Environment and Natural Resources Journal

Volume 24
Issue 6
2026

Integrating Phytoremediation and Socio-Economic Potential of Water Hyacinth for Sustainable Post-Mining Void Management

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ARTICLE INFO

Received: 14 Nov 2025
Received in revised: 3 Jul 2026
Accepted: 16 Jul 2026
Published online: 29 Sep 2026
DOI: 10.32526/ennrj/24/20250324

Keywords:
Ecological restoration/ Post-mining management/ Phytoremediation/ Sustainable development/ Water hyacinth

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ABSTRACT

Post-mining void represents critical environmental challenges due to water contamination, unstable slopes, and limited ecological recovery. These problems persist in many coal mining areas in Indonesia, threatening surrounding ecosystems and communities. Addressing these challenges requires an integrated reclamation approach that combines ecological and socio-economic functions. Therefore, this study aimed to develop an integrated reclamation model using *Eichhornia crassipes* (water hyacinth) as a phytoremediation agent for sustainable post-mining void management. A qualitative literature synthesis was conducted using Scopus, Web of Science (WoS), and Garuda databases, focusing on peer-reviewed articles published between 2017 and 2025. References were screened based on publication type, language, ecological relevance, and applicability to tropical environments. The selected studies were analyzed through content analysis, tabulation, and conceptual design synthesis to identify phytoremediation mechanism and formulate a reclamation model. The results showed that *E. crassipes* effectively removed heavy metals, nutrients, and organic pollutants across diverse wastewater conditions, while the harvested biomass offered opportunities for value-added utilization. This multifunctional approach connects ecological restoration with community participation and circular biomass management. However, pilot-scale validation and economic feasibility assessments remain necessary before broader implementation in post-mining landscapes.

HIGHLIGHTS

- A nature-based reclamation model using *E. crassipes* in the proposed model.
- The design integrates phytoremediation and local livelihoods.
- *E. crassipes* improves water quality in post-mining void.
- Biomass utilization creates added socio-economic value.
- The model supports sustainable post-mining management.

1. INTRODUCTION

Coal mining activities have generated extensive post-mining void that pose persistent environmental challenges worldwide, particularly in major coal-producing countries (Pambudi et al., 2025). In Indonesia, hundreds of mining voids remain after extraction activities, many of which contain stagnant water characterized by low pH, elevated concentrations of dissolved metals, and poor ecological productivity (Pagoray and Ghitarina, 2020; Pambudi et al., 2023). These abandoned voids not only threaten surrounding aquatic ecosystems but also increase the risk of slope instability, accidental drowning, and long-term environmental degradation (Martyushev et al., 2025).

Acid mine drainage (AMD) is one of the most critical issues associated with post-mining void (Moyo et al., 2024). Oxidation of sulfide minerals, particularly pyrite, produces acidic conditions that mobilize toxic metals such as Fe, Mn, Pb, Cd, and Cu

Citation: Pambudi PA, Utomo SW, Handoko RS. Integrating phytoremediation and socio-economic potential of water hyacinth for sustainable post-mining void management. Environ. Nat. Resour. J. 2026;24(6):737-750. (https://doi.org/10.32526/ennrj/24/20250324)

into water column (Mahanta et al., 2024; Shi et al., 2025). Previous studies have reported pH values below 4 and heavy metal concentrations exceeding environmental thresholds in several tropical coal mining voids, thereby limiting natural recovery processes and constraining post-mining land utilization (Srivastava et al., 2017; Woodbury et al., 2020). Consequently, reclamation strategies are required to comply with regulatory obligations, restore ecological functions, and reduce risks to nearby communities (Pambudi et al., 2025; Yuan et al., 2024).

Conventional remediation approaches for mining voids commonly rely on physical and chemical treatments, including liming, coagulation, and an active neutralization system (Edo et al., 2024; Noor et al., 2024). Despite being effective in improving water quality, these methods are often expensive, energy-intensive, and require continuous maintenance, thereby limiting long-term applicability, particularly in developing countries (Mothetha et al., 2023; Pambudi et al., 2025; Sekhohola-dlamini et al., 2022). This limitation has stimulated growing interest in nature-based solutions that are environmentally compatible and economically feasible.

Bioremediation can be further classified into phytoremediation (plants) (Sharma et al., 2023), mycoremediation (fungi) (Shruthi and Hemavathy, 2024), phycoremediation (algae) (Ordóñez et al., 2023), microbioremediation (Abo-Alkasem et al., 2023), and zoobioremediation (animals) (Reich et al., 2023). Each group plays a specific remedial role depending on the contaminated medium and pollutant characteristics (Chen and Ding, 2023). Among these methods, phytoremediation is the most widely used and well-known approach (Sharma et al., 2023), employing plants to reduce or even eliminate environmental pollutants, specifically in water and soil (Buslima et al., 2025; Sachin and Sonal, 2023). Common plants used in phytoremediation include *Eichhornia crassipes* (water hyacinth) (González-Tavares et al., 2023; Serafini et al., 2024), *Helianthus annus* (Waseem et al., 2024), *Azolla pinnata* (Soliman et al., 2025), *Pistia stratiotes* (Khambali et al., 2024), and *Salvinia molesta*. Among these species, *E. crassipes* has attracted considerable attention because of its rapid growth, extensive root system, high adaptability, as well as remarkable capacity to accumulate heavy metals and excess nutrients from contaminated water (Pagoray and Ghitarina, 2020; Ullah and Rahman, 2024).

