; Yatawara, M. Phytoremediation of Industrial Sewage Sludge with *Eichhornia crassipes*, Salvinia molesta and *Pistia stratiotes* in Batch Fed Free Water Flow Constructed Wetlands. *Bull. Environ. Contam. Toxicol.* **2020**, *104*, 627–633. [CrossRef]
29. Kumar, V.; Singh, J.; Saini, A.; Kumar, P. Phytoremediation of copper, iron and mercury from aqueous solution by water lettuce (*Pistia stratiotes* L.). *Environ. Sustain.* **2019**, *2*, 55–65. [CrossRef]
30. Rodrigues, A.C.D.; de Castro Rocha, M.V.; Lima, E.S.A.; de Pinho, C.F.; dos Santos, A.M.; dos Santos, F.S.; do Amaral Sobrinho, N.M.B. Potential of water lettuce (*Pistia stratiotes* L.) for phytoremediation: Physiological responses and kinetics of zinc uptake. *Int. J. Phytoremediat.* **2020**, *22*, 1019–1027. [CrossRef]
31. Igarashi, T.; Herrera, P.S.; Uchiyama, H.; Miyamae, H.; Iyatomi, N.; Hashimoto, K.; Tabelin, C.B. The two-step neutralization ferrite-formation process for sustainable acid mine drainage treatment: Removal of copper, zinc and arsenic, and the influence of coexisting ions on ferritization. *Sci. Total Environ.* **2020**, *715*, 136877. [CrossRef]
32. Alegbe, M.J.; Ayanda, O.S.; Ndungu, P.; Nechaev, A.; Fatoba, O.O.; Petrik, L.F. Physicochemical characteristics of acid mine drainage, simultaneous remediation and use as feedstock for value added products. *J. Environ. Chem. Eng.* **2019**, *7*, 103097. [CrossRef]
33. Chukwuka, K.S.; Akpabio, U.S.; Uka, U.N. Bioaccumulation of Zinc and Cadmium by two aquatic plants: *Eichhornia crassipes* (Mart.) Solms and *Pistia stratiotes* L. under nursery conditions. *Trop. Plant Res.* **2020**, *7*, 229–237. [CrossRef]
34. Riaz, U.; Athar, T.; Mustafa, U.; Iqbal, R. Economic feasibility of phytoremediation. In *Phytoremediation*; Elsevier Inc.: Amsterdam, The Netherlands, 2022; pp. 481–502. ISBN 9780323898744.
35. Ali, H.; Khan, E.; Sajad, M.A. Phytoremediation of heavy metals-Concepts and applications. *Chemosphere* **2013**, *91*, 869–881. [CrossRef] [PubMed]
36. Budihardjo, M.A.; Wibowo, Y.G.; Ramadan, B.S.; Serunting, M.A.; Yohana, E. Syafrudin Mercury removal from modified activated carbon of peat soil and coal in simulated landfill leachate. *Environ. Technol. Innov.* **2021**, *24*, 102022. [CrossRef]
37. Kumar, P.S.; Korving, L.; van Loosdrecht, M.C.M.; Witkamp, G.J. Adsorption as a technology to achieve ultra-low concentrations of phosphate: Research gaps and economic analysis. *Water Res. X* **2019**, *4*, 100029. [CrossRef] [PubMed]
38. Lewandowski, I.; Schmidt, U.; Londo, M.; Faaij, A. The economic value of the phytoremediation function—Assessed by the example of cadmium remediation by willow (*Salix* ssp). *Agric. Syst.* **2006**, *89*, 68–89. [CrossRef]
39. Molinos-Senante, M.; Hernández-Sancho, F.; Sala-Garrido, R. Economic feasibility study for wastewater treatment: A cost-benefit analysis. *Sci. Total Environ.* **2010**, *408*, 4396–4402. [CrossRef]
40. Tulika, T.; Mala, A. Pharmaceutical potential of aquatic plant *Pistia stratiotes* (L.) and *Eichhornia crassipes*. *J. Plant Sci.* **2015**, *3*, 10–18. [CrossRef]
41. Koffuor, G.A.; Kyei, S.; Woode, E.; Ekuadzi, E.; Ben, I.O. Possible Mechanism of Anti-Inflammatory Activity and Safety Profile of Aqueous and Ethanolic Leaf Extracts of *Pistia stratiotes* Linn (Araceae). *J. Ghana Sci. Assoc.* **2012**, *14*, 69–81.