The majority of existing studies on *E. crassipes* have focused on domestic wastewater (Buslima et al., 2025), industrial effluents, rivers, lakes, or artificial ponds (Panneerselvam and Priya, 2023; Tumembouw et al., 2024). Studies investigating its application in coal mining remain scarce and predominantly evaluate only pollutant removal efficiency (Hasani et al., 2021; Pagoray and Ghitarina, 2020). Furthermore, previous studies rarely extend the discussion beyond technical remediation outcomes, overlooking how harvested *E. crassipes* biomass could generate socio-economic benefits that support the sustainability of reclamation programs.

Although phytoremediation capacity of *E. crassipes* has been extensively documented, limited attention has been given to integrating ecological restoration functions with biomass-based livelihood opportunities in post-mining landscapes. This integration is important because the harvested biomass has demonstrated potential as a feedstock for compost production (Gezahegn et al., 2024), handicrafts (Ifa et al., 2023), animal feed supplements (Guchhait et al., 2025), and bioenergy products (Nandiyanto et al., 2023), thereby creating incentives for community participation in reclamation activities.

The novelty of this study lies in proposing an integrated conceptual model that combines phytoremediation function of *E. crassipes* with socio-economic utilization to support sustainable post-mining void reclamation. In contrast to previous investigations primarily assessing pollutant removal performance, this study develops a reclamation design that simultaneously addresses water quality improvement, ecological recovery, biomass valorization, and local community empowerment. Therefore, this study aimed to investigate the potential of *E. crassipes* as a phytoremediation agent for coal mining void reclamation and to formulate an integrated reclamation model based on ecological and socio-economic considerations. By connecting environmental restoration with community-based biomass utilization, the results contribute a nature-based and socially inclusive approach that may enhance the effectiveness and long-term sustainability of post-mining management.

2. METHODOLOGY

This study employed a qualitative approach aimed at understanding the potential of *E. crassipes* as a phytoremediation agent. The process started with determining the study topic, followed by selecting the

databases that would be used for literature exploration. To improve transparency and reproducibility, the literature synthesis followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) model as a guiding procedure for identification, screening, eligibility assessment, and inclusion of relevant studies (Page et al., 2021). Although this study did not aim to conduct a quantitative meta-analysis, the PRISMA approach was adopted to minimize selection bias as well as ensure a systematic and traceable review process. The number of records identified, screened, excluded, and retained at each stage was documented and summarized using PRISMA flow diagram (Figure 1). Three databases were selected to ensure comprehensive and credible sources, namely Scopus and Web of Science (WoS) as an international database and Garuda (Garba Rujukan Digital), a trusted national database. The selection of Scopus, WoS, and Garuda databases was based on complementary considerations. Scopus and WoS were selected because both represent two of the largest international abstract and citation databases, covering high-quality peer-reviewed journals across environmental science, ecological restoration, and mining disciplines. Meanwhile, Garuda was included to capture nationally relevant studies and Indonesian experiences related to post-mining reclamation and the use of *E. crassipes* that may not be indexed internationally. The combination of both databases enabled broader coverage of global scientific evidence while maintaining contextual relevance to tropical and Indonesian post-mining conditions.

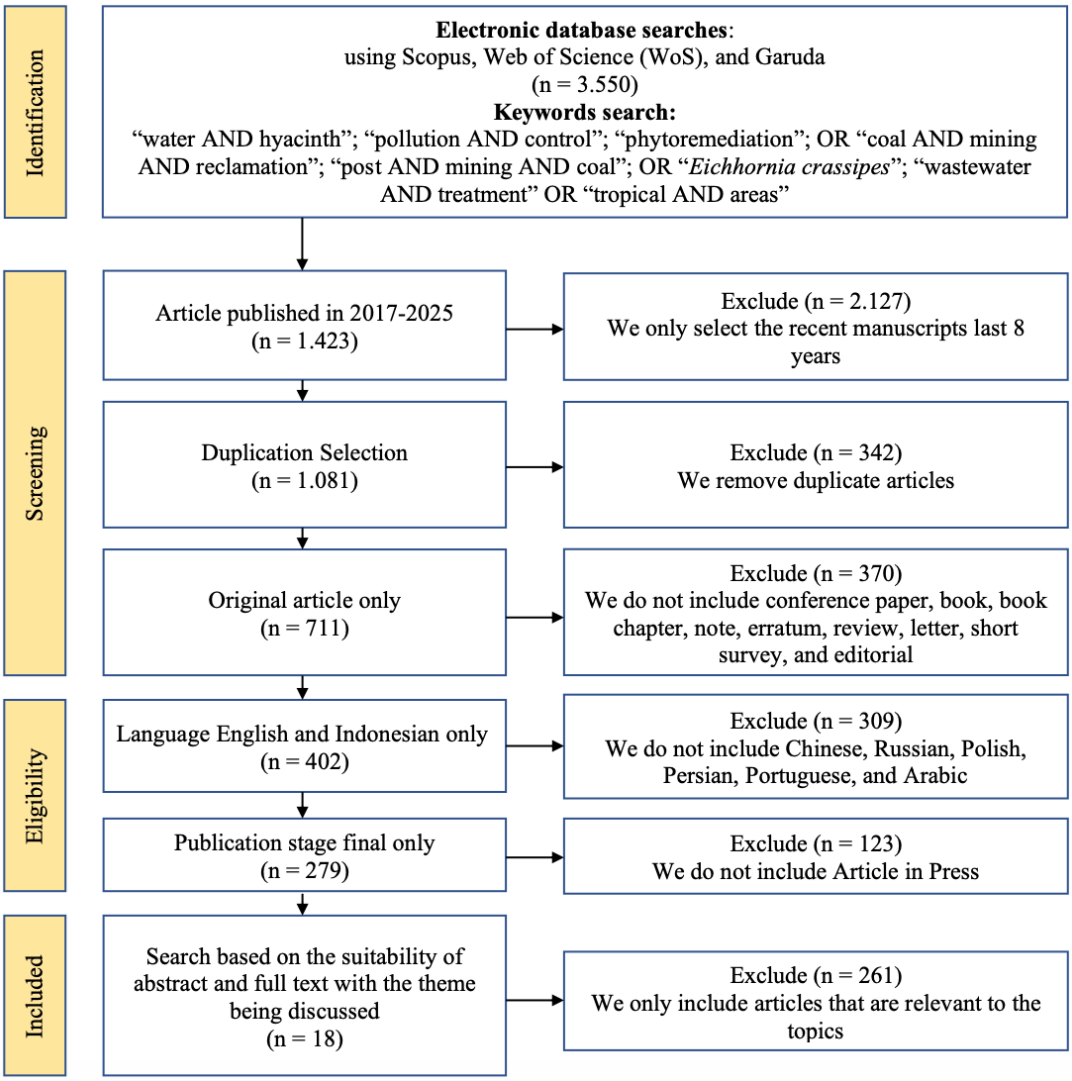


Figure 1. PRISMA workflow

In both databases, a set of specific keywords was applied to guide and refine the search process. These keywords included waste management, pollution control, bioremediation, phytoremediation,

water hyacinth, and *E. crassipes*. Using the same keyword sets across databases ensured consistency in identifying relevant and comparable studies.

The next step involved the selection of references based on several criteria:

(1) The source must be an article-type publication,

(2) Published between 2017 and 2025,

(3) Written in English and Indonesian, and

(4) Focused on tropical areas, where *E. crassipes* commonly grows and is widely utilized.

The publication period of 2017-2025 was intentionally selected to capture the most recent developments in phytoremediation studies and post-mining reclamation practices. During this period, there has been a growing emphasis on nature-based solution circular economic considerations in environmental restoration initiatives. Restricting the review to studies published in the last decade ensured that the synthesized evidence reflected current technological advancements and evolving perspectives on sustainable mine reclamation. Moreover, the selected timeframe coincides with the increasing recognition of *E. crassipes* not only as a phytoremediation agent but also a potential biomass resource, thereby aligning the reviewed literature with the integrated ecological and socio-economic focus of this study. The criteria ensured that the reviewed literature was current, relevant, and aligned with ecological context of the study. After the references were screened and selected, data processing was carried out in three stages:

1. Content analysis to extract core findings related to phytoremediation ability of *E. crassipes*,

2. Tabulation analysis to organize data systematically into tables, matrices, and comparable categories, and

3. Illustrations, where visual summaries and diagrams were developed to enhance clarity and understanding.

The processed information was then used in the data analysis stage, employing exploratory descriptive analysis to interpret patterns, mechanisms, and applications of *E. crassipes* in pollutant removal. Since this study proposed a conceptual reclamation design, a validity assessment was conducted through triangulation of evidence derived from the reviewed literature. The proposed model was developed only from design components that consistently emerged across multiple studies concerning phytoremediation performance, post-mining rehabilitation requirements, and biomass utilization pathways. The conceptual design was subsequently evaluated using four criteria adapted from design-based environmental studies, including environmentally sustainable, economically profitable, socially acceptable, and technologically manageable. This process strengthened the credibility of the proposed model and ensured that it was supported by convergent evidence rather than isolated results.

3. RESULTS AND DISCUSSION

3.1 Ecosystem services of water hyacinth (*E. crassipes*)

E. crassipes is an aquatic plant that offers diverse benefits across multiple dimensions. Environmentally, it is highly effective as phytoremediation agent due to the remarkable ability to absorb heavy metals and pollutants, thereby contributing to the rehabilitation of aquatic ecosystems (Nooryaneti et al., 2022). Economically, the plant can be processed into handicrafts, compost, animal feed, and even biogas feedstock, all of which have the potential to enhance community income (Guchhait et al., 2025; Ifa et al., 2023; Maulidyna et al., 2021). From a social perspective, the utilization creates new employment opportunities and fosters local community empowerment (Goel and Kalamdhad, 2018; Islam et al., 2021). Figure 2 shows the various potential benefits of *E. crassipes* across social, economic, and environmental aspects.

E. crassipes offers substantial potential benefits across social, economic, and environmental dimensions. From a social standpoint, it can be used as a raw material for creative industries and small and medium enterprises (Ifa et al., 2023). Furthermore, women farming groups or community organizations, such as the family welfare and empowerment organization (PKK), may process *E. crassipes* into handicraft products such as bags, mats, and other woven goods with high market value (Agustin et al., 2023). This plant has also been used in the production of traditional medicine due to the bioactive compounds. Gebrehiwot et al. (2022) identified several properties in *E. crassipes*, including anti-inflammatory, antioxidant, antifungal, anti-aging, anticancer, hepatoprotective, and antibacterial activities. Considering these bioactive properties, the plant holds strong potential to enhance community productivity through community-based economic empowerment initiatives.