42. Khan, M.A.; Marwat, K.B.; Gul, B.; Wahid, F.; Khan, H.; Hashim, S. *Pistia stratiotes* L. (Araceae): Phytochemistry, use in medicines, phytoremediation, biogas and management options. *Pak. J. Bot.* **2014**, *46*, 851–860.
43. Kiristos, T.G.; Kebede, A.; Chaithanya, K.K.; Zenebe Teka, M. Evaluation of in vitro antibacterial potential of *Eichhornia crassipes* leaf extracts. *Drug Invent. Today* **2018**, *10*, 3824–3831.
44. Begum, S.L.R.; Himaya, S.M.M.S.; Afreen, S.M.M.S. Potential of Water Hyacinth (*Eichhornia crassipes*) as Compost and its Effect on Soil and Plant Properties: A Review. *Agric. Rev.* **2021**, *43*, 20–28. [CrossRef]

45. Rakotoarisoa, T.F.; Richter, T.; Rakotondramanana, H.; Mantilla-Contreras, J. Turning a Problem Into Profit: Using Water Hyacinth (*Eichhornia crassipes*) for Making Handicrafts at Lake Alaotra, Madagascar. *Econ. Bot.* **2016**, *70*, 365–379. [CrossRef]
46. Hernández-Shek, M.A.; Cadavid-Rodríguez, L.S.; Bolaños, I.V.; Agudelo-Henao, A.C. Recovering biomethane and nutrients from anaerobic digestion of water hyacinth (*Eichhornia crassipes*) and its co-digestion with fruit and vegetable waste. *Water Sci. Technol.* **2016**, *73*, 355–361. [CrossRef] [PubMed]
47. Yan, S.H.; Song, W.; Guo, J.Y. Advances in management and utilization of invasive water hyacinth (*Eichhornia crassipes*) in aquatic ecosystems—A review. *Crit. Rev. Biotechnol.* **2017**, *37*, 218–228. [CrossRef] [PubMed]
48. Sharma, P.; Pandey, A.K.; Udayan, A.; Kumar, S. Role of microbial community and metal-binding proteins in phytoremediation of heavy metals from industrial wastewater. *Bioresour. Technol.* **2021**, *326*, 124750. [CrossRef]
49. Rezania, S.; Ponraj, M.; Talaiekhozani, A.; Mohamad, S.E.; Md Din, M.F.; Taib, S.M.; Sabbagh, F.; Sairan, F.M. Perspectives of phytoremediation using water hyacinth for removal of heavy metals, organic and inorganic pollutants in wastewater. *J. Environ. Manag.* **2015**, *163*, 125–133. [CrossRef]
50. Hegazy, A.K.; Abdel-Ghani, N.T.; El-Chaghaby, G.A. Phytoremediation of industrial wastewater potentiality by *Typha domingensis*. *Int. J. Environ. Sci. Technol.* **2011**, *8*, 639–648. [CrossRef]
51. Mustafa, H.M.; Hayder, G.; Mustapa, S.I. Circular Economy Framework for Energy Recovery in Phytoremediation of Domestic Wastewater. *Energies* **2022**, *15*, 3075. [CrossRef]
52. Germaine, K.J.; Byrne, J.; Liu, X.; Keohane, J.; Culhane, J.; Lally, R.D.; Kiwanuka, S.; Ryan, D.; Dowling, D.N. Ecopiling: A combined phytoremediation and passive biopiling system for remediating hydrocarbon impacted soils at field scale. *Front. Plant Sci.* **2015**, *5*, 759. [CrossRef]
53. Siswoyo, E.; Utari, A.W.; Mungkari, L.G.N. Adsorption Combined Phytoremediation System for Treatment of Laundry Wastewater. *MATEC Web Conf.* **2019**, *280*, 05002. [CrossRef]