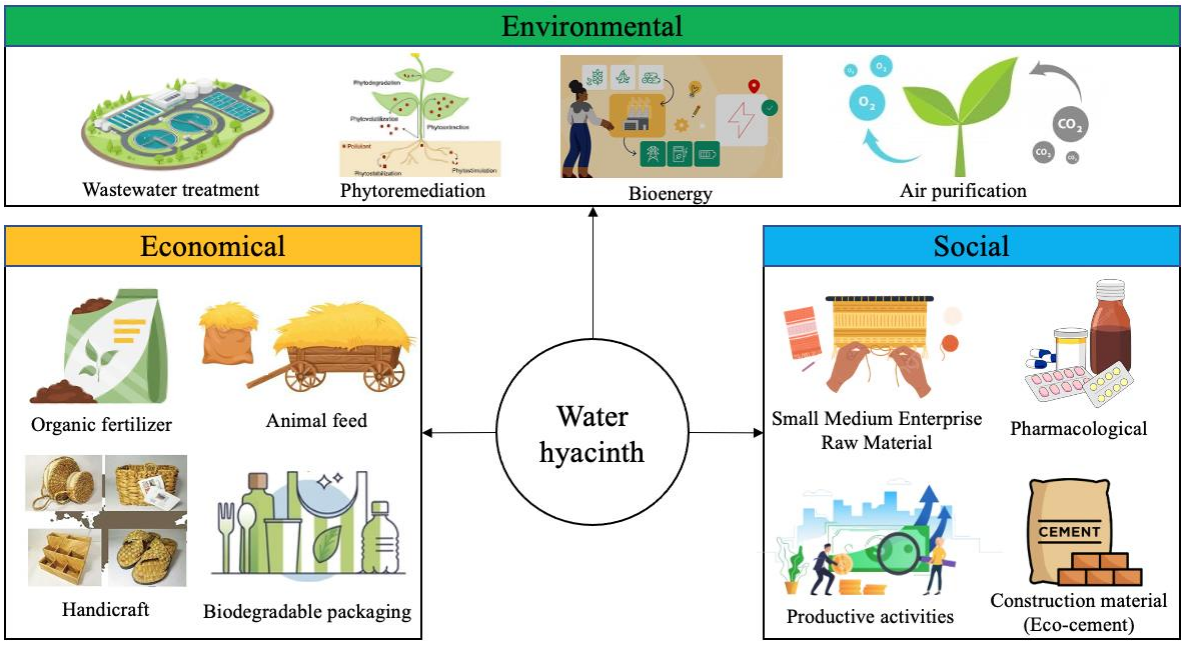


Figure 2. Potential benefits of *E. crassipes* from social, economic, and environmental perspectives. Source: Authors illustration

From an economic perspective, *E. crassipes* offers considerable potential for value addition. The plant can be processed into high-quality organic fertilizer. Sofyan et al. (2023) reported that compost made from *E. crassipes* combined with N, P, K, and S fertilizers significantly improved shallot yields, as evidenced by greater fresh and dry weights and a higher number of bulbs. These results indicate that compost can enhance agricultural productivity while reducing dependence on chemical fertilizers. Furthermore, Fanta et al. (2024) found that the plant could replace up to 37.5% of commercial concentrate used for the growth and fattening of sheep and goats. This implies that the plant serves as a functional feed alternative and lowers livestock production costs. In addition, *E. crassipes* also serve as a raw material for handicrafts, including bags and other accessories. According to Ifa et al. (2023), handicraft products, such as baskets, are sold for 55,000-65,000 IDR, while placemat baskets are priced at 24,000-30,000 IDR, marketed both offline and online through platforms including Instagram, TikTok, websites, Shopee, Tokopedia, and Facebook marketplaces. Albushairi and Huda (2021) further demonstrated that *E. crassipes*-based handicrafts possess high market appeal, particularly when promoted as eco-friendly products aligned with the principles of green products and behaviour. Moreover, Duruin et al. (2022) showed that eco-friendly packaging, particularly bioplastics made from *E. crassipes*, is increasingly in demand as a sustainable alternative to single-use plastics.

From an environmental perspective, ecological value is closely related to the ability to support pollutant removal and ecosystem restoration, which are discussed in detail in the following section (Panneerselvam and Priya, 2023). Studies have shown that *E. crassipes* can reduce levels of biochemical oxygen demand (BOD), total dissolved solids (TDS), and heavy metals such as lead in domestic wastewater (Huynh et al., 2021). Moreover, the plant holds great potential as a source of bioenergy, particularly biogas and biofuel, due to the high cellulose and hemicellulose content (Nandiyanto et al., 2023; Archibong and Ekanim, 2023). *E. crassipes* also contributes to air purification by absorbing airborne pollutants and enhancing oxygen levels in the surrounding environment (Iqbal et al., 2025).

3.2 Application of water hyacinth (*E. crassipes*) as a phytoremediation agent

E. crassipes is highly effective as a phytoremediation agent, capable of absorbing pollutants including nitrates, phosphates, and heavy metals from aquatic environments (Singh and Balomajumder, 2021). The plant shows rapid growth and strong adaptability to polluted water conditions (Iqbal et al., 2025). According to these characteristics, *E. crassipes* has significant potential to improve water quality and support the restoration of aquatic ecosystems, including those found in mining areas, particularly in void ecosystems. Table 1 shows data on the use of *E. crassipes* as a phytoremediation agent.

Table 1. Application of *E. crassipes* as a phytoremediation agent

No	Type of Waste	Contaminant	Country	Results	References
1	Domestic wastewater	COD, NH3-N, & PO_4^{3-}	Malaysia	Reduce COD by 86.7-100%, NH_3-N by 79-99.6%, and PO_4^{3-} by up to 80%.	Buslima et al. (2025)
2	Organochlorine pollutants	POPs	Indonesia	POPs absorbed in roots up to 1.12 ppm, stems 0.88 ppm, and leaves 0.53 ppm on average.	Tumembouw et al. (2024)
3	Industrial wastewater	Cu, Al, Pb, Hg, Cd, Ar, PO_4^{3-}, & N	Colombia	Reduces concentrations of Cu, Al, Pb, Hg, Cd, and Ar up to 70% and PO_4^{3-}, and N compounds by 50%.	Monroy-Licht et al. (2024)
4	Industrial wastewater	Ni & Cu	Mexico	At 30°C, absorbed Ni at 349 mg/g and Cu at 294.1 mg/g.	González-Tavares et al. (2023)
5	Industrial wastewater	Pb	Indonesia	After 12 days of treatment, biomass reached 75.46 g for 4 ppm Pb and 79.00 g for 2 ppm Pb.	Fahruddin et al. (2023)
6	Textile industry wastewater	pH, COD, TS, TSS, Cl, & SO_4	India	Increased pH by 25.62%, reduced COD by 69%, TS by 25.71%, TDS by 34.61%, Sulphate and Chloride by 45%.	Sachin and Sonal (2023)
7	Textile industry wastewater	TSS	Indonesia	Reduced TSS by 54 mg/L, equivalent to 71.12%.	Nooryaneti et al. (2022)
8	Petroleum effluent	COD & BOD	Indonesia	At 20% effluent concentration after 2 months, COD and BOD decreased by 3.73 mg/L and 9.14 mg/L, respectively at 30% concentration, COD and BOD decreased by 3.73 mg/L and 1.22 mg/L.	Hardestyariki and Fitria (2022)
9	Reclaimed coal mining in South Kalimantan, Indonesia	Fe	Indonesia	The application of organic material (OM) in *E. crassipes* media increased Q_{max} values from 2,077 to 2,348-3,259 mg/kg.	Saidy et al. (2021)
10	Lake Tana, Ethiopia	DO, SRP, TP, NO_3-N, & TN	Ethiopia	Increased DO from 3.3 to 4. Mg/L, SRP from 0.012 to 0.023 mg/L, TP from 0.24 to 0.28 mg/L, NO_3-N from 0.074 to 0.097 mg/L, and TN from 2.1 to 3.2 mg/L.	Endgaw (2021)
11	Wastewater	Phenol & CN-	India	Reduced phenol by 96.42% (300 mg/L) and cyanide by 92.66% (30 mg/L).	Singh and Balomajumder (2021)
12	Domestic wastewater	COD, BOD, & pH	Indonesia	Reduced pH from 9 to 7, maintained COD at 296.45 mg/L, and increased BOD from 14.813 mg/L to 80.850 mg/L.	Rahmawati and Warsito (2020)
13	Industrial wastewater	Cr^{6+}	Indonesia	At 120 ppm for 14 days, remediated Cr^{6+} by 62-68%.	Taufikurahman et al. (2020)
14	Laboratory-based small-scale experiment	Cr & Cu	Pakistan	Cr accumulation in root was 90 mg, in leaves 53 mg and Cu accumulation in root was 86 mg, in leaves 50 mg. The heavy metal significantly decreased from day 1 to day 30.	Tabinda et al. (2020)
15	Ramsar Wetland, Central Mexico	Co, Zn, As, Ni, Cu, Pb, Ti, Cr, Ba, Mo, & V	Mexico	*E. crassipes* absorb potential toxic metals from the water in the total plant was (all values in mg/kg of dry weight), is Co 21±9, Zn 408±300, As 12±6, Ni 93±21, Cu 93±69, Pb 53±29, Ti 1,067±643, Cr 78±55, Ba 362±39, Mo 14±0.6, and V 96±35.	Tabla-Hernandez et al. (2019)
16	Batujai Reservoir Pollution	Pb	Indonesia	Average Pb accumulation in roots reached 33.83 bioconcentration factor (BAF), ranging from 19.74 70 42.11 BAF.	Rahim and Soeprobowati (2018)

Notes: BOD (Biological Oxygen Demand), Cd (Cadmium), Cl (Chloride), CN- (Cyanide), COD (Chemical Oxygen Demand), Cu (Copper), Cr (Chromium), Cr^{6+} (Hexavalent Chromium), DO (Dissolved Oxygen), Pb (Lead), POPs (Persistent Organic Pollutants), SRP (Soluble Reactive Phosphorus), TP (Total Phosphorus), TN (Total Nitrogen), TSS (Total Suspended Solids)

Table 1 shows that *E. crassipes* has broad phytoremediation capabilities across diverse wastewater types, ranging from domestic and industrial effluents to petroleum, textile, and reservoir pollution. A consistent trend arising from these studies is the species ability to improve key water quality parameters, including reductions in COD, BOD, TSS, nutrients, and selected toxic compounds, while simultaneously accumulating heavy metals, namely Pb, Cu, Cr, Ni, Hg, and Cd. However, remediation performance was not uniform among contaminants. Organic pollutants and nutrients generally showed relatively high removal efficiencies, as reflected by COD reductions reaching 86.7-100% and ammonia removal up to 99.6% (Buslima et al., 2025), while heavy metal uptake varied considerably depending on the metal species, exposure duration, wastewater characteristics, and environmental conditions. These variations suggest that the effectiveness of *E. crassipes* is highly context-dependent and influenced by factors such as pH, pollutant concentration, hydraulic retention time, and plant physiological responses.

Despite these promising results, several limitations remain evident in the existing literature. Most studies were conducted under controlled experimental conditions or focused on conventional wastewater systems, while evidence from more complex environments such as post-mining void remains scarce. Mining void waters are typically characterized by acidic conditions (Woodbury et al., 2020), elevated dissolved metal concentrations (Gupta et al., 2025), fluctuating hydrological regimes (Martyushev et al., 2025), and low ecological productivity (Sukarman and Gani, 2020), which may affect phytoremediation performance differently from municipal or industrial wastewater systems. In addition, previous studies have predominantly emphasized short-term pollutant removal efficiency while paying limited attention to post-harvest biomass management, long-term maintenance requirements, and socio-economic feasibility. These gaps underscore the need for future studies to evaluate *E. crassipes* under actual post-mining conditions and to adopt integrated approaches that combine remediation effectiveness with sustainable biomass utilization and community participation to support long-term reclamation outcomes.

3.3 Opportunities and challenges of water hyacinth (*E. crassipes*) as a phytoremediation agent

E. crassipes has great potential for utilization as a phytoremediation agent. However, several challenges must be addressed to ensure the effective and sustainable application. To provide a more comprehensive understanding, Table 2 presents a summary matrix of the key opportunities and challenges associated with the use of *E. crassipes* in environmental remediation. This matrix aims to help readers gain an integrated overview and make informed decisions regarding the appropriate strategies for remediating environmental pollution.

Table 2. Opportunities and challenges of *E. crassipes* as a phytoremediation agent

Aspect	Opportunities	Challenges
Availability	Widely distributed, abundant, and easily obtained.	Potentially invasive, may dominate aquatic environments, and disrupt ecosystem stability.
Remediation capacity	Effective in stabilizing pH, reducing COD, TSS, and BOD, and absorbing heavy metals and excess nutrients.	Effectiveness varies depending on environmental conditions.
Cost	Low-cost due to easy accessibility and simple processing.	Requires post-mining handling for optimization and further treatment.
Socio-Economic	Potential to enhance community income through the production of handicrafts, compost fertilizer, and biogas.	Requires training and capacity building to produce value-added products.
Ecological	Contributes to improving and restoring water quality (aquatic habitats) affected by mining activities.	Risk of invasiveness leading to eutrophication and massive surface coverage.
Technological	Opportunities for integration with ecological engineering and technology to optimize remediation performance.	Limited research and development in certain regions and a need for stronger financial support.

Based on Table 2 and considering both the opportunities and challenges, *E. crassipes* demonstrates strong potential to serve as a phytoremediation agent in mining void due to the high adaptability and rapid colonization capability. According to Singh and Balomajumder (2021),

E. crassipes possesses a fibrous root system that extends deeply into the water column, enabling it to trap a wide range of pollutants. Hardestyariki and Fitria (2022) also reported that the plant hollow stems and broad leaves allow for pollutant accumulation in both tissue structures.

The opportunities and challenges associated with *E. crassipes* underscore a common trade-off in nature-based remediation strategies. The same biological characteristics that contribute to the remediation efficiency, including rapid growth and extensive biomass production, also underline the invasive potential (Correa-Mejía and Garcés-Gómez, 2025). Consequently, successful implementation depends not only on pollutant removal capacity but also on adaptive management strategies such as periodic harvesting, biomass monitoring, and stakeholder involvement. Without these supporting mechanisms, *E. crassipes*-based remediation may inadvertently generate new ecological problems despite its environmental benefits.

Socio-economic utilization should not be viewed only as an additional benefit but a mechanism to enhance the sustainability of reclamation programs. By converting harvested biomass into compost, handicrafts, or bioenergy products, operational costs associated with biomass disposal can be reduced while simultaneously creating incentives for community participation. This circular approach transforms waste management into value creation and may improve the long-term viability of phytoremediation initiatives in post-mining regions.

The variability in remediation performance observed across the studies presented in Table 1 suggests the effectiveness of *E. crassipes* is governed not only by external environmental conditions but also a series of physiological and biochemical adaptations that enable the plant to tolerate and process contaminants. Understanding this mechanism is important for interpreting why this species consistently performs well across different wastewater matrices while showing differences in removal efficiency among pollutant types. Figure 3 shows the principal pathways involved in metal uptake, translocation, detoxification, and sequestration in *E. crassipes*, providing a mechanistic explanation for the trends identified in the reviewed studies.

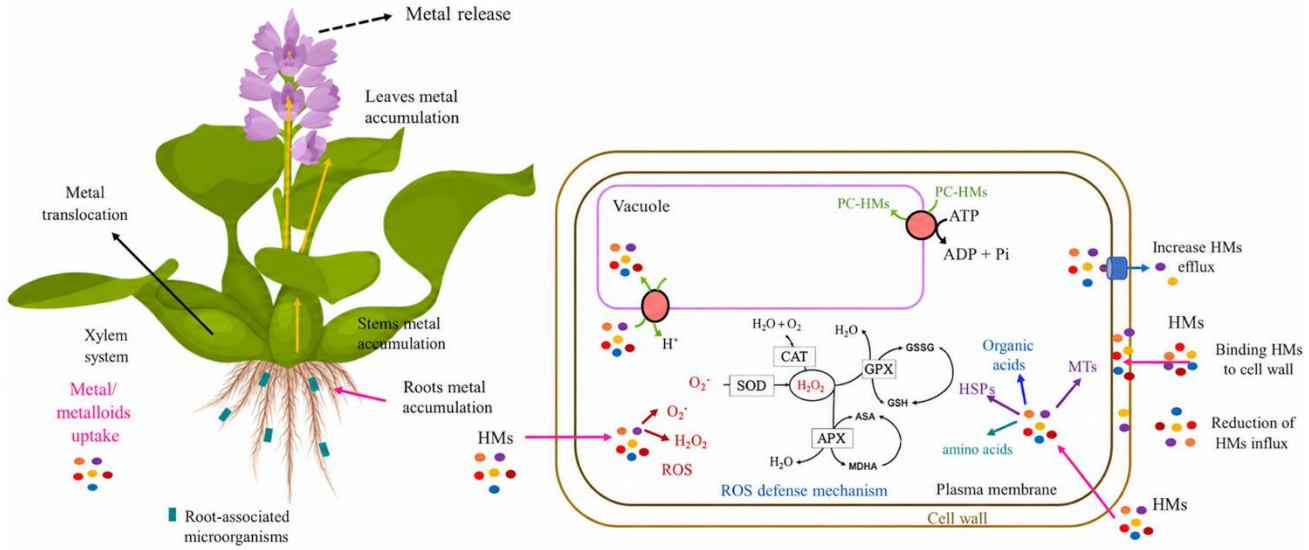


Figure 3. Mechanism of heavy metal elimination/accumulation at the cellular level. Notes: (CAT: Catalase, GPx: Glutathione peroxidase, GSH: Glutathione, GTS: Glutathione S-transferase, HMs: Heavy metals, PC: Phytochelatins, SOD: Superoxide dismutase). Source: Processed from Monroy-Licht et al. (2024)

As shown in Figure 2, phytoremediation by *E. crassipes* involves a coordinated process starting with the absorption of contaminants through the root system, followed by translocation through xylem tissues and subsequent accumulation in roots, stems, or leaves. Once inside plant cells, excess metals can trigger the formation of reactive oxygen species (ROS), which are counteracted by antioxidant enzymes such as superoxide dismutase (SOD), catalase (CAT), glutathione peroxidase (GPX), and ascorbate peroxidase (APX). In parallel, detoxification mechanisms involving phytochelatins,

metallothioneins, organic acids, and vacuolar sequestration reduce metal toxicity and allow the plant to survive under contaminated conditions (Monroy-Licht et al., 2024). These mechanisms help explain the broad contaminant spectrum reported in Table 1 and suggest that the adaptability of *E. crassipes* may be advantageous for the reclamation of mining void waters characterized by multiple stressors. However, the efficiency of these physiological responses may decline under extreme acidity or excessive metal loads commonly found in acid mine drainage environments, indicating that field-scale validation under actual post-mining conditions remains necessary (Pagoray and Ghitarina, 2020).

3.4 Integrated reclamation model for sustainable post-mining void management

Mining void or post-mining pond is an ecological legacy of extraction activities that pose serious environmental challenges (Christian et al., 2023), particularly concerning poor water quality (Mugova and Wolkersdorfer, 2025), elevated concentrations of dissolved heavy metals (Gupta et al., 2025), unstable slopes, and declining ecological functions (Du et al., 2023). Within this context, *E. crassipes* can serve as a nature-based solution due to the high phytoremediation capacity, ecological adaptability, and potential socio-economic benefits (Pagoray and Ghitarina, 2020). However, contrary to previous investigations that primarily focus on pollutant removal efficiency, this study proposes an integrated reclamation model combining ecological restoration with biomass valorization and community participation. The proposed model shifts reclamation practice from a remediation-oriented approach toward a multifunctional system capable of generating environmental, economic, and social benefits simultaneously (Ifa et al., 2023). A simplified schematic design of the proposed reclamation model is shown in Figure 4.



Figure 4. Simple Design of Void Management Based on *E. crassipes*. Source: Authors illustration

The system consists of five interconnected components, including floating *E. crassipes* rafts, vegetative buffer zones, controlled inlet-outlet channels, water quality monitoring points, and biomass utilization areas. Floating rafts act as the primary phytoremediation units, facilitating the uptake of heavy metals and excess nutrients from void waters through an extensive root system (Buslima et al.,

2025). Buffer vegetation established around void perimeter contributes to slope stabilization, runoff filtration, and erosion prevention, particularly important given that mining void slopes may range from 3° to 47° and are highly susceptible to degradation processes (Pambudi et al., 2023). Controlled hydraulic structures regulate circulation patterns and hydraulic retention time to optimize purification efficiency, while monitoring points located at the inlet and outlet sections enable adaptive management through periodic assessment of pH, dissolved oxygen, TSS, and heavy metal concentration (Gupta et al., 2025; Ma et al., 2021). The technical characteristics of each component are summarized in Table 3.

Beyond the technical functions, the proposed model emphasizes the integration of ecological and socio-economic objectives as a prerequisite for long-term sustainability. Periodic harvesting of *E. crassipes* biomass not only prevents uncontrolled proliferation of this invasive species but also creates opportunities for producing compost, handicrafts, animal feed, bioplastics, and bioenergy products. This circular approach transforms harvested biomass from a potential environmental liability into an economic resource that can strengthen local livelihoods and foster community participation (Agustin et al., 2023). The multifunctionality of each system component, as summarized in Table 4, shows that successful mining void reclamation should extend beyond pollution control to ecosystem recovery, economic empowerment, and local stewardship.

Table 3. Design elements of void reclamation system

Component	Function	Technical description	Reference
Floating *E. crassipes* zone	Phytoremediation of water contaminated with heavy metals, nitrates, and phosphates	Constructed using bamboo or recycled plastic rafts	Nash et al. (2019)
Edge buffer vegetation	Absorbs surface runoff and stabilizes void edges/slopes	Planted with vetiver, elephant grass, or *Acacia* sp.	Abba and Sabarinath (2025)
Inlet-outlet flow channels	Regulates circulation and extends hydraulic retention time	Inlet flow from surface runoff or rainfall	Iqbal et al. (2025)
Water quality monitoring points	Measures phytoremediation performance periodically	Fixed side points for pH, heavy metals, DO, TSS, and TDS	Correa-Mejía and Garcés-Gómez (2025)
Biomass utilization area	Harvesting zone for *E. crassipes* to produce handicrafts, fertilizers, bioplastics, and bioenergy	Scheduled based on optimal growth cycle	Nandiyanto et al. (2023)

Table 4. Ecological and socio-economic function matrix of the system design

Component	Function	Technical description	Reference
E. crassipes	Absorbs heavy metal	Used for handicrafts, animal feed, fertilizers, and bioenergy	Gezahegn et al. (2024), Guchhait et al. (2025), Ifa et al. (2023), Nandiyanto et al. (2023)
Artificial floating raft	Supports phytoremediator habitat	Community engagement in raft construction	Agustin et al. (2023), Iqbal et al. (2025)
Buffer vegetation	Prevents erosion and improves landscape	Provides fodder plants and supports soil conservation	Krishnani et al. (2025), Prasetyo et al. (2022)
Water monitoring zone	Evaluates system effectiveness continuously	Generates scientific data and provides community training	Datta et al. (2021), Dechassa (2020), Pambudi et al. (2026)
Biomass harvesting area	Regulates plant life cycle	Alternative source of local income	Degaga (2019), Maulidyna et al. (2021)

The proposed model reflects a transition from conventional post-mining rehabilitation practices toward integrated landscape restoration. This study positions phytoremediation in a broader sustainability perspective in which ecological resilience, circular biomass utilization, and community engagement are mutually reinforcing. However, because the model was developed through literature synthesis, its operational effectiveness under field conditions should be validated via pilot-scale implementation in actual mining void environments. Future studies should evaluate system performance under varying

hydrological and geochemical conditions while assessing economic feasibility and social acceptance among surrounding communities.

Despite the potential advantages, the practical implementation of this model requires careful consideration of operational feasibility and scale-related constraints. The use of floating phytoremediation systems based on locally available materials such as bamboo and recycled plastics may reduce initial investment costs compared to conventional chemical treatments or large-scale engineered remediation technologies (Malik et al., 2025). However, the effectiveness of the proposed system is possibly to vary according to void size, hydrological characteristics, contaminant loads, and maintenance capacity. A larger mining void may require phased implementation strategies and periodic harvesting programs to maintain treatment efficiency and prevent excessive proliferation of *E. crassipes.* Although nature-based solutions are generally considered cost-effective over the long term due to lower energy requirements and the possibility of biomass valorization (Gezahegn et al., 2024), detailed cost-benefit analysis and pilot-scale studies are still needed to determine economic viability under specific site conditions. Therefore, field-based experimentation involving local stakeholders should be prioritized to validate system performance, identify operational limitations, and refine the proposed model before wider adoption in post-mining reclamation practices.

4. CONCLUSION

In conclusion, the reclamation system designed for post-mining void using *E. crassipes* demonstrates a promising, eco-socio-technical approach to sustainable land and water restoration. The integration of floating phytoremediation zones, vegetative buffer strips, controlled inlet-outlet channels, water quality monitoring points, and biomass utilization areas effectively enhances water purification, stabilizes void slopes, and supports local livelihoods. The results confirm that *E. crassipes* efficiently absorbs heavy metals and nutrients, while supporting ecosystem resilience and socio-economic empowerment through biomass valorization. The system is consistent with sustainable reclamation principles, bridging ecological restoration and community-based resource management. Future studies should focus on quantifying long-term remediation efficiency, optimizing plant-microbe interactions, and developing scalable models adaptable to diverse post-mining landscapes. Strengthening policy integration and community participation will be crucial to mainstream this nature-based solution into broader sustainable development and post-mining management models.

AUTHOR CONTRIBUTIONS

Conceptualization; literature search; literature review; writing manuscript: Pambudi PA. Concept-ualization; reviewing manuscript: Utomo SW. Literature search; literature review; illustrating: Handoko RS.

DECLARATION OF CONFLICT OF INTEREST

The authors declare no conflict of interest.

